FMGM 2015 – PM Dight (ed.)

doi:10.36487/ACG_rep/1508_02_Lowen

LiDAR — systems for stability proof of a reservoir dam

J Hofmann *University of Siegen, Germany*

M Löwen *University of Siegen, Germany*

RA Herrmann *University of Siegen, Germany*

Abstract

This paper presents an innovative use of a light detection and ranging (LiDAR) system for stability investigation and reporting required by authorities for the Alfsee reservoir, Germany. That report has to provide updates on the stability of the dam structure of the flood control reservoir. Air-borne drones and terrestrial vehicles equipped with optical sensor systems are used to provide geo-referenced point data as a base for a digital model of the terrain. By using this information, it is easily and quickly possible to generate sections of the dam structure and reservoir for the analyses. Slope stability analyses can then be performed more precisely and rapidly than by relying on information from conventional measurements.

1 Introduction

The flood control reservoir Alfhausen-Rieste is under the direction of the ´Niedersächsischen Landesbetriebes für Wasserwirtschaft und Küstenschutz´ and is located in the district of Osnabrück, between Bremen and Hannover, Germany (Figure 1). With a storage capacity of 20.8 million m³, it belongs to the second largest reservoir in Niedersachsen and was built from 1971 to 1982 (NLWKN 2009).

The construction consists of three segments: sedimentation reservoir, main reservoir and standby reservoir. It was designed to be an effective flood protection for an estimated 25-30 year return period flood. In accordance to the German Institute for Standardization (2004), the reservoir is classified as a large basin, so an annual safety report and a recessed safety report are required every ten years. The Institute of Geotechnics at the University of Siegen was selected to carry out the geotechnical investigations for the recessed safety report.

The investigations comprised stability analyses of the dams as well as a proposal for the redesign of the drainage systems at the foot of the dam. For that reason, georeferenced point data was requested to compile a digital terrain model (DTM) of the whole construction. The intention was to readily identify weak areas along the dam profile and to use the LiDAR data to create an accurate surface profile for the stability analyses using GGU-STABILITY (GGU 2013).

Figure 1 Location of flood control reservoir Alfhausen-Rieste (source: http://maps.google.de, supplemented)

2 Technical data of the flood control reservoir Alfhausen-Rieste

2.1 Dam

The dam encompasses the flood control reservoir and is close to transport infrastructure (Figure 2). The crest is located 3.5 and 8.0 m above the natural terrain, at +43.05 to +44.35 m above sea level (ASL). The crest width is continuously 4.0 m, with the exception of 13 m width between main basin and reserve basin. For improved trafficability, the crest of the main and reserve basins are covered with tracking plates. The dam slope on the upstream face is 1:3.5 to 1:8 and on 1:2.5 to 1:3.0 on the downstream face. The dams are constructed on the naturally occurring silt with sand lenses. The sandy upstream fill has a surface sealing comprising sandy silt. Within the downstream fill slope, there are seepage elements and drainage branches (NLWKN 2009).

2.2 Sedimentation reservoir

The water flows from the supply ditch into the sedimentation reservoir so that the suspended particles can settle. The construction has an area of around 12.5 ha with a base height of +37.00 m ASL. The water in the sedimentation reservoir is always kept at the same height through an overflow sill at +39.00 m ASL. On the basis that the sedimentation reservoir has no significance for the slope stability analyses of the main reservoir dam, there are no recordings of its construction (Figure 2) (NLWKN 2009).

2.3 Overflow sill

The overflow sill separates the sedimentation reservoir from the main reservoir (Figure 2). Incoming water flows through ten box culverts to the main reservoir at a maximum rate of 7 m³ per second. Greater runoffs cause overflow of the construction (NLWKN 2009).

