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Digital twins for flood defense systems a case study in Amsterdam-Rhine Canal

Eleni Smyrniou, Antonis Mavritsakis, Kin Sun Lam
Deltares, The Netherlands, eleni.smirniou@deltares.nl

Stefan de Graaf, Tim Ebben, Brian de Vogel, Henk Scholten
Sogelink, The Netherlands

ABSTRACT: Digital twins are increasingly pivotal in modern flood defence systems, offering advanced capabilities for monitoring, safety risk prediction, and decision-making. This study explores the application of digital twins in flood defences, focusing on technological innovations that integrate real-time and historical data to assess system safety and optimize emergency measures. A case study in the Amsterdam-Rijn Canal demonstrates the ability of digital twins to assess the current and historical safety of levees under varying return periods. By integrating historical and real-time hydrological data with geotechnical models using Pastas for groundwater dynamics and D-Stability for structural integrity, the digital twin provides a centralized platform for informed decision-making. A visualisation system plays a critical role in communicating these complex relationships, offering clear and actionable insights to stakeholders. Key outcomes include enhanced situational awareness and improved emergency response strategies, enabling asset managers to proactively address vulnerabilities. This work underscores the transformative potential of digital twins in flood defense, providing a scalable framework adaptable to diverse geotechnical and hydrological contexts. Lessons learned highlight the value of integrating multidisciplinary data streams into actionable insights for future applications in adaptive infrastructure management.

KEYWORDS: Digital twin, slope stability, monitoring, flood defences

1 INTRODUCTION

Flood protection systems face increasing challenges as they are both reaching their end of life and are dealing with ever changing conditions of the climate, such as new extremes of rainfall and droughts. Asset managers of these flood protection systems need to be prepared for these extreme scenarios that could fall outside the design specifications of such constructions.

A digital twin is a virtual model that aims to replicate a physical system as closely as possible. In that way, a digital twin allows for real time monitoring of the system and simulation of scenarios. Digital twins play a key role in industries like manufacturing, healthcare, aviation and automotive (Yin et al., 2024). Appreciating their potential in such fields, their performance in managing flood protection assets is investigated in this study.

Digital twins for flood defenses are becoming increasingly relevant as climate change continues to exacerbate the frequency and severity of flooding, as they can create dynamic models that integrate real-time data from various sources to simulate flooding scenarios (Mankowski, 2020; Williams, 2020). There are different applications of digital twins in flood defenses. Digital twins can be used as decision support systems, in which the hydrodynamic modelling is combined with simulation techniques to manage flood risk. Recent examples include a digital twin of the Ahr valley (Water, 2024) or the Resilient Hydro Twin project (den Heijer et al., 2023).

Apart from that, digital twins facilitate enhanced flood prediction and management by enabling cities and municipalities to analyze risks and optimize protective measures against extreme weather events. Successful implementations of digital twins in projects, such as those in Austin (Kim, Oh and Bartos, 2024), Euskirchen and Dresden (Jucho, 2024), demonstrates their potential to contribute to sustainable urban planning and effective flood protection strategies.

The Amsterdam-Rhine Canal (ARC) digital twin extends the above mentioned functionality to scenario simulation and mitigation strategies. One of the core applications of digital twins is the ability to run "what-if" scenarios that simulate the impact of extreme events on urban infrastructure. This allows planners to evaluate current flood risks and assess the efficacy of proposed mitigation measures, such as constructing higher levees or enhancing stormwater systems. With these simulations, cities can make data-driven decisions to improve resilience, such as increasing reservoir capacity prior to anticipated flood events or deploying temporary flood protection devices.

Therefore, the focus of the ARC digital twin is to demonstrate how real-time and historical monitoring data can help manage assets more effectively, as well also evaluate the twin's ability to predict safety under different hydraulic loading and corrosion scenarios.

