

Decision Support System for Monitoring and Stability Assessment of The Tailings Storage Facility

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ABSTRACT

The article presents the main functionality of the DSS class system for monitoring and stability assessment of tailings storage facilities. The presented demonstrator was deployed on the example of the Żelazny Most reservoir - the largest active facility of this type in Europe and the second one in the world. Considered a high-risk structure, it demands a system capable of online analysis of big data from various sources using machine learning, 3D modeling, or GIS mapping with the functions of interactive time-spatial analysis. In this paper, we present a complex calculation module with an integrated user interface.

INTRODUCTION

A Tailings Storage Facility (TSF) is a complex hydrotechnical facility that is the final stage in mining material flow during the Life of Mine. Its constant monitoring aims to avoid disasters caused by damage to the dam. Unfortunately, such accidents have happened many times, and each time they pose a threat to human life and the environment [1-5]. Some of the main reasons for TSF failure are slope instability, inadequate foundations, overflow, earthquake loading, and seepage [2, 6]. In the literature, there are a lot of different analyses aimed at monitoring the stability of the dam. For example, in [7] the problem of capillary phenomena caused by, for example, violent storms that affect the stability of the dam even for several decades after the closure of the facility. The problem of simulations that allow for predicting the behavior of a TSF in various conditions is also often studied [8, 9]. Predictive models are created for a similar purpose [10].

The management of the Tailings Storage Facility is a very challenging task, not only in analytical terms. There is a large amount of data that needs to be analyzed to assess the stability of the structure. The data come from the sensors (geodetic benchmarks,

inclinometers, open stand-pipe piezometers, etc.), the laboratory tests (physical property analysis, odometer tests, triaxial tests, etc.) and the field tests (Cone Penetration Tests, Dilatometer Tests, Cross-Hole tests, etc.). In addition, the data from different sources sometimes are not consistent and they may tell a different story. For this reason, dam stability monitoring systems using the internet of things and cloud computing are becoming more and more popular [11, 12]. One of the main tasks of an engineer is to manage all of the inconsistencies, complexity, and uncertainties and deliver solutions that will work. Unfortunately, when the problem is too complex, people tend to focus on the details and often lose the general perspective. To overcome this issue, a decision support system (DSS) has been created and tested on Zelazny Most TSF (Figure 1).



Figure 1. Photo and approximate location of Zelazny Most TSF [13]

The Zelazny Most TSF has been in use since 1977. The foundations of the ring dam lie on Pleistocene sediments, under which there is a sequence of Pliocene sediments. In terms of dam stability, a particularly important aspect is the location of the reservoir in an area where at least three large glaciations occurred during the Pleistocene. This resulted in the occurrence of large shear zones at a depth of about 100 m in this place [14]. For this reason, monitoring the stability of the dam is particularly important.

This article has the following structure. At the beginning, the functionality of the monitoring system is presented. Next, the individual modules that the system contains are described. First, the visualization module and the statistical module are introduced, then two examples from the analytical module for pore water pressure and shear zones are presented, the last module, which also combines information from the others, is the decision-making module, and conclusions are presented at the end.

FUNCTIONALITY OF THE SYSTEM

The system is divided into several modules:

- The visualization module presents all of the data from the sensors, laboratory tests, and field tests in an adequate form in order to easily browse through them. All the plots and drawings are dynamic, which allows them to zoom, translate, or scale in real time.

- The statistical module is used to analyze the data and visualize the statistics on the plots or maps.
- The data analysis module uses several Machine Learning (ML) algorithms to help analyze the data.
- The decision-making module is used to check the stability calculations and visualize the danger zones.

The modules will be described in the following part of the article, with emphasis on the ML functionalities.

VISUALIZATION MODULE

The visualization module is used to present all of the data from TSF in the form of plots, graphs, and diagrams. Every sensor or test should be visualized to present the information in the clearest and simplest form possible. All of the plots and drawings are dynamic, which allow them to zoom, translate, or scale in real time. The module is able to calculate and visualize all of the values that are derived from the formulas, like the velocity and acceleration from displacement or calculation of the sand-to-fine ratio (SFR) based on the grain size distribution curve. The visualization module is able to present the data from: geodetic benchmarks (Figure 2), open-stand pipe piezometers, vibrating-wire piezometers, inclinometers, boreholes (Figure 3), SCPT-u tests, DMT tests, cross-hole tests, physical property and mechanical laboratory tests.