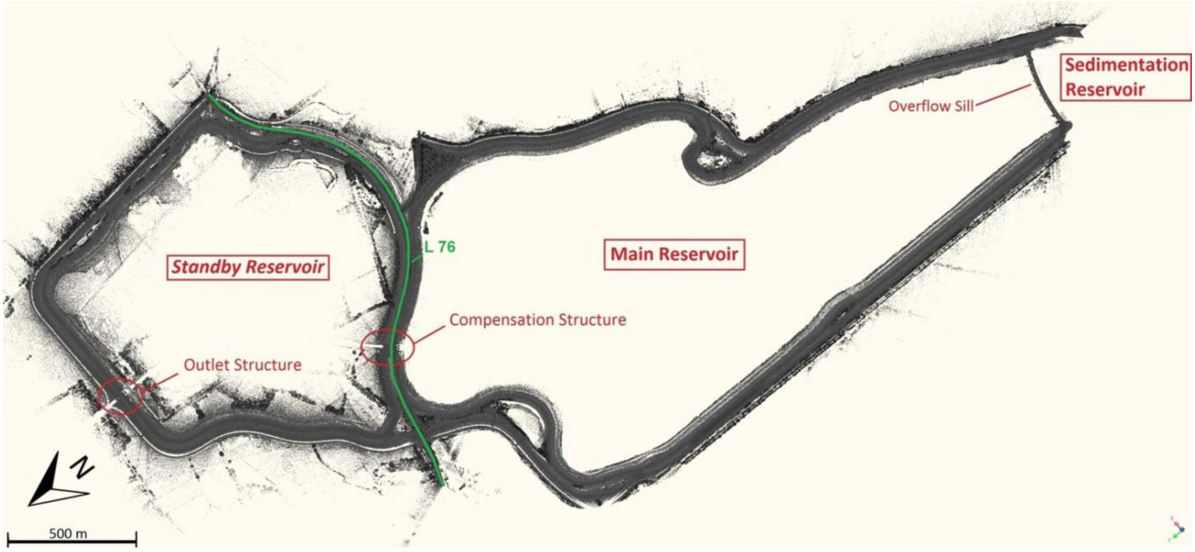

Figure 2 Plan view showing the whole point cloud of the flood control reservoir Alfhausen-Rieste (Trimble 2015)

2.4 Main reservoir

The main reservoir represents a typical lowland storage where material has been excavated from the basin for use as construction material for the surrounding dams. Figure 3 shows a typical cross-section from the main reservoir to the western drainage trench. The main reservoir dam is mainly constructed of sand, with a seal of sandy silt and a seepage element, which should absorb water from the perfusion as well as from the undertow. Table 1 shows significant data of the water levels and storages (NLWKN 2009).

2.5 Compensation structure

The so-called compensation structure lies in the dam between the main reservoir and standby reservoir and carries road L76 (Figure 2). It is constructed out of reinforced concrete and has an average width of 37.70 m. The top edge lies at +36.15 m ASL. During normal dam operation, the compensation structure regulates the normal top water level of the main reservoir at +36.75 m ASL. Small flood waves can be safely absorbed and stored in the main reservoir.