2 METHODOLOGY

The digital twin focuses on the Betuwepand location including both the west and east side of the canal as it can be seen in Figure 1.

2.1 *Data Collection & Processing*

The first step of constructing the digital twin is collecting all relevant information regarding this particular embankment. An overview of the locations of said data can be seen in Figure 1. The following sources are used to set up the model and calculation:

- Evaporation and rainfall data from the Roal Dutch Meteorological Institute (KNMI) in the station De Bilt. These measurements are both historical, real-time and forecasted.
- Water level of the ARC in the station Mauriksewetering, used for both historical and real-time calculations.
- Water discharge of station Tiel, this includes historical, real-time and 48 hour predictions.
- Various wells installed along the embankment both in the east and west side of the ARC, these measurements are only historical.

Apart from sensor data the digital twin uses cross sections that were created during the stability assessment of the embankment (Ministerie van Infrastructuur en Waterstaat, 2020).

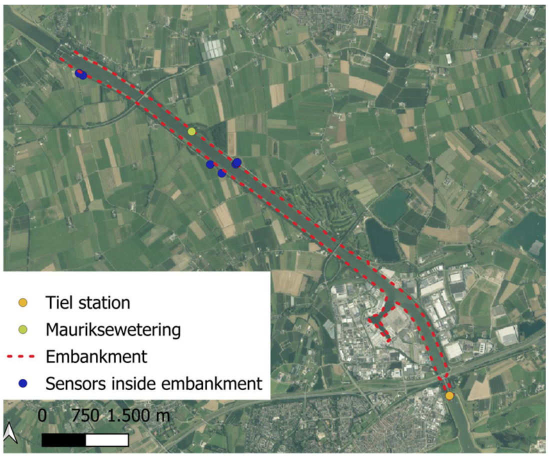

Figure 1 Location of measuring stations along the ARC interest area

2.2 *Modelling Tools*

The ARC digital twin integrates a suite of specialized modelling tools to simulate the behaviour of the levee system under varying hydraulic and geotechnical conditions. These tools are selected to reflect the complex interactions between water levels, soil response, and structural integrity, and are calibrated using both historical and real-time data.

Pastas (Collenteur et al., 2019) is employed for time series analysis, specifically to model the relationship between canal water levels and the phreatic line within the levee. This open-source Python framework allows for the decomposition of groundwater head fluctuations into components driven by rainfall, evaporation, water discharge and surface water levels. In the ARC case, Pastas is calibrated using historical data from KNMI, water discharge and water level measurements from Mauriksewetering, enabling accurate prediction of groundwater responses to hydrological events.

D-Stability is used to assess the factor of safety (FoS) of the levee under different hydraulic loading scenarios. This forms the analytical backbone of the digital twin. The outputs are integrated into a centralized platform that supports scenario simulation, real-time monitoring, and decision-making. The modular architecture ensures that each tool can be updated independently as new data becomes available or as modelling techniques evolve.

2.3 *Digital Twin Architecture*

The Digital Twin is a cloud-based platform on which the software components can be deployed and interfaced. An infrastructure of interconnected modules was designed within this platform to integrate real-time data streams, historical datasets, predictive modeling tools.

The platform connects data inputs with scenario execution. A scheduler runs tasks automatically or on demand, while a parallel processor speeds things up by splitting work across multiple threads. The system leverages external APIs, including the KNMI API for meteorological forecasts and the Waterinfo API for real-time and historical water level data. These inputs are essential for assessing the embankment's stability under both observed and hypothetical conditions. All incoming data are stored and managed via M-IO object storage, which serves as the centralized repository for site-specific information, sensor outputs, model configurations, and simulation results.

