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# INNOVATIVE APPROACHES TO A SOLUTION FOR SURFACE DEFORMATIONS ON EARTH STRUCTURES OF LINEAR TRAFFIC CONSTRUCTION

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Abstract. The modification of the slopes of linear transport structures includes humus and grassing which is intended to improve their resistance to erosion. Nevertheless, these slopes are increasingly affected by landslides of the surface layers with the key factors being extreme precipitation fluctuations and the influence of new earthwork technologies. The solution requires an interdisciplinary approach and the introduction of innovative measures. An important role is also played by geodetic monitoring and outputs from modern methods (3D scanning) which provide detailed data on slope changes. A pilot project focused on embankment monitoring in the Hradec Králové region showed the importance of these technologies in dealing with landslides.

Keywords: Laser scanning, slope stability, risk management, maintenance.

## 1. Introduction

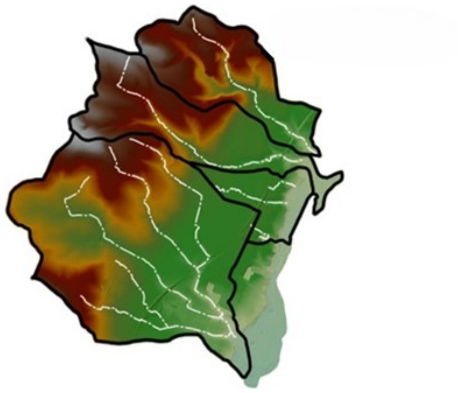
The adjustment of the slopes of linear transport structures consists in leveling, humus and grassing to protect their surfaces from erosion by running water. A humus-covered and grassy slope with an established root system prevents the development of erosive phenomena [1]. However recently, shallow landslides have been occurring more and more frequently on linear transport structures, mainly due to an unstable vegetation layer, including woody plants and herbaceous layers. Solving this problem requires an interdisciplinary approach (geology, hydrogeology, rainfall-runoff ratios, pedology, vegetation). At the same time, high pressure is being exerted on the greening of the earthen bodies of road constructions, which can lead to problems, e.g. to insufficient bonding between the humus layer and the structure of the earth body. The significant effects of these disturbances include an uneven distribution of rainfall with extreme fluctuations in rainfall intensity throughout the year and especially within recent years. Another important factor is the influence of new earthwork technologies such as soil treatment with hydraulic binders with a high calcium content [2, 3]. Capillarity does not work in the embankment environment treated with this binder, and plant roots therefore do not have the opportunity to draw water and nutrients from greater depths. Surplus rainwater is not retained in the vegetation layer, and so the sorption capacity of the subsoil cannot be used, and this leads to erosion, with plants either not thriving or simply dying [4].

When designing geotechnical structures, it is necessary to take into account the new requirements of the second generation of Eurocodes EN 1997, which place more emphasis on risk analysis. The design of constructions should include an assessment of all the impacts on the surrounding environment (the introduction of consequence classifications) not only for large-scale constructions such as dams or power plants, but also for ordinary constructions. This change reflects modern approaches to environmental protection and the prevention of negative effects of construction activity on the wider surroundings [5].

In this aspect, the issue of geodetic and geotechnical monitoring is a key concern. The development of innovative technologies such as 3D laser scanning opens up new possibilities, especially for higher and less accessible geotechnical structures. Standard technological procedures and materials can be used to eliminate defects on the slopes of the cuts and embankments of linear constructions and to extend the life of a structure, such as e.g. vegetation blocks, gravel ribs, use of geosynthetics [6, 7]. The function of meliorating and strengthening trees is especially important for the slopes of forest roads. This function can be fulfilled by maintaining a suitable species composition [8]. At the same time, it is necessary to take into account the species composition throughout the life of the structure. With the help of forest management, it is also possible to influence the mass of the stand, represented by deep woody species and indirectly to a certain extent, the hydric conditions of the surface layer of the territory.

This paper currently deals with a suitable geodetic monitoring technology that can be applied to such broken slopes. With regard to the area of interest of

FIGURE 1. View of the site of interest with a collapsed slope.