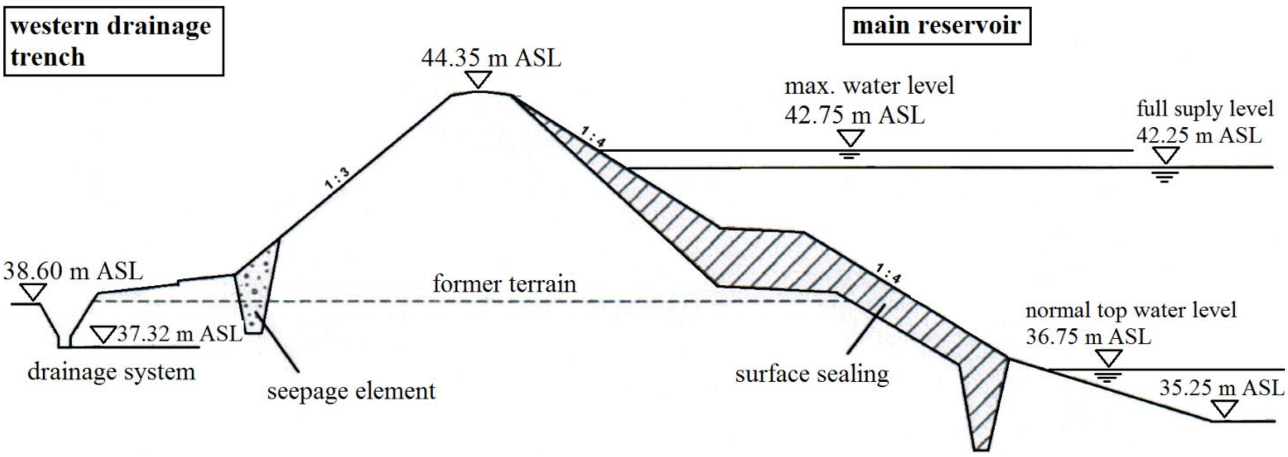

Figure 3 Main reservoir system

Table 1 Parameters of the flood control reservoir Alfhausen-Rieste

Basin	Level	Elevation above sea level	Type of storage	Volume (m³)
Sedimentation reservoir	Normal top water level	+39.00 m ASL	Permanent storage	0.43 million
Main reservoir	Normal top water level	+36.75 m ASL	Permanent storage	3.1 million
	Full supply level	+42.25 m ASL	Flood storage	12.7 million
	Maximum water level	+42.75 m ASL	Surcharge flood storage	14.3 million
	Dam crest	+44.35 m ASL		
Standby reservoir	Full supply level	+41.25 m ASL	Flood storage	7.25 million
	Maximum water level	+41.75 m ASL	Surcharge flood storage	8.10 million
	Dam crest	+44.00 m ASL		

2.6 Standby reservoir

In the case of big flood waves that would turn on the internal spillway, the standby reservoir commences filling. Normally the diverted water passes directly without any backing up through the standby reservoir (NLWKN 2009).

The standby reservoir serves as a buffer in the case of floods, which the main reservoir is not able to store. It has no permanent storage and, in contrast to the main reservoir, the materials of the dam were not sourced from the basin. Therefore, the topsoil was preserved together with its natural cover which, in the case of filling, offers a retarding infiltration (NLWKN 2009).

2.7 Outlet structure

The outlet structure is located at the northern end of the standby reservoir and is constructed of reinforced concrete. In the event of the standby reservoir filling, the internal gates control the water output into the drainage channels of the flood control reservoir Alfhausen-Rieste. The regulation devices are two radial gates (NLWKN 2009).

3 Ground conditions

3.1 Soil conditions

In the range of the sedimentation reservoir, the main reservoir and the standby reservoir, there is an approximately 50 m thick strata consisting of sand and gravel with silty and clayey admixtures over marl.

From the soil profiles, the following can be observed:

- Near-surface peat with a thickness of 2.60 m was removed during the reservoir excavation and stored as unusable soil. Accordingly, the turf under the contact area of the dam was exchanged.
- Thin layers of peat are locally still present in the soil.

- There are pure sand layers in the bottom of the local reservoir. This allows inflows into the dam via these imperfections at the dam contact area.
- Silt layers with sandy additions were removed from the basin and rebuilt into the surface sealing.
- The standby reservoir has not been excavated. The natural surface, composed of silty layers, has a dampening effect on the infiltration (NLWKN 2009).

3.2 Groundwater conditions

The groundwater conditions in the range of the reservoir are characterised by the following properties:

- In the zone of the head of the reservoir, the bottom lets with up to 2 m into the groundwater.
- The normal water level at 36.75 m ASL is located slightly below the natural groundwater level.
- In the compensation structure, the natural ground water level is situated approximately at the bottom of the reservoir.
- Before the construction of the reservoir, the groundwater levels fluctuations ranged between 1.0 and 1.9 m.
- The groundwater situation especially influences the head of the main reservoir, the subsurface hydraulic conditions and thus the stability of the main reservoir dams (NLWKN 2009).

4 Data recording, processing and analysis

The general basis for preparation of the point cloud has been on the one hand an air-borne drone equipped with a digital camera plus GPS device, and on the other hand a car with 3D laser scanner (Figure 2). The system used was LiDAR survey, which is closely related to radio detection and ranging (RADAR). It is a relatively new remote sensing technology that allows collection of a very dense point sample of features in 3D. It does this by measuring distance through illuminating a target with a laser and analysing the reflected light. LiDAR has evolved to become a common source of geographic data in a geographic information system (GIS). Each point in the LiDAR point cloud can have additional attributes such as RGB colour values, intensity or class codes. The points are typically stored in LAS format.