For visualizing model outcomes within a geographic context, a web application was built using Sveltekit featuring a custom user interface. Svelte components are used to build dynamic front-end dashboards using the fetched data. The application features an integrated map viewer built with CesiumJS, which is an open-source library for large-scale 3D geospatial data visualization. Both 3D datasets (OGC 3D Tiles) and 2D map layers (WMS/WMTS/GeoJSON) can be loaded, as well as 3D terrains in quantized mesh format. In this case, a quantized mesh was generated for all of the Netherlands based on the open AHN elevation model using the open-source tool 'Cesium Terrain On Demand' (Sogelink, 2025)

The web app connects to the ARC backend to fetch data and show it on the map. Custom shaders draw 3D slip planes accurately on the terrain. It also pulls real-time water levels from Rijkswaterstaat and weather data from KNMI.

3 CASE STUDY: AMSTERDAM-RIJNKANAAL

3.1 *Site Description*

The Amsterdam–Rhine Canal (ARC) site is selected for the digital twin implementation, the embankment is subjected to different hydraulic and geotechnical conditions, necessitating tailored modelling approaches.

The geometry of the site includes an average heigh 4 m. Almost along the whole stretch of the east and west side of the embankment there is a ditch where the water is regulated by the water authorities responsible for the area. The embankment is constructed either by sandy or clayey material, with stratigraphy characterized by clayey and peaty soils until the first sandy layer roughly at depth of 8 meters.

Typical water level variations in the ARC are influenced by upstream discharge, precipitation, and operational controls. At the Mauriksewetering station, historical data shows fluctuations ranging from 1.3 to 5.7 meters with seasonal peaks usually in January, February and December. These variations directly affect the phreatic line within the levee, which is monitored via a network of wells installed along both banks.

The hydraulic boundary conditions for modelling are derived from water level and discharge data at Tiel, which provides both real-time and forecasted inputs. These are critical for simulating return period scenarios and assessing the levee's response under extreme loading conditions.

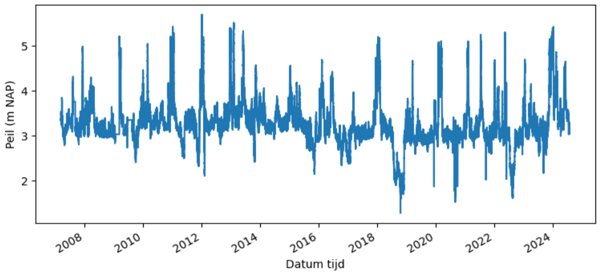

Figure 2 Sensor data of the well in Mauriksewetering for 2008 to 2025

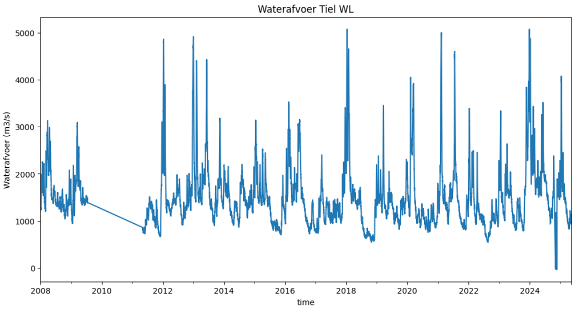

Figure 3 Water discharge in station Tiel

3.2 *Scenario Definition*

There are four scenarios implemented for the ARC digital twin. While each one represents a unique purpose for the asset manager, all of them assess the safety of the embankment .

- Case 1 - Historical situation: In this case the safety of the embankment is calculated for the maximum water level per month from 2008 to 2024.
- Case 2 - Actual situation: In this case, the current water level of the canal together with the KNMI prediction of the current hour are used in the Pastas model to calculate the phreatic line.
- Case 3 - Operational situation: This case illustrates the effect of canal depth on the stability of the embankment. As there is a relationship between dredging (due to inland water traffic), soil resistance and the water pressure in the aquifer.
- Case 4 - High water situation: This case is split into two parts the high water event with mitigation measures and the prediction situation. In the first case the digital twin will calculate the factor of safety during the high water event and how mitigation measures influence the safety factor. The second case is triggered when the station at Tiel predicts a high discharge level, higher than 3000 m/s^3. In this case, the Pastas model is used to make a prediction for the coming 24 hours with a 4 hour interval.