Drainage lines - Fourth-order watershed

FIGURE 2. Area of interest with drainage lines on the basis of watershed IV. order and digital model [10].

the monitoring and the desired result, it is necessary to choose a geodetic monitoring method that captures the facts in their detail. For the relevant capture of all changes on the body, such as erosion grooves, cracks, landslides and other phenomena, it is necessary to describe the fact in high detail and quality, and for this reason classic point measurement (tachymetry) is not suitable. With the advent of modern technologies such as photogrammetric imaging using a UAV and 3D scanning with a lidar, which is placed on a carrier device, very high-quality and dense point clouds can be obtained in a very short time and at a relatively low cost, which can then be further evaluated.

As a pilot project for the validation of this technology, the embankment body of highway constructions was chosen. In the period July–August 2024, in the Hradec Králové region, there were repeatedly higher rainfall totals, which resulted in landslides of surface layers on several sections of highway constructions in this region, see Figure 1. Intense rainfall totals caused surface and subsurface runoff in permeable soil layers. Subsequently, due to the influence of gravity, the water-saturated layers of soil moved down the slope. The shear surface was formed at the border of a very impermeable subsoil and a layer of very permeable soil (humus).

## 2. Natural conditions of the location of interest

In the entire area of interest, the terrain is mostly level and flat without significant elevations. The area slopes eastward toward the Great Elbe River, ultimately draining into the Elbe River (see Figure 2). The area of interest lies in the warm climate zone T2 (according to Quitt, 1971 [9]). The area is characterized by a long summer, warm and dry, a very short transitional period with a warm to moderately warm spring and autumn, a short, moderately warm, dry to very dry winter, with a very short duration of snow cover. The long-term annual rainfall in the area is around 500–600 mm. The average annual temperature is 8–9 °C.

### 2.1. Geology

Pre-Quaternary bedrock is generally made up of fine-grained Upper Cretaceous sedimentary rocks. Lithologically, these are calcareous claystones, marlstones, calcareous spongilitic siltstones and sandy marlstones with positions and concretions of sandy limestones, siltstones with a higher content of calcium carbonate to argillaceous limestone. Calcareous siltstones are generally dominated by siltstones. The covering formations of the area of interest include anthropogenic (overburden), aeolian and aeolian-deluvial (deposited by the wind) and fluvial (alluvium) soils (see Figure 3) [11, 12].

### 2.2. Hydrogeology

Two basic types of hydrogeological environment can be defined in the investigated area:

(1.) Underground water in an environment with permeability in the overlying Quaternary sediments, which are almost entirely aquifers.

(2.) Groundwater in an environment with fissure permeability in rocks of the pre-Quaternary bedrock.

A channel collector of gravelly and sandy sediments was historically documented at the site of interest, in which a shallow near-surface aquifer is formed on a relatively impermeable bedrock with a raised and stabilized groundwater level at a level of around 1.9 to 2.2 m below the ground. Locally, the surface may be moderately tense due to the fine-grained admixture in the youngest floodplain sediments. The groundwater level can fluctuate by several meters seasonally in a shallow gravelly and sandy aquifer, depending on rainfall and the water level in surface streams, in extreme cases. Based on archival surveys, the filtration coefficient near the site of interest is around $\mathbf{10^{-4}\,m\,s^{-1}}$.