The recordings of the flood control reservoir Alfhausen-Rieste were made by the German surveying company GIL GmbH, Dettelbach, Germany, a partner business of Trimble — one of the leading providers of positioning technologies. In total, the produced point cloud consists of 1.082.541.456 points with a grid distance of 1-4 cm (Figures 3 and 5). The survey itself was carried out in just one day in November 2014. The points of the standby reservoir dams and the eastern and western dam of the main reservoir were collected by a car-mounted device (Figure 4). For the difficult-to-access terrain, a quadrocopter-mounted device was used (Figure 4).

A major problem has been the file size of the produced point cloud. The recording was made with the point attribute of RGB. However, the display of 1.1 billion survey points combined with their RGB information was not compatible with a loadable file size. Even the visualisation in grey levels produced a point cloud file with a size of 21 gigabyte. For the further examination and analysing process, a lot of different software for LiDAR point clouds was tested. Many failed attempts to load and process such a huge point cloud. In this regard, two programs have proven to be very efficient and have demonstrated smooth working with large LiDAR data exchange files (LAS) Trimble Real Works and LP360. More detail is provided in the following sections.

Figure 4 GIL Quadrocopter (a) and Trimble MX8 Mobile Spatial Imaging System (b) (source: GIL GmbH)

4.1 Graphical visualisation

For the 3D visualisation and the preparatory work, the software ´Trimble Real Works 9´ by Trimble Navigation (Trimble, 2015) was used. What sets this software apart from other applications is that it offers a unique display of almost all points in conjunction with free selectable views. This allows the point cloud to be observed from all angles and positions. In this process, the viewer is able to change the luminosity, contrast and colour of the point cloud as well as the background. Tasks such as segmentation or thinning of certain sections for further examinations can be completed rapidly.

4.2 Profile cutting and transformation

LP360 is an extension to ArcGIS that specialises in visualisation and processing of very large point clouds. The software provider is QCoherent Software, a GeoCue company based in Madison, Wisconsin. GeoCue is a supplier of kinematic LiDAR processing tools and LP360 is currently the world’s most widely used tool for exploiting point cloud data in an ArcGIS environment (GeoCue Group 2015).

LP360 provides an intuitive and user-friendly interface with various analysis tools. It is programmed to load and visualise the point cloud by degrees that allow smooth and comfortable working. Additionally, the user has the option of changing the number of displayed points very precisely and forcing all points for a predefined section. These options make the program extremely adaptable.