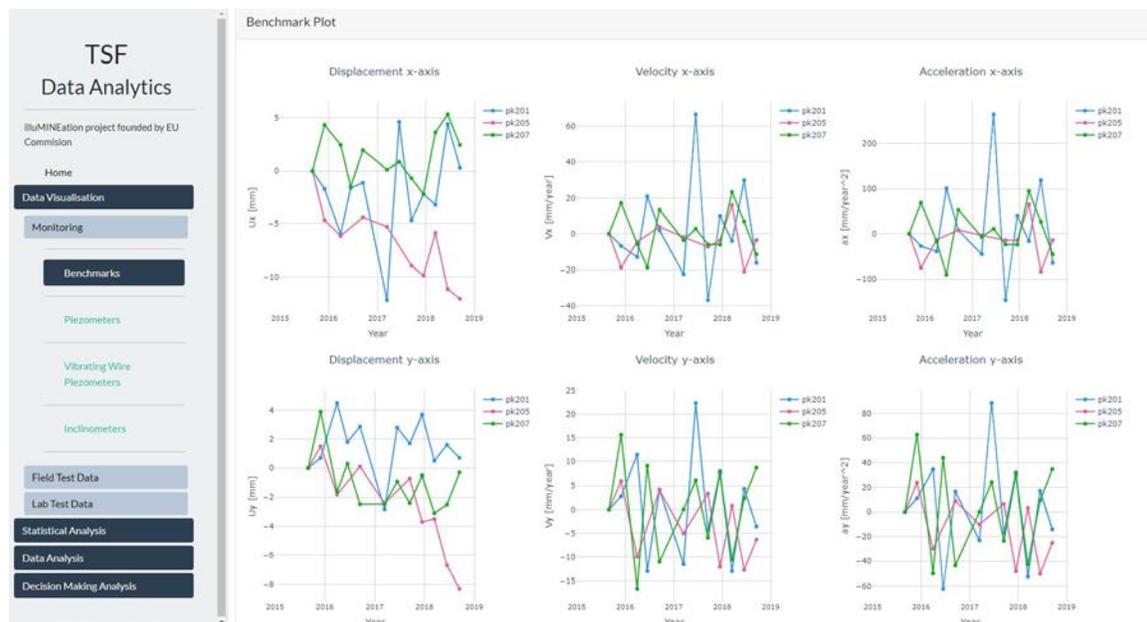


Figure 2. Visualization module - geodetic benchmark dashboard

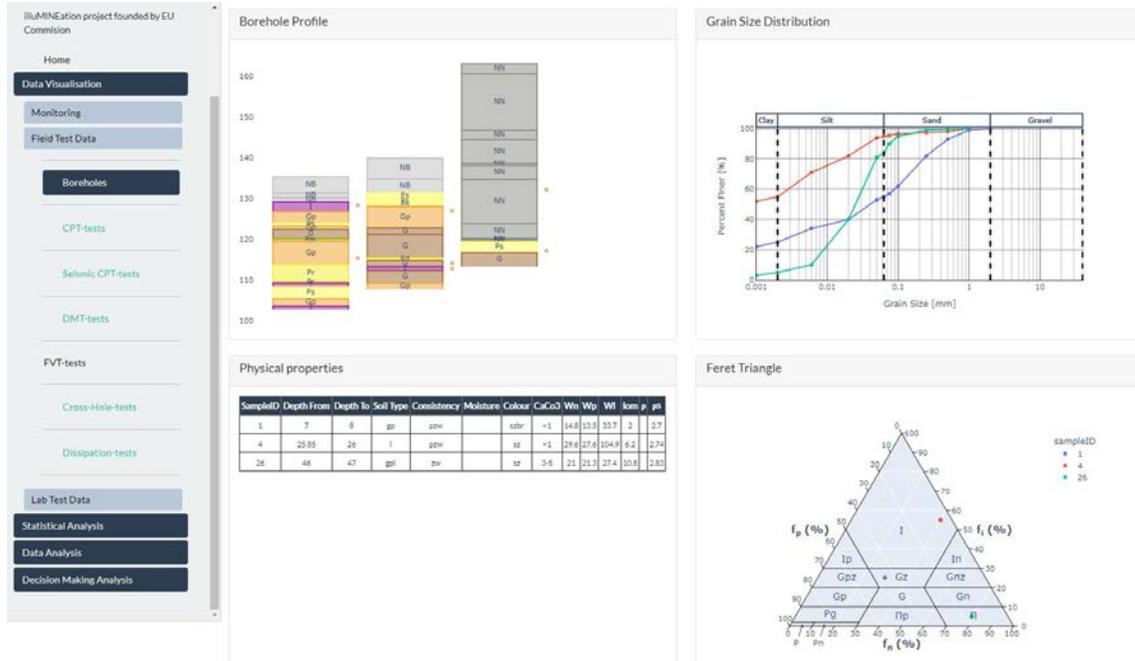


Figure 3. Visualization module - borehole dashboard

STATISTICS MODULE

The statistics module provides functions for the mathematical statistics of the data (Figure 4). The module can calculate and visualize the statistical parameters and create probability distributions for the random variables. The very useful functionality is to visualize the data on the maps using hexagon bin plots. In a hexagonal bin plot, the data range is covered by hexagons that are equally-sized, and a color gradient is used to indicate the density of data points that fall inside. With this functionality, one can easily visualize the areas where there is a lot of data and where data is missing. All of the statistics, like mean, standard deviations, etc., can also be visualized in these regions. The operator of the system is able to manipulate the size of the area in order to visualize the region that he needs. In addition to the hexagon bin plot, Figure 4 also shows the histogram of displacements.