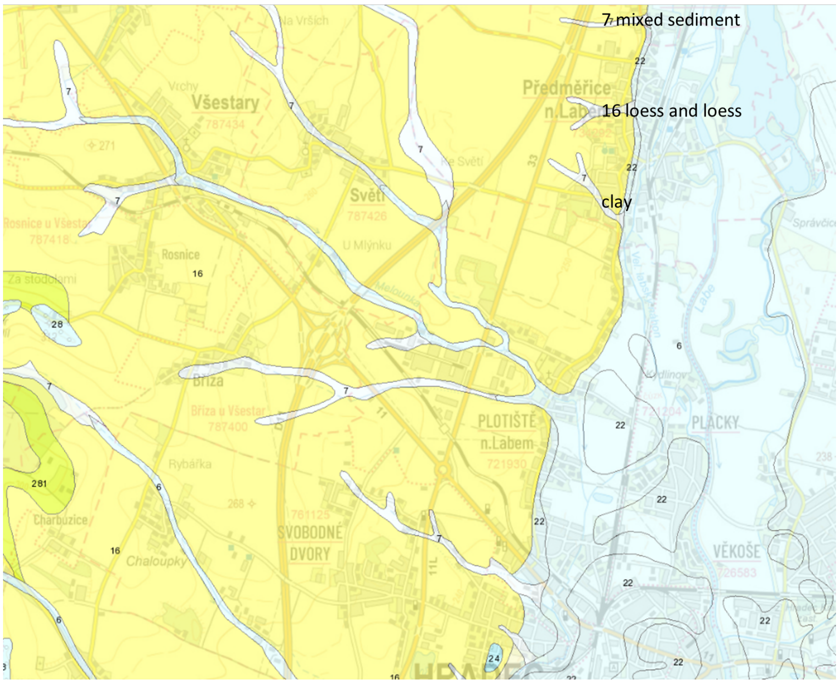



Figure 3. Geological map of the site (scale 1:50 000) [13].

## 3. Embankment – geotechnical construction – humusing

The embankment body was made with a slope of 1:2 and a height of approximately 6 m in accordance with ČSN 73 6133 [14] and TKP 4 [2]. The construction of the embankment was realized from modified soil with an admixture of binder in an amount of up to 3 %, while technological discipline was observed during mixing and compaction of the mixture. On the slopes of the earthen body, a layer of rootstock with a thickness of approximately 0.3 m was applied, which serves to improve the vegetation cover and protect against erosion. Subsequently, hydroseeding was carried out with the aim of stabilizing the slopes and supporting the growth of vegetation, which contributes to the long-term stability of the embankment.

The core of the embankment was strengthened using hydraulic binders and thoroughly compacted in accordance with the requirements of technical regulations to ensure sufficient bearing capacity and long-term stability of the structure. The compaction control was carried out in accordance with the relevant standards and regulations, while the parameters of the degree of compaction achieved and the moisture content of the material were monitored.

## 4. 3D laser scanning technology

3D geodetic monitoring of landslides is a modern and effective method for monitoring and analyzing movements of the earth's surface in areas affected by landslides. This monitoring uses advanced geodetic and geotechnical technologies that enable precise measurement of spatial changes in real time, this method being used, for example, by [15]. The main goal is the detection and evaluation of deformations and movements that may signal the risk of landslide activation or escalation. Monitoring 3D terrain changes provides a comprehensive picture of movement dynamics and is a key tool for early warning and putting in place preventive measures.

Geodetic methods for monitoring landslides on highway bodies not only enable timely detection of movements, but also serve as a basis for deciding on intervention measures. Monitoring the stability of slopes and landslides is important for minimizing risks and ensuring traffic safety. If problem areas are identified, interventions such as slope stabilization, installation of drainage systems, or the creation of protective barriers can be carried out. It is also important for monitoring to regularly evaluate meteorological conditions and hydrological factors that can affect the stability of slopes, and to implement them into the overall monitoring system. Currently, specialized software can handle the evaluation of laser scanning in combination with the evaluation of data on altitudes and the position of target points in S-JTSK (Křovák's display) and thus assessment of their deviations between individual stages of geodetic monitoring.

### 4.1. 3D monitoring technology

For a comprehensive analysis of movements on highway bodies, it is advisable to use laser scanning (LiDAR), which provides detailed 3D models of the terrain and allows the capturing of even minor changes in the topography. LiDAR is particularly valuable in monitoring the evolution of landslides over the long term, as it provides very accurate data for comparing terrain changes over time.