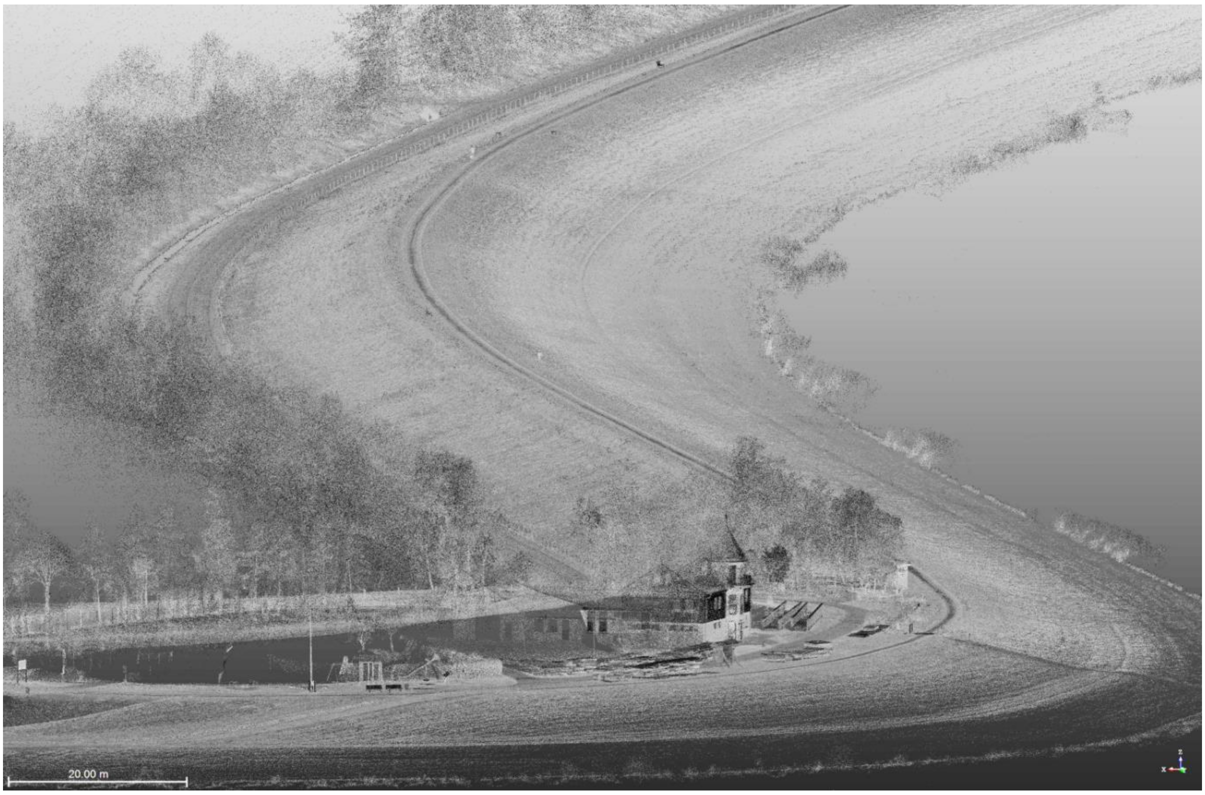

Figure 5 Oblique view of the eastern main reservoir dam with the small boat dock in the foreground (Trimble 2015)

The main and control windows show the data in 2D from top view, as in the left image in Figure 6. Certain areas can then be selected to be displayed in 3D, as in Figure 6 top right. One display type is the TIN surface visualisation, which is very well known in the GIS community, as pictured top right in Figure 6. "TINs are a form of vector-based digital geographic data and are constructed by triangulating a set of vertices (points). The vertices are connected with series of edges to a form of a network of triangles." (ArcGIS Resources 2014). At the lower right of Figure 6, you can see the profile of the selected section, displayed with its width and length. In this profile, it is possible to identify every single point with its exact x, y and z coordinates in the global system. Great advantages of this tool are the ability to modify the profile width very exactly and to classify points. In particular, the classification of points helps significantly to determine a suitable profile for the further processing. Inaccuracies of the point cloud caused by vegetation or other interferences can be marked, classified and hidden upon request.

As an example for this paper, the western dam of the main reservoir was analysed along its 2 km distance. Because of its extremely straight shape, the analysis of profile changes can be carried out in less than 20 minutes. The red marked section, shown in Figure 6, is located in the south of the eastern main reservoir dam and is defined as station 0+000. From this starting point, the dam profile can be displayed right along its vertical axis at any distance. In this case, a distance of 100 m was chosen.