3.3 *Digital Twin Implementation*

3.3.1 *Calibration of Pastas models*

To simulate the groundwater response on the east side of the ARC levee, Pastas models were developed using time series data from multiple sources. The models aim to capture the influence of meteorological and hydraulic drivers on phreatic levels observed in monitoring wells. Essentially there is one Pastas model per monitoring location, in total 5 models are created.

The model integrates the following datasets:

- Groundwater head measurements from sensors B014 to B016 for the east side and MBP_W625050_AL and MBP_W652090_AL for the west side, interpolated to hourly frequency.
- Canal water levels from Mauriksewetering station, interpolated to hourly frequency.
- Water discharge data from TielWL, processed to remove outliers and resampled to hourly frequency.
- Meteorological data (rainfall and evaporation) from KNMI station 260 (De Bilt), converted to hourly resolution.
- Real-time water level data fetched via the Rijkswaterstaat Waterinfo API.

The time series are synchronized to an hourly frequency and missing values are filled using forward and backward interpolation to ensure continuity.

Each of the sensors is calibrated independently using the same Pastas framework. The model includes a Recharge Model combining rainfall and evaporation using a flexible recharge function (FlexModel) and a Gamma response function. Two stress models are also added in the model one using the canal water level as a boundary condition and one using the water discharge as a proxy for regional hydraulic pressure. These stress models are added to a Pastas Model object, which is then solved using historical data starting from 2021. The performance of each sensor can be seen in Table 1. The accuracy of all sensors is consistently above 80%, therefore the values are deemed acceptable for using them for the digital twin.

Table 1 Accuracy of Pastas models per sensor.

Simulated sensor	R^2	RMSE
B014	87.03%	0.13
B015	92.43%	0.08
B016	81.62%	0.12
MBP_W625050_AL	96.34%	0.06
MBP_W652090_AL	95.50%	0.06

The Pastas models are ultimately used to determine the phreatic line in the levee. To translate the sensor simulation to phreatic line we determine the water level at certain characteristic points along the dike, these are shown at Figure 4. The water level is determined as follows for each point:

- Outer Ground Level: Same water level as outer ground, indicating hydrostatic connection to river.
- Outer Crest: Groundwater level at river plus a default bulge effect of 0.5 m.
- Inner Crest: Same bulge effect assumption as the outer crest
- Inner Toe: Because of the drainage effect the water level remains stable at the same level as the toe.
- Ditch: The same water level as the inner toe.
- Inner ground level: Inner water level is determined by the water level of the ditch.

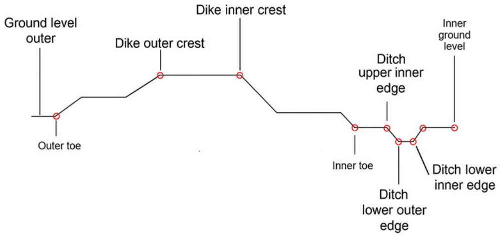

Figure 4 Characteristic points along a dike cross-section

3.3.2 *Setting up the API's and workflows*

To support the implementation of the four defined scenarios, a set of workflows are configured within the ARC digital twin environment. A central scheduler governs the execution of tasks at defined intervals: real-time monitoring and prediction scenarios (Case 2) are triggered every hour to ensure up-to-date safety assessments, while and user-defined high water scenarios (Case 4) are executed on demand or according to user input. The historic (Case 1) and operational (Case 3) scenarios are pre-calculated and the API is just responsible for getting this information to the viewer.