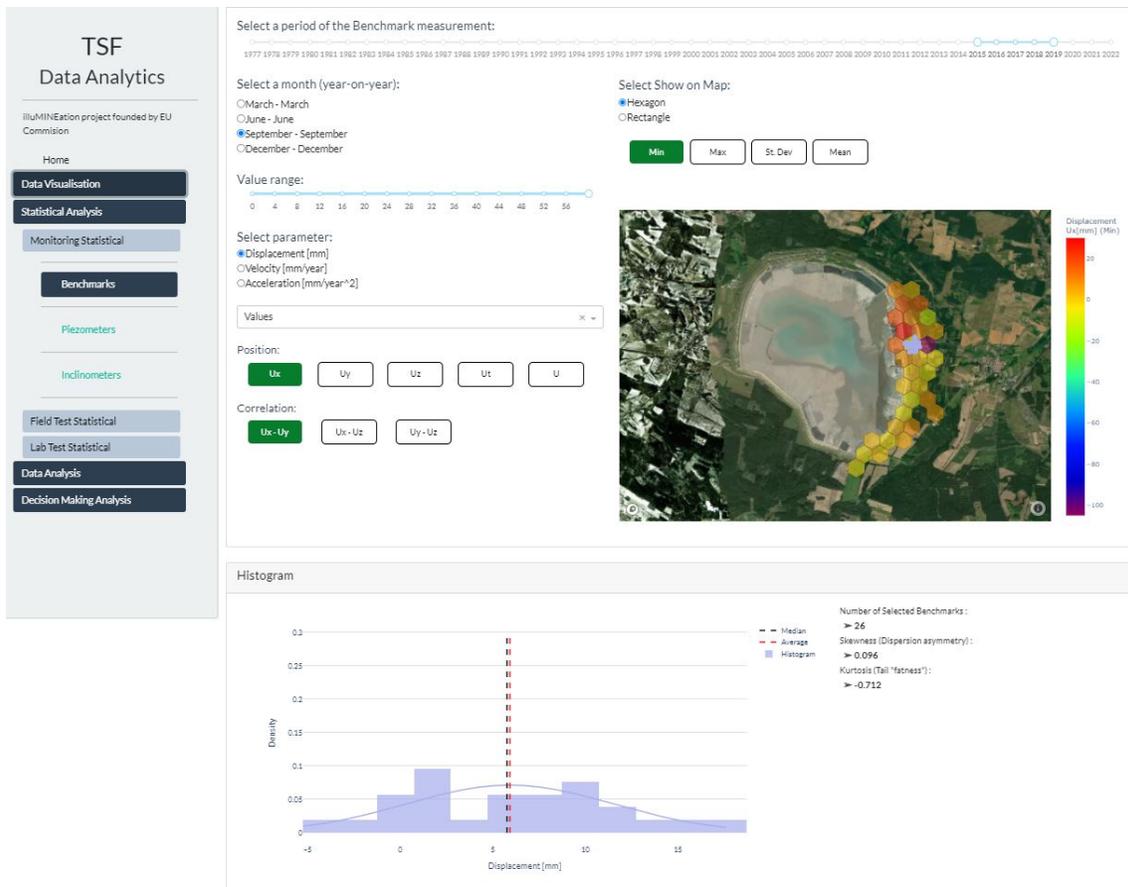


Figure 4. Statistical module

DATA ANALYSIS MODULE

The data analysis module uses ML algorithms and other techniques to analyze the data from the sensors, field tests, and laboratory tests. The few techniques used to analyze different parameters will be described in detail in the following section.

Pore water pressure

Pore water pressure is the pressure in the water placed in the voids of the tailings material. This is influenced by the type of soil and water flow. Pore pressure is very important in geotechnical engineering. Ground movement and slope instability can be caused by variations in effective stress. The difference between the total stress and the pore pressure is called the effective stress. It controls soil behavior such as strength or deformation, which is important to monitor.