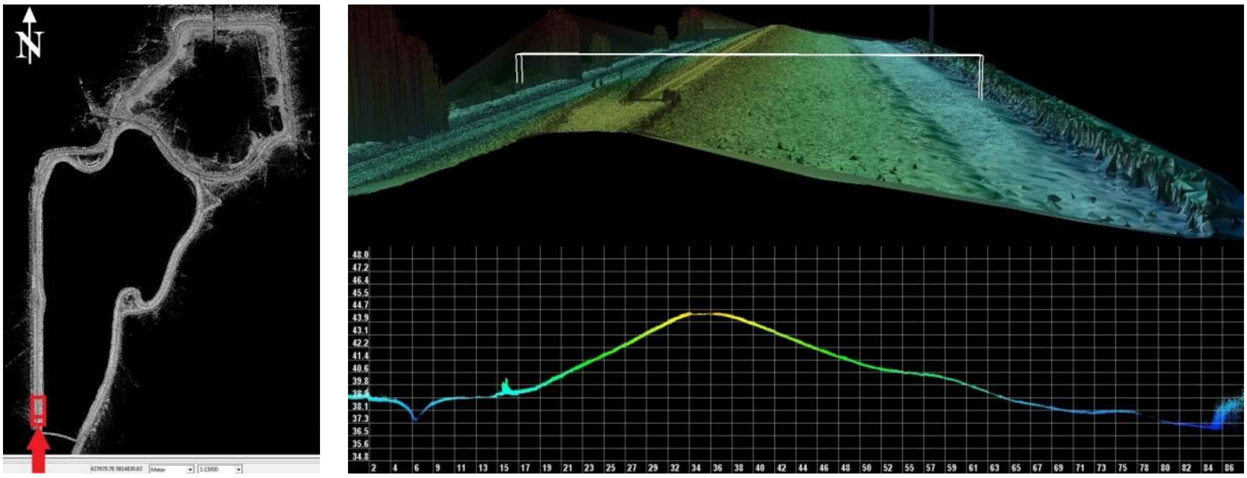

Figure 6 Left: reservoir overview with red marked section on the western dam: top right: 3D visualisation of the selected section; bottom right: 2D profile of the section

In order to give a clearer picture of the results, only the actual weakest and the design profile are displayed in Figure 7. The design versus actual comparison shows that the shape of the western main reservoir dam is constructed with close conformance to design.

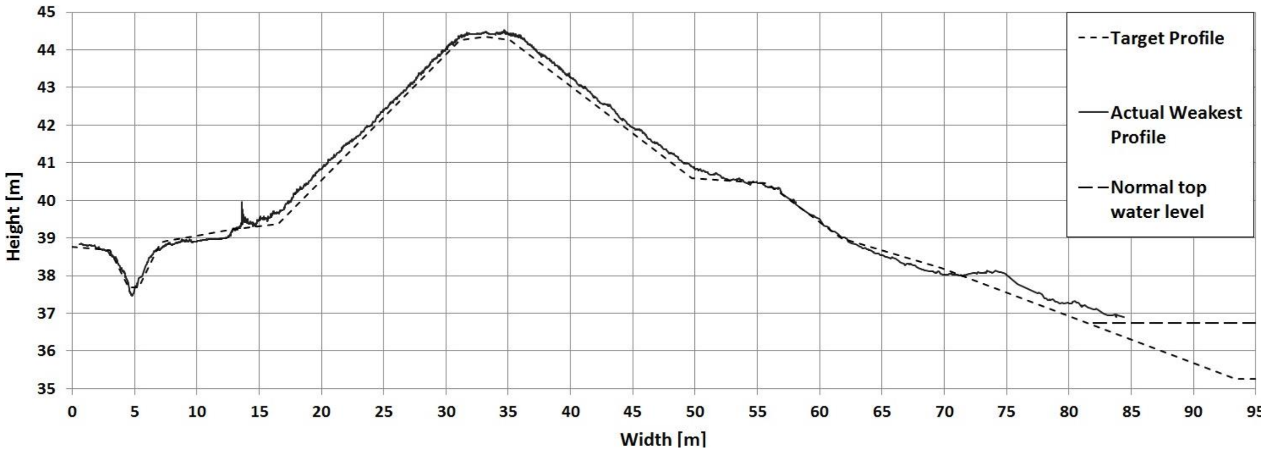

Figure 7 Comparison of target and actual weakest profile of the western main reservoir dam with an oversized vertical axis

In connection with onsite estimations and the soil as well as the groundwater conditions, the potential weakest cross-section was selected for the further analysis. Therefore, the coordinates of the terrain were transferred from the LP360 profile to the slope stability analysis software GGU-STABILITY (GGU 2013). During this procedure, points needed to be complemented because of the missing data capture of the terrain under the water surface. These points have been complemented true to scale with the information from the construction drawings.

5 Slope stability analysis of the western main reservoir dam

For the slope failure analysis the software program GGU-STABILITY, Civilserve GmbH in Steinfeld, Germany, (GGU 2013) was used.

> *"The program GGU-STABILITY allows slope failure investigations according to German Standard DIN 4084, DIN 4084:1996 and DIN 4084:2009, using circular slip surfaces (Bishop) and polygonal*

slip surfaces (Janbu, General Wedge method and Vertical slice method). The fundamentals of analysis using partial factors are given in EC7/DIN 1054:2010" (Buß 2014).