Each of the four scenarios (historical, actual, operational, and high water) is encapsulated as a modular workflow that retrieves relevant inputs, invokes the Pastas model for phreatic line estimation, and calculates the factor of safety. Results are then published to the digital twin interface, providing real-time feedback and supporting decision-making processes. External access to data, model outputs, and status indicators is enabled through standardized RESTful API endpoints, facilitating integration with external tools and dashboards. The Pastas models are recalibrated once per day to ensure that the models represent the most current data.

To support the implementation of the four defined scenarios, a robust API and workflow infrastructure was established within the ARC digital twin environment. As illustrated in Figure 5, the architecture is composed of interconnected modules that integrate real-time data streams, historical datasets, predictive modelling tools, and a dynamic user interface, in that the user can define their own scenario's.

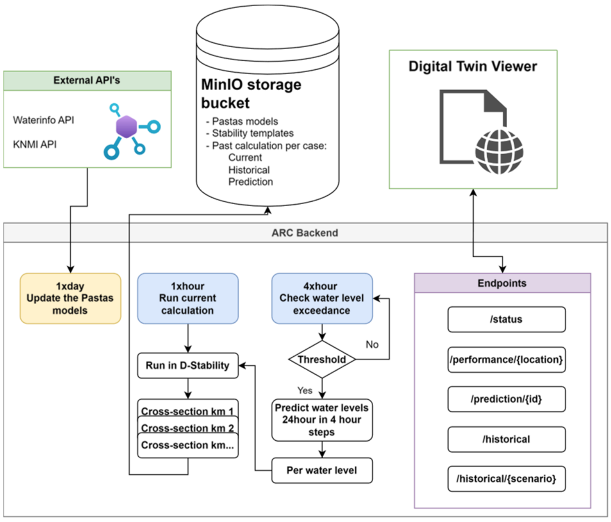

Figure 5 Backend architecture

4 RESULTS

To assess the results of the digital twin we inspect visualisation aspects together with the geotechnical stability analysis. Upon opening the web application, the modelled locations are fetched from the ARC API and visualized on the map. Locations are marked with colour indicators based on the FoS to highlight areas of elevated risk. For example, in Figure 6 kilometres 65.4 to 66.3 appear as high risk, however this is known to the asset manager as these are areas where the assessment of the dike stretch is still under renewal. Evidently giving the asset manager an first view on the areas that require computational or actual improvements.

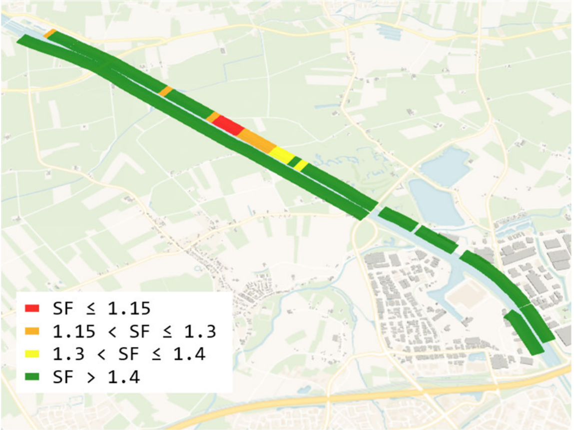

Figure 6 Aerial view of safety along the embankment

Per location, slip planes are rendered and plotted on a cross section styled based on the GeoTOP (TNO – GDN, 2025) to provide lithological context. For each kilometre along the embankment the actual (real-time) safety can be inspected via a dashboard (Figure 7). The current safety factor along with the water level and rainfall is shown together with the slip surface as calculated from D-Stability. In this case a safety factor of 1.44 for a specific water level of 2.94 in the river and an expect rainfall of 54mm, apart from the failure surface of the stability analysis is displayed. In this case this concerns a small superficial failure with a high factor of safety, indicating to the asset manager that there is potentially no alarming conditions.