The water in the ground is under pressure, either due to the weight of the soil or because of external forces. This pressure is called the pore water pressure u . When there is no flow and the soil is saturated, the pore pressure at depth d below the water table is equal:

$u=dg$, where g is the unit weight of the water. The water table is defined as the level in the ground at which the pore pressure is zero (equal to atmospheric).

Unfortunately, in the case of Zelazny Most Reservoir, we are dealing with an unstable environment, so the previously shown formula does not describe the real state. To be able to determine the actual pressure values on the cross-sections of the tailing dam, information from field testing had to be selected and analyzed.

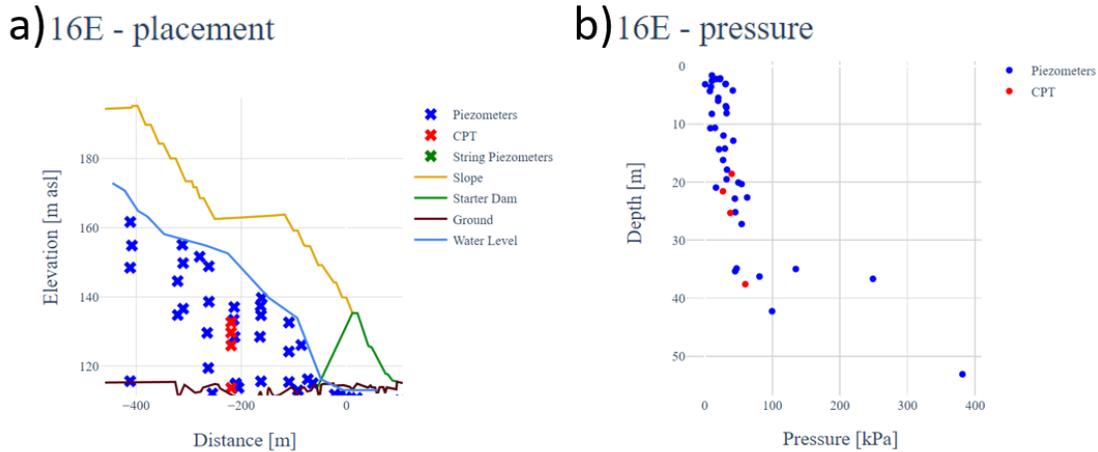


Figure 5. Data plots for cross-section 16E, a) distribution of test data on section plot, b) relationship between pressure and depth for the available data

The following tests were used to determine the pressure:

- piezometers - the test consists of making a geological hole in the ground. The water in such a hole stabilizes at a certain level. Then the measuring device measures the level of the water pressure there.
- CPT - the test consists in pressing an electric cone into the ground with a system of sensors recording soil parameters. During probing, the pore pressure is recorded.

Test values are assigned to a given section depending on their distance from the selected section. Then their placement is adjusted on the section. The layout of data for an example section is presented in Figure 5 a). To obtain the dependence of the pressure on the depth, the distance from the zero pressure level (the level of the water table was determined manually by appropriate experts) was calculated to the available pressure points. The result is shown in Figure 5 b). Then the curve was constructed that has the best fit to a series of data points. An attempt was made to fit exponential and logarithmic functions as well as polynomials of various degrees. The best results (with the slightest RMS error) were obtained for the logarithmic function. The function determined in this way was used to estimate the pressure on the entire section. For comparison, pressure was also determined by interpolating the area using only the measurement points and with the assumption of no flow (hydrostatic pressure). Figure 6 shows the results of this process.