During the planning phase, no stability investigations were made because of the very flat slope angles of the dams. In our stability analysis, the following considerations were carried out.

The investigations assumed the profile in Figure 8 because of the problematic subsurface hydraulic conditions, as explained in Section 3.2.

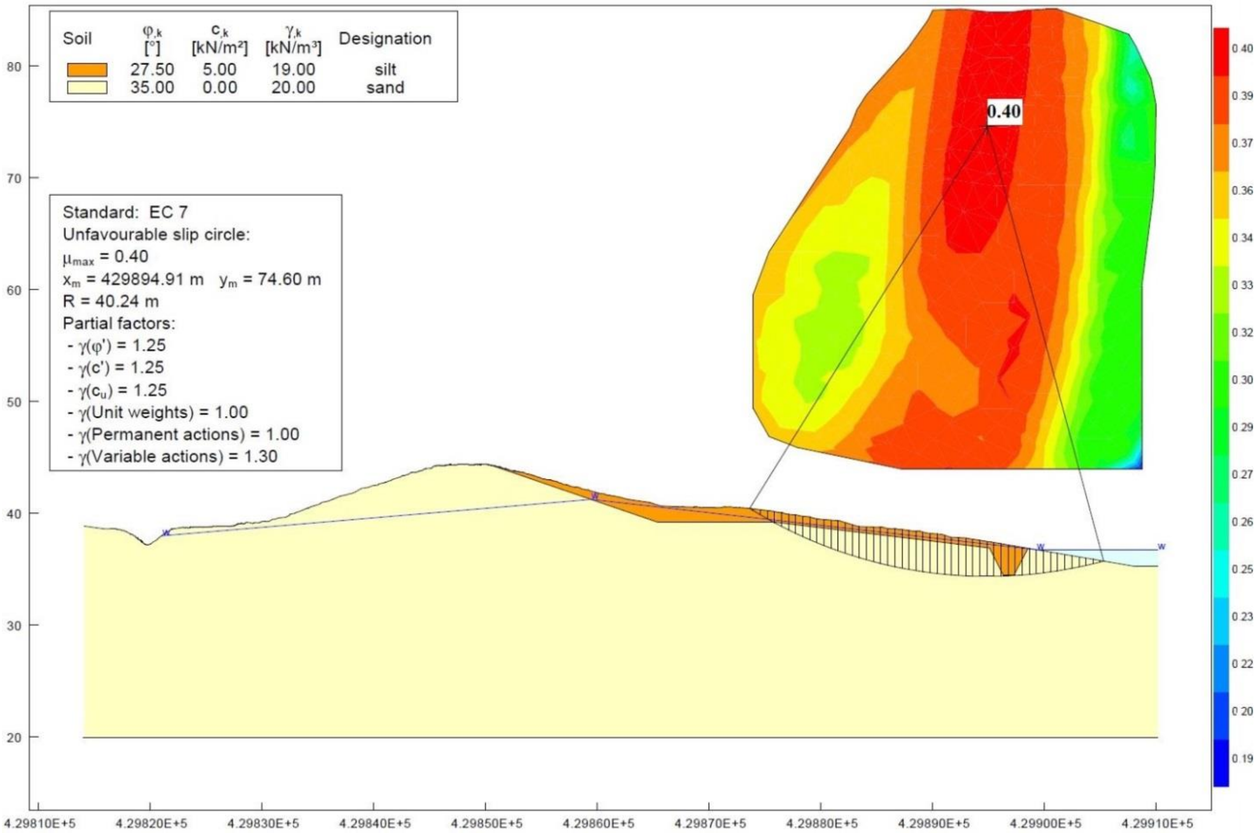

Figure 8 Slope stability analysis for selected profile of western main reservoir dam using Bishop (circles/slices) calculation method

Of relevance to the structural stability of the upstream facing slope is the loading case for rapid drawdown of 6 m from maximum water level (42.75 m ASL) to normal top water level (36.75 m ASL), with a high seepage line of 41.25 m ASL at the bottom edge of the surface sealing.

This assumption is extremely unfavourable since it appeared that with a decrease of the water level in the main reservoir, the water level in the monitoring wells, though delayed, also decreased.