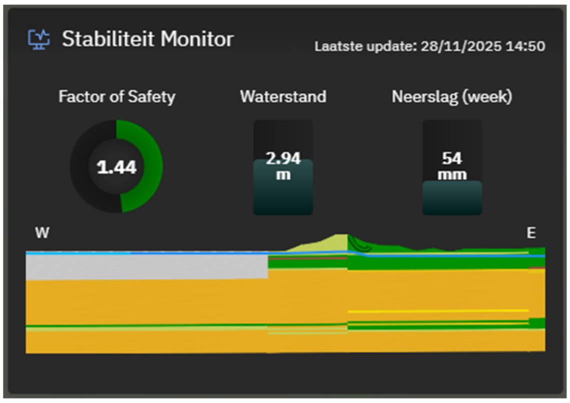

Figure 7 Real-time stability monitor

The historical stability monitor (Figure 8) can also be viewed per cross-section via the dashboard. The user can also view the safety factor, failure surface and water level at that specific timestep. In this case the embankment has a safety factor from 1.0 to 1.3 (in the worst case scenario) from 2008 to 2022. After 2022, the embankment was reinforced that leads to a higher stability factor of roughly 1.5 from 2022. In this case the digital twin helps the asset owner to gain insight into the history of the embankment without having to search through documents of older assessments, increasing the transparency of these reinforcement choices.

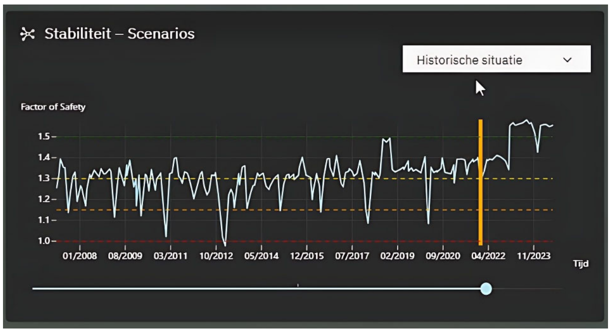

Figure 8 Historic stability monitor

The operational stability of the cross-section is also visible in the dashboard, the stability factor at different dredging levels can be inspected. In this case an assumption is made on how the dredging of the canal bottom would affect the response factor of the aquifer, changing the hydraulic conditions for the stability calculation. As the response factor increases so does the water level which in turns leads to lower safety factors. In this case the impact is from 1.61 to 1.40. In this case the lower dredging of 0.5m has a relatively small failure surface compared to the wider and deeper failure surface when the canal is dredged at 1m. Giving an insight into which threshold could be applied to the dredging of the canal so as not to disturb the dike stability.

A high water scenario with potential mitigation measures is available. In Figure 9 an example of that is shown, in this case the safety factor is below 1.0 when no mitigation measures are applied. However, by implementing either closing the lock doors or by filling in the ditch safety factor increases to an acceptable level. Note that the safety factor is here below 1.0

for demonstration purposes only as the high water scenario chosen for this case is outside what can occur in this area.

Figure 9 High water scenario

The high water scenario is also triggered when the station at Tiel predicts a high discharge level, higher than 3000 m/s^3. In the historical high water level case that happened between 8 and 9 January of 2022 the water level rose to 4.6 m NAP . During this period the stability of the whole Betuwepand stretch was calculated hourly. In this case, there were 18 locations where the safety factor was smaller than 1.42. Each location reveals a specific safety factor and failure surface per time step giving the asset managers the unique ability to inspect specific locations through time as well as having an overview of the whole asset.