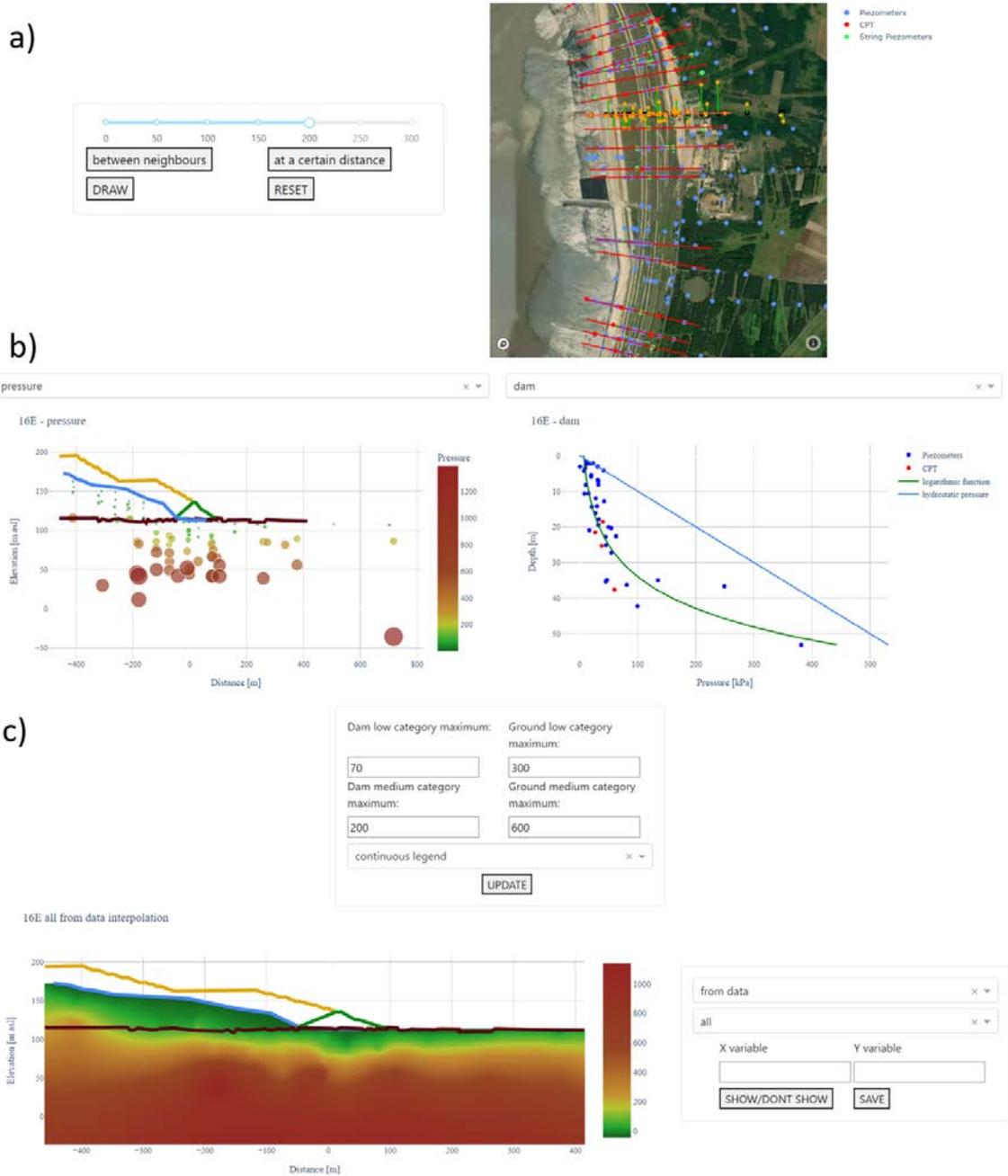


Figure 6. Report layout for cross-section pressure

Shear zones

One of the important issues in the case of TSF stability monitoring is the detection and control of underground shear zones [15]. Such underground displacements can be recorded by inclinometers. The data from the inclinometer is displacement values relative to the original state (the first measurement) [16, 17]. The values are recorded with a frequency of 0.5 m depth intervals, and measurements are made approximately once a year. The sudden

change in values (shear) is plain to see, but a tool for automatic shears detection surely makes the process faster, especially when the number of measurements is large. The shear displacement detection for each measurement gives the possibility of investigating a shearing progression by its speed and acceleration. In addition, by exploring the topic of shearing spatially, it is possible to find the shearing areas by analyzing the relationships between neighboring inclinometers.

The shear detection method uses the DBScan algorithm [18], which is an unsupervised density-based machine learning method. This algorithm makes it possible to divide data into groups without having to determine their number. In addition, it indicates values that do not fit into any group as outliers. The method requires setting two parameters: ϵ and *MinPts*. ϵ is the neighborhood radius, which is the maximum distance between points classified as neighbors. *MinPts* is the minimum number of observations in the group.

The operation of DBScan can be presented in the following steps:

1. Neighbors are found for each point relative to the ϵ value.
2. Each observation that has at least *MinPts* neighbors is called a “core point”.
3. Combine the core points into groups if they satisfy the ϵ distance condition.
4. Include the remaining non-core points in the created groups if they are neighbors.
5. Classify all other points as outliers.

A procedure for the detection of shear displacements from each inclinometer and their analysis in the context of time and space was developed. It is fully automated by following steps.

1. Smoothing a signal of displacement by the median filter. This avoids classifying small changes as shears while not affecting larger ones.
2. Calculate the derivative of smoothed displacement. This variable delineates where there has been a rapid change in value (the displacement variance increases).
3. Using the DBScan method [18] on variables: displacement, derivative, and elevation. Recognition of unclassified values in any group (outliers) as shears.
4. Validation of a recognized shear by its pitch (the angle between the displacement curve and the ground surface). Removal of such detected shears for which the pitch value exceeds the set limit. This avoids incorrectly detecting less rapid non-shear changes in value.
5. Using the procedure of 1-4 steps for each measurement.
6. Combination of shears of similar elevation and close to each other into one shear area. For this purpose, the DBScan algorithm is used for the location and elevation values.
7. Determination of the speed and acceleration of the shear displacement at each point by calculating annual increments.