The partial factors were:

- $\gamma(\varphi') = 1.25.$
- $\gamma(c') = 1.25.$
- $\gamma(c_u) = 1.25.$
- $\gamma(Unit\ weight) = 1.00.$
- $\gamma(Permanent\ \ actions) = 1.00.$
- $\gamma(Variable\ \ actions) = 1.30.$

From Figure 8 the stability is calculated using the Bishop (circles/slices) method as:

$$\mu = 0.40 \ < \ \mu = 1.00 \ (EC\ 7,\ DIN\ 4084,\ DIN\ 19700) \quad (1)$$

This high Factor of Safety is due to the very shallow slope.

6 Geomonitoring — using consecutive LiDAR surveys for deformation analysis

The LiDAR survey serves to determine possible deformations in the process of time by comparing following LiDAR-measurements. The presented initial measurement is the starting point of surveying the dam structures of the flood control reservoir Alfhausen-Rieste again after the next flood event, at the latest, however, when the next recessed safety report is required.

Outlets of percolating water on the air side indicate a defect of some drainage systems. This implies providing a shift of the seepage–water line which, as expected, could lead to deformations to occur at the dam structures. With a superimposition of consecutive LiDAR surveys, the dimension of the displacements could be displayed with a millimetre precision in the global coordinate system.

7 Conclusion

LiDAR systems offer fundamental assistance for slope stability analysis by producing a digital terrain model with georeferenced data points. Mobile mapping is easy, fast and replaces the hard work of manual measurements that can take thousands of hours. In addition, LiDAR can be applied to almost any area of the world and gives more precise results than conventional land surveys.

This research indicated that the selection of suitable point cloud software is of great relevance. The size of the survey area, and therefore the size of the LAS file, can determine which program to use. Working with a very large amount of data requires a thinning of the point cloud if the performance of computer system is not adequate.

Conclusions from the study include:

- The extremely high point density allows 3D visualisation with a high level of detail. Thus, the observer can move freely through the digital terrain model and obtain a realistic picture of the investigated area.
- Cross-sections and or profiles of the reservoir dam can be rapidly defined.
- The transformation of the profile coordinates into GGU-STABILITY is simple.
- Having precise coordinates of each single survey point allows constructions — such as new drainage systems — to be planned with incredible accuracy.
- Interfering elements such as tree vegetation can be classified either automatically or manually, and their display can be toggled. This option facilitates data adaption for additional types of analysis.
- The use of precise terrain data to represent the real ground surface improves the accuracy of stability analyses, including allowing sliding areas or slope failures to be identified; traditionally, it has been common to simplify the land surface.

These new advantages support a significant step forward in the investigation and assessment of civil structures.

References

ArcGIS Resources 2014, *ArcGIS Help 10.1: What is a TIN surface?,* ArcGIS Resources, Redlands, CA, viewed 10 March 2015, http://resources.arcgis.com/en/help/main/10.1/index.html#/na/006000000001000000/

Buß, J 2014, ´GGU STABILITY, Slope stability analysis and analysis of soil nailing and reinforced earth walls to DIN 4084 and EC 7´, Steinfeld, Germany.

GeoCue Group 2015, Madison, AL, viewed 5 March 2015, http://www.geocue.com

German Institute for Standardization 2004, ‘DIN 19700-12: Dam Plants – Part 12: Flood Retarding Basins’, German Institute for Standardisation (DIN), Berlin.

GGU 2013, *Slope Stability Analysis Software Suite*, http://www.ggu-software.com/software/geotechnical_software.html

Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten und Naturschutz (NLWKN) – Betriebsstelle Cloppenburg 2009, ´Hochwasserrückhaltebecken Alfhausen-Rieste, Talsperrenbericht, Berichtsjahr: 2008-2009´, Cloppenburg, Germany. (Lower Saxony State Office for Water Management, Coastal Defence and Nature Conservation Agency – operating agency Cloppenburg 2009, ´Flood Control Reservoir Alfhausen-Rieste, Dam Report, Reporting Year: 2008-2009´, Cloppenburg, Germany.)

Trimble 2015, Trimble Real Works 9, 3D scanning software, Trimble Navigation Limited, http://www.trimble.com/3d-laser-scanning/realworks.aspx