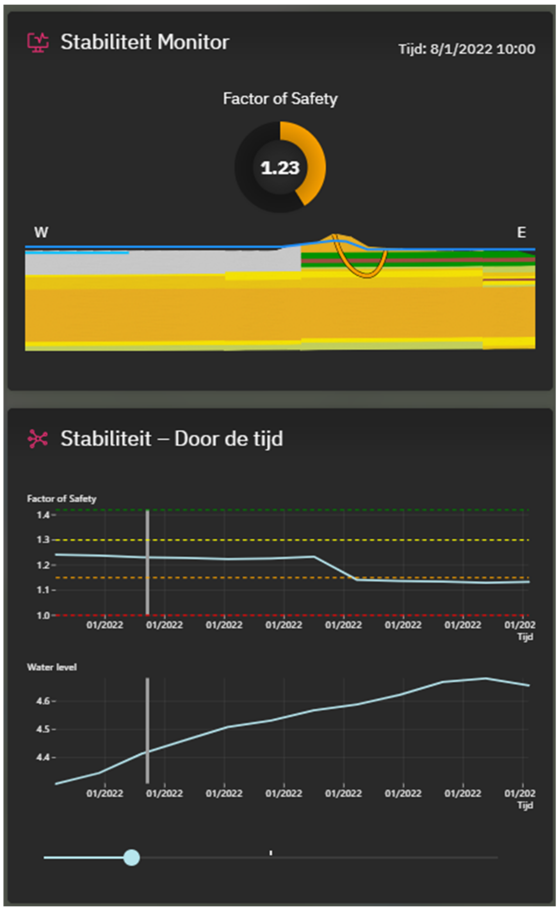

Figure 10 Stability for prediction of one specific cross-section during a high water scenario (East side kilometer 64.7)

5 DISCUSSION

The ARC digital twin demonstrates the potential of integrating real-time and historical data to proactively manage flood defense infrastructure. A major novelty lies in the system's ability to process and visualize complex geotechnical and hydrological data streams in near real time. Achieving this required addressing several computational challenges: ensuring low-latency data ingestion from external APIs, distributing model calculations across parallel threads to reduce execution time, and maintaining synchronization between predictive models and live sensor inputs. These optimizations allow safety assessments that traditionally required days of engineering work to be completed within minutes by asset managers.

Emergency drills and decision-making processes are now informed by real-time data and predictive modelling, reducing response times and enhancing coordination among stakeholders. The modular architecture also allows for seamless updates and integration of new data sources, ensuring the system remains adaptive to evolving conditions.

Despite its strengths, the digital twin faces limitations. For the purpose of this digital twin several assumptions have been made for the scenario simulations (e.g., dredging impact on aquifer response) that may not fully capture the complex subsurface interactions. This implies that the digital twin should be adaptive to new insights about the physics governing these behaviors. The challenge is to find a way to allow the user to interact with such assumptions and modify them.

Compared to traditional dike assessments procedures and drills for crisis situations the digital twin offers a unique way to make decision on the fly that are still based on engineering judgment. It also allows different parties that are not necessarily geotechnical engineers to gain an insight into the state of the asset.

6 CONCLUSIONS

This study demonstrates the significant potential of digital twins in enhancing the safety and resilience of flood defense systems. Through the implementation of the ARC digital twin, we have shown how real-time and historical data integration can support proactive asset management and informed decision-making. These key outcomes include:

- Predictive capabilities: The system successfully forecasts safety dips up to 24 hours in advance, enabling timely interventions.
- Robust modelling: Tools like Pastas and D-Stability provide accurate simulations of groundwater behavior and structural integrity under various scenarios.
- Interactive visualization: The user interface allows stakeholders to explore complex geotechnical data intuitively, improving situational awareness and communication.

The modular architecture of the ARC digital twin is designed for scalability. This flexibility ensures long-term applicability and relevance across diverse geotechnical contexts.

In the future the ARC digital twin will be extended to include sheet pile components located on the north side of the canal. Apart from that the digital twin could be extended to include a systems approach where the input or output of different disciplines is integrated into the current state of the embankment. For example, the integration of when different locks are open or closed and the how pumping of the area from the local authorities effects the embankment.

Overall, the ARC digital twin represents a forward-looking approach to flood defense management, combining engineering precision with digital innovation to safeguard infrastructure in an era of climate uncertainty.

7 ACKNOWLEDGEMENTS

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