An example of the result of the shear detection method is shown in Figure 7. Shears at three different elevations were correctly detected, which are visible in both the displacement signal and the derivative.

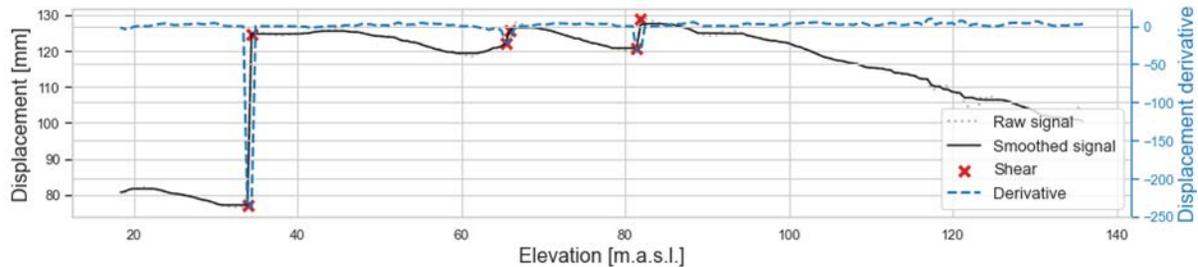


Figure 7. The example of the displacement from one measurement, its derivative and detected shear points

Appropriate visualization of all detected shear zones enables the specialist to quickly monitor and detect any threat. For this reason, an interactive report can be created (Figure 8) which contains sliders to display the desired information: the selected time range, and information about the size, speed, and acceleration of the displacement caused by shear with the appropriate ranges (Figure 8a). This makes it possible, for example, to filter only more critical phenomena. The table in Figure 8b shows the details of each shear case. The locations of all inclinometers (black points) and cases of detected shears (other colors) are displayed on the map (Figure 8c). The chosen marker size, indicates the size, speed, or acceleration of the given shear. Shears belonging to one area are marked with one color, and their range is marked with a line. In addition, it is possible to display cases only for the selected elevation. The table and map allow for selecting a shear for more detailed analysis. Figure 8d shows the values measured by the inclinometer with selected shear points marked. Information about the change in displacement, velocity, and acceleration relative to time for the selected shear is shown in Figure 8e. All this gives the opportunity to monitor all the shear zones spatially and quickly look at each of them closely.