### 4.2. UAV (Unmanned aerial vehicle)

Another suitable non-contact method can be aerial photogrammetry, or aerial photography. For example, a drone equipped with suitable hardware equipment can be used for imaging [16]. Drones enable the collection of a large amount of high-resolution data in a relatively short time, and when using this technology, office preparatory work is especially important, e.g. planning the most suitable flight path. Given this flexibility, UAVs can also operate in difficult-to-access or dangerous areas where traditional methods would be time-consuming or costly. Images taken by UAVs can be processed into orthophoto maps, 3D terrain models or digital elevation models. It is important to mention that when using this method, it is necessary to split the responsibilities of the Office for Civil Aviation (authorization to use technology, equipment registration, etc.).

### 4.3. Classical geodetic methods – tachymetry

Tachymetric measurement is a method suitable for monitoring landslides, which enables precise and repeated monitoring of terrain movements on a suitably chosen point grid. Using electronic total stations (tachometers) can measure the position of selected points on the slope with high accuracy, which allows detecting even small changes in their position over time. This method is especially suitable for long-term monitoring of risk areas, but for the purposes of evaluating large areas in a short time frame, it has its limitations. Nevertheless, it can be suitably used for aiming at the insertion points for 3D laser scanning.

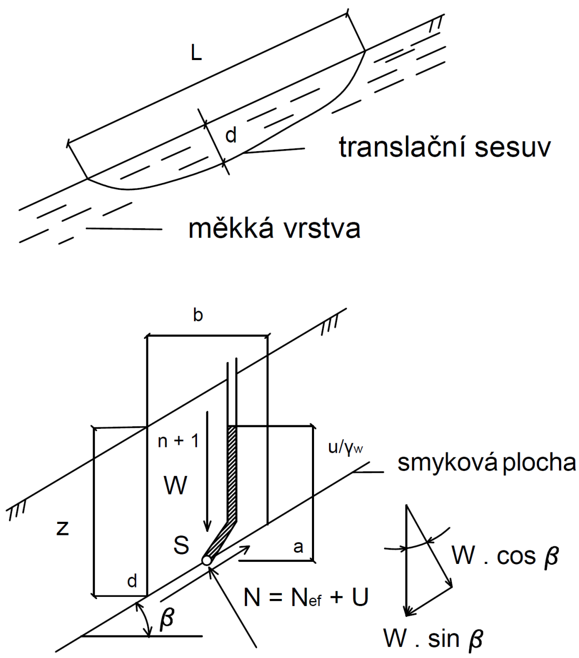



Figure 4. A planar shear surface parallel to the slope approximately replaces most shear surfaces in translational movements [17, 18].

| | | | | |
|---|---|---|---|---|
| $\phi'$ | = | $0{,}0058 \,.\, Ip^{1{,}73} - 0{,}32 \,.\, Ip + 36{,}2$ | = | 33,6 ° |
| $\phi_r'$ | = | $0{,}0084 \,.\, Ip^{1{,}4} - 0{,}75 \,.\, Ip + 31{,}9$ | = | 25,4 ° |

Figure 5. The empirically determined values of the effective and residual angles of internal friction based on the plasticity index.

## 5. Geotechnical data collection and analysis

A location damaged by repeated landslides of surface layers was selected for experimental research. The area of interest was affected by extreme rainfall totals in the months of July and August 2024, which caused a response in the basin involving similar flash floods with accompanying mudflows. In September 2024, the territory was affected by another rainfall episode. On 19$^{\text{th}}$ August 2024, precipitation totals of 80–100 mm (corresponding to a 20- to 50-year daily total) were recorded at the nearest CHMÚ station [10].

Based on the analytical assessment of the translational landslide, it is clear that the resulting slope stability value is very sensitive to the nature of the slope and the change in pore pressures (see Figure 4). The effective and residual shear strength parameters used in the analysis were determined empirically from the plasticity index, as shown in Figure 5. When assessing the stability of a geotechnical structure, the generation and optimization of the finite element network is normally performed with an assessment of the change in pore pressures. Analytical assessment of translational landslide can be the first signal to carry out subsequent detailed analysis using suitable numerical methods. The sensitivity of the stability degree to changes in slope inclination, pore pressure and shear strength parameters is documented in Table 1.