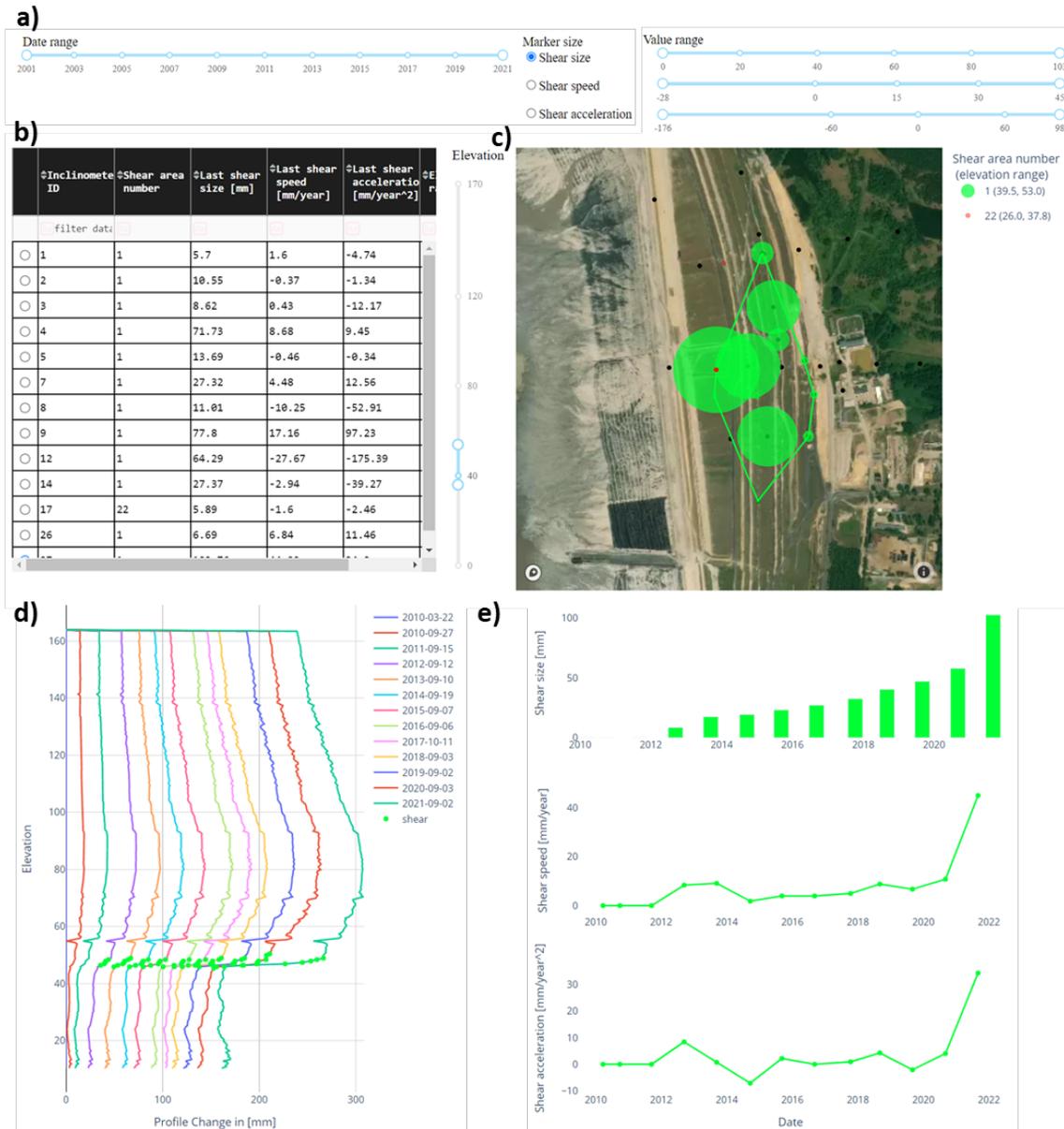


Figure 8. Report layout for shear zones

DECISION MAKING MODULE

The decision-making module combines all the data from the sensors, field, and laboratory testing, as well as the analyzed data from the statistical and data analysis modules, and uses the data to assess the stability of the TSF structure. The module is linked to the calculation software via an Application Programming Interface (API) and sends as an input the geotechnical model (Figure 9) with the mechanical parameters of each layer and the pore pressure distribution.

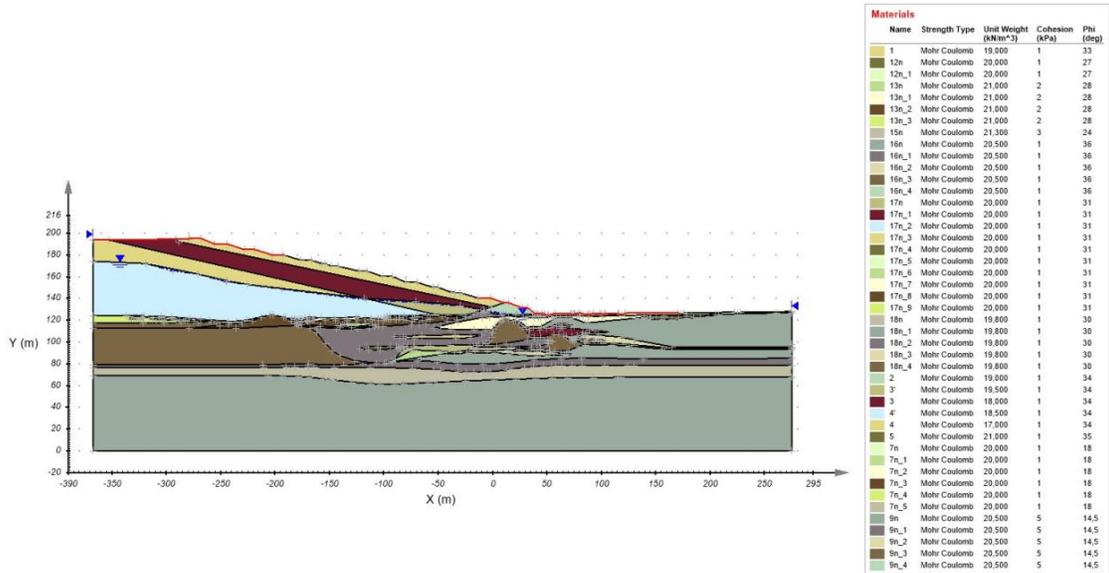


Figure 9. Computational geotechnical model

The mechanical parameters are analyzed statistically, and for each layer, the parameters are randomly selected according to the statistical distribution. Thus, many variants of the model are created. To visualize all of the variants and the results for every variant, a parallel storyline plot is generated so that one can track all of the inputs and outputs for each variant (Figure 10).