It is usually necessary to subject the earthen structure to a careful geotechnical inspection and to limit the adverse influence of surface or underground water. It is necessary to ensure an assessment of the rainfall-runoff conditions. To ensure the resistance of the earth body against the increased water level, it is especially necessary to prevent the washing out of fine soil particles from the body and erosion at the face of the slope. Already in the project documentation, it is also necessary to design and assess the long-term effective drainage of rainwater, surface and underground, in such a suitable and feasible way that its action does not negatively affect the earth body throughout the life of the building, even in the case of extraordinary rainfall totals.

Computational geotechnical control is required if it is proven in any way that the calculation values of the strength parameters must be further modified to the detriment of the deformation and the earth body and its behavior during implementation. The inspection

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **F (stability degree)** | 1.0 | 1.7 | 0.6 | 1.3 | 1.3 | 1.4 | 2.5 | 0.9 | 1.9 | 2.0 |
| **Cef [kPa]** | 0.8 | 0.8 | 0 | 0.8 | 0 | 0.8 | 0.8 | 0 | 0.8 | 0 |
| **Z [m]** | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| **y [kN m$^{-3}$]** | 18.5 | 18.5 | 18.5 | 18.5 | 18.5 | 18.5 | 18.5 | 18.5 | 18.5 | 18.5 |
| **β [°]** | 26.6 | 26.6 | 26.6 | 26.6 | 26.6 | 18.5 | 18.5 | 18.5 | 18.5 | 18.5 |
| **u [kPa]** | 2.4 | 0 | 2.4 | 1.2 | 0 | 2.7 | 0 | 2.7 | 1.3 | 0 |
| **$y^w$ [kN m$^{-3}$]** | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| **$\varphi^{ef}$ [°]** | 33.6 | 33.6 | 33.6 | 33.6 | 33.6 | 33.6 | 33.6 | 33.6 | 33.6 | 33.6 |
| **m** | 1 | 0 | 1 | 0.5 | 0 | 1 | 0 | 1 | 0.5 | 0 |

TABLE 1. Orientation sensitivity analysis of the degree of stability of a planar shear surface.

| **Designation of samples** | **Sampling depth [m]** | **w [%]** | **k [m s$^{-1}$]** | **lp** | **Soil classification according to ČSN 73 6133** | **Soil classification according to ČSN EN ISO 14688-2** |
|---|---|---|---|---|---|---|
| S1 (humus layer) | 0.2–0.3 | 22.75 | 1.17.10$^{-6}$ | 8.86 | F4 CS | grsaSi |
| S2 (embankment core) | 0.3–0.4 | 13.95 | 4.06.10$^{-6}$ | – | S4 SM/S5 SC | grclSa |

TABLE 2. Laboratory analysis results.

takes place also on the spot especially during or after the occurrence of extraordinary loading or stressing of the structure (such as excessive amounts of torrential rainfall, erosion, soil erosion, etc.). Slope deformations during the implementation of the building or during the use of the building are a clear signal of the need to carry out an immediate verification of the stability of the slope.

On selected research areas of the subject landslide, field work was carried out in the form of mapping of the landslide area, and laboratory tests were also carried out on the samples taken. A total of 2 samples were taken from the embankment core and samples from the humus layer. The basic physical and hydraulic properties of the tested soils, including moisture content, filtration coefficient and soil classification, are summarized in Table 2. The analysis was carried out for the purpose of soil classification according to ČSN 73 6133 [14] and ČSN EN ISO 14688-2 [19] (density analysis and sieving test, consistency limits according to ČSN EN ISO/TS 17892-12 [20] and moisture determination according to ČSN EN ISO 17892-1 [21]. Latitude and altimetry measurements used 3D scanning with lidar and high-speed laser scanning. Aerial photogrammetry data taken using a drone was available.

### 5.1. Results of laboratory research

The laboratory analysis showed significantly different properties of structural and humus layers, which are manifested especially in the values of the filtration coefficient (determined according to Hazen) and humidity. The grain size distribution of the humus layer sample S1 (0.2–0.3 m) is shown in Figure 6, while the grain size distribution of the embankment core sample S2 (0.3–0.4 m) is shown in Figure 7.

### 5.2. Results of 3D scanning

In the course of 2024, two landslide locations were detected within the monitored area. A Trimble X9 device was used to scan the first landslide. The device has high-speed scanning with a speed of up to 1 million points per second, with a range of up to 150 m and with an average measurement error of around 2 mm. The device enables automatic calibration, and automatic leveling with geodetic accuracy for quick and simple settlement of the position (23$^{rd}$ October 2024). As a result of the scanning, the detected volume of the first landslide was approximately 48 m$^3$ of soil (see Figure 8), and the second landslide was 23 m$^3$ (see Figure 9).

The output of the scanning can be a table or a drawing with a graphical representation of positional or elevation deviations between selected measurement stages. By evaluating the point clouds and the digital models created from them, captured using laser scanning, it is also possible to compare individual measurement stages (see Figure 10). These data can provide significant benefits to infrastructure managers in terms of maintenance or site analysis.

## 6. Conclusion

In the case of intense rainfall, it can be expected that the embankment bodies may become unstable more often in the future. Also of course this happens in other European countries, e.g. Portugal is experiencing climate change, which has a frequent effect on landslides [22]. The solution could be the recognition of the base rock without humus, reduction of the slope of geotechnical constructions treated with binders, roughening before spreading the vegetation layer, elimination of the use of higher plantings, and use of suitable anti-erosion grass-herb mixtures. As

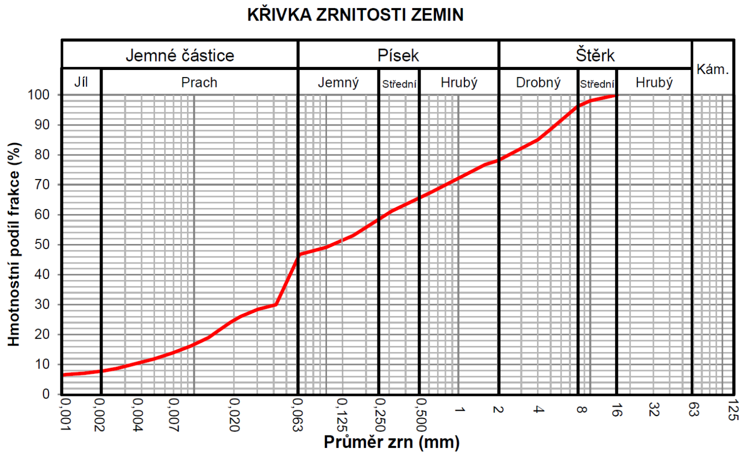



Figure 6. The grain size distribution curve from the soil sample (humus layer), S1 (0.2–0.3 m).

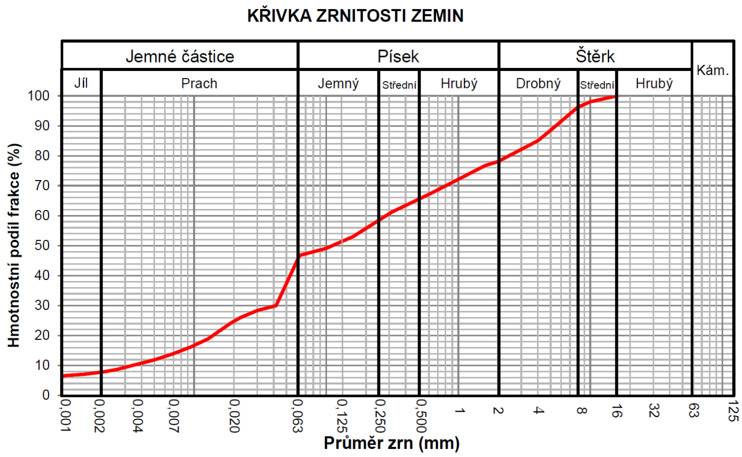



Figure 7. The grain size distribution curve from the soil sample S2 (0.3–0.4 m).