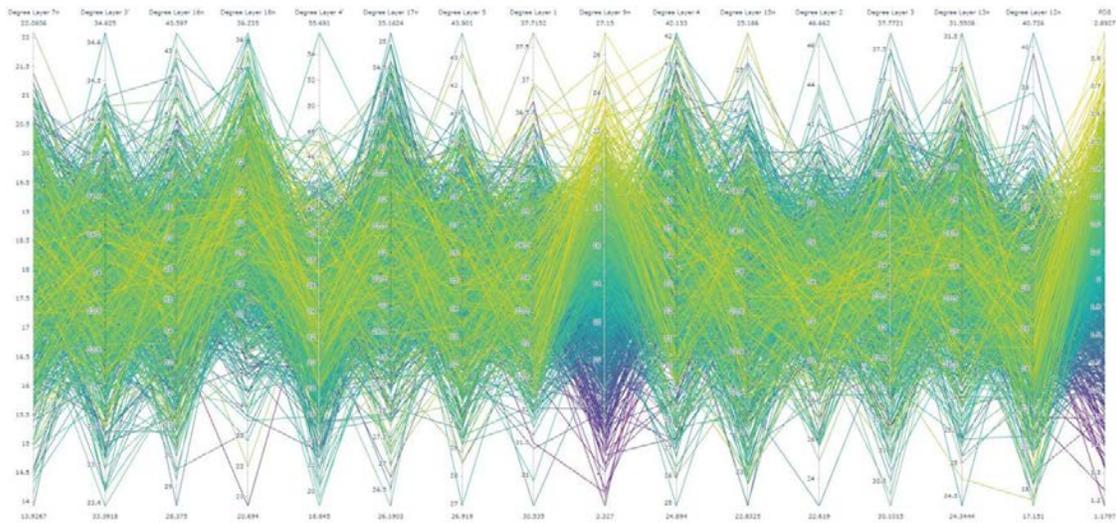


Figure 10. Parallel storyline plot for stability calculations

The module can also perform a sensitivity analysis of the mechanical parameters by changing the mechanical parameters of one layer and checking how it can influence the results. The plot is created to visualize the sensitivity of each geotechnical layer (Figure 11).

Using the decision-making module, one can easily verify the stability of the TSF structure for every geotechnical cross section. Moreover, the probability distribution of the factor of safety is created. Therefore, one can easily see the range of possible values. This approach allows capturing the natural variability of the mechanical parameters and provides a probability of failure for the structure, which is more valuable information to tailings managers than a deterministic value of the Factor of Safety.

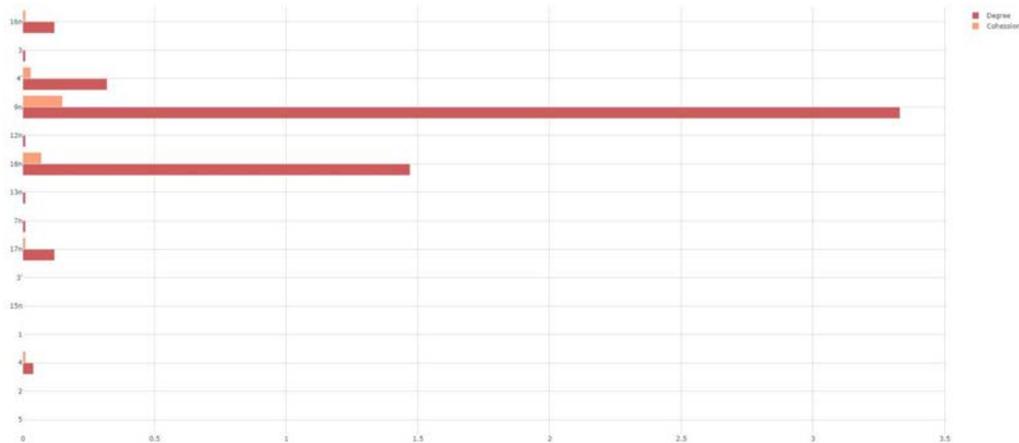


Figure 11. Sensitivity analysis of the model

CONCLUSION

The DSS system for the Tailings Storage Facility was presented in the article, which can help manage the large amount of data coming from the sensors, laboratory tests and field tests. The proposed DSS has a modular structure, each module was described in detail in the article. Moreover, the machine learning algorithms that can help automate the analysis of the different parameters of the TSF were presented. The statistical approach helped to see the variability and inconsistency of the data. The decision making module considered all of the data and all of the analyses and gave the final answers to the questions: “Is the structure safe?” and “How sure are we about it?”.

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