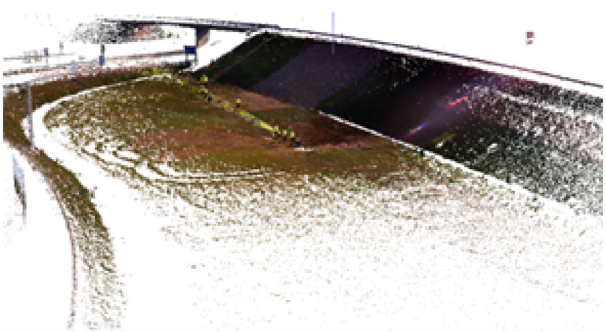


Figure 8. Example of point clouds from 3D laser scanning from the Trimble X9 device.

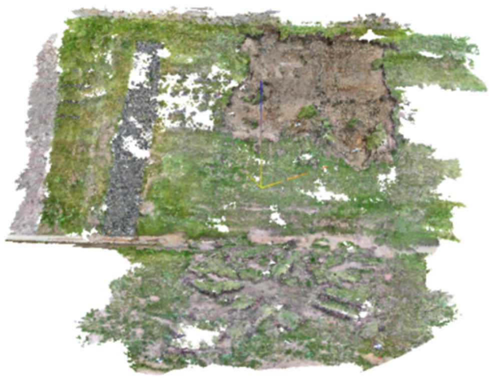


Figure 9. An illustrative example of point clouds from 3D scanning using an iPad Pro tablet with a LiDAR sensor ($8^{th}$ October 2024). This is used only for a rough estimate of the damage extent.

part of maintenance, it is advisable to monitor and evaluate the results of measurements for selected objects, to carry out long-term geodetic and geotechnical monitoring. The first steps include the design of the measuring network and the installation of permanent tracking points necessary for monitoring the structure/object. Performing a zero measurement before handing over the work is another important step for the subsequent monitoring of geotechnical structures.

Despite a number of advantages, 3D geodetic monitoring of landslides is still relatively expensive and technologically demanding. It is necessary to have high-quality equipment, trained specialists and also sufficient funds for long-term monitoring. In addition, the challenges of data availability and the integration of different monitoring methods into one homogeneous

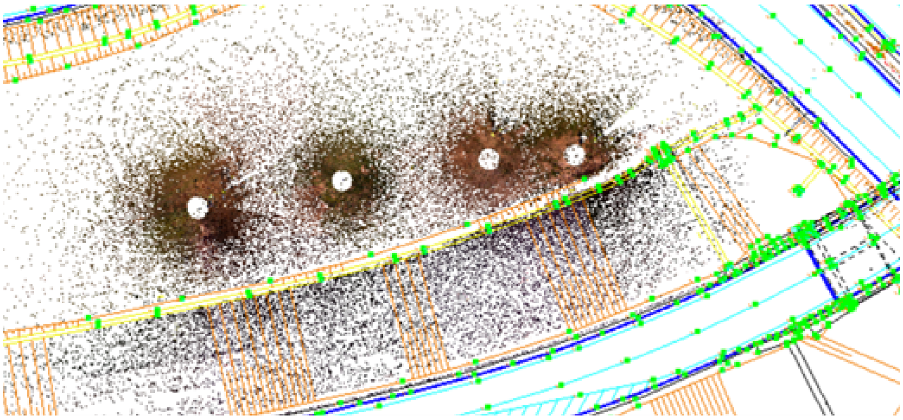


FIGURE 10. The output of laser scanning is a set of point clouds, which can be registered according to individual viewpoints, georeferenced with the laser track, and precisely measured alignment points in the S-JTSK coordinate system (23rd October 2024).

system need to be addressed. For the above reasons, it follows that it is necessary to choose a suitable method for the given purpose, taking into account the required aspects, such as measurement accuracy, quality of the digital model, time required and last but not least, price.

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