Evaluation of State of the Art Methods for Surface Monitoring of Earth Filled Dams

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Earth filled dams are commonly used as flood prevention dams and for hydroelectric power plants. Their stability is critical for an uninterrupted operation and a reliable protection from catastrophic incidents.

Graz University of Technology carried out a series of life-size experiments to evaluate different state of the art methods for monitoring surface movements of earth filled dams. Controlled vertical load was applied in these experiments to an earth filled dam and the resulting deformations were measured with geodetic and fiber optic methods.

Single points on the slope were continuously tracked with robotic total stations. Additionally, the whole dam surface was monitored using a scanning total station. Finally, relative movements between points on the dam were measured with fiber optic sensors based on fiber bragg gratings.

The achievable measurement precision and the relation between acting load and resulting deformation is investigated in detail for every measurement technique.

We show in our evaluation that absolute deformations can reliably be detected with the geodetic methods. However, individual loading steps cannot be resolved due to the limited precision of the geodetic measurements. Our results demonstrate that the sensitivity of the structural health monitoring (SHM) system can be significantly increased with the fiber optic sensors and the scanning data also contribute to assess the stability of the experiment setup.

Structural Health Monitoring; Deformation Analysis; Fiber Bragg Grating; Scanning Total Station; Flood Prevention Dam

I. Introduction

In 2012 a new hydroelectric power plant was built on the river Mur in the south of Graz, Austria. Earth filled flood protection dams were erected on both sides of the river as part of the safety plan of this project [8].

An experimental dam with 3.5m (width) x 3.0m (height) x 27.0m (length) was constructed in the vicinity of the water plant to verify the stability of the flood prevention dams. The dam material of the test dam was the same as the material used for the flood prevention dams. The slope angle was 60°. In the experiments slope failures in longitudinal direction were forced by applying vertical loads up to 800kN/m² on the dam crest. The goals of these experiments were to determine the shear parameters of the dam material, to evaluate the performance of modern slope stabilization methods and to assess different monitoring methods. In this paper we focus on the evaluation of the geodetic and fiber optic monitoring program developed for this project.

II. Loading Experiments

Several loading experiments have been carried out. In each experiment vertical load was applied onto the dam crest with a steel traverse and two hydraulic presses, see Fig. 1. Surface deformations of several centimeters were predicted from numerical simulations.

The dam was either not stabilized, stabilized with two Spideranchors as indicated in Fig. 2, or stabilized with two Spideranchors and a geotextile. A Spideranchor consists of an iron anchor head and iron rods which are screwed through this anchor head in different angles into the ground [9]. The idea of the Spideranchor is to stabilize the dam like the roots of a tree.

Figure 1. Experimental dam in the vicinity of the hydroelectric power plant

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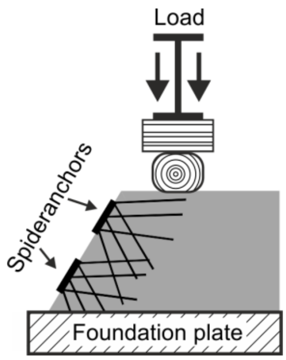

Figure 2. Experimental setup: stabilization with Spideranchors

III. MONITORING PROGRAM

The monitoring program has been designed by the Institute of Engineering Geodesy and Measurement Systems (EGMS) of Graz University of Technology. The reaction of the dam surface to the applied load had to be measured in order to assess the stability of the dam. Furthermore, the movements of the anchor points were of special interest. The developed monitoring program consists of a geodetic and a fiber optic component.

A. Geodetic Monitoring

The geodetic monitoring in this project is based on two robotic total stations and one scanning total station. Due to the expectation that the dam suddenly fails under load continuous 3D measurements with high precision and high sampling rate were necessary. The positions of the Spideranchor heads were continuously measured with two total stations in tracking mode. Therefore, special adapters for prism mounting and fiber pre-straining were developed, see Fig. 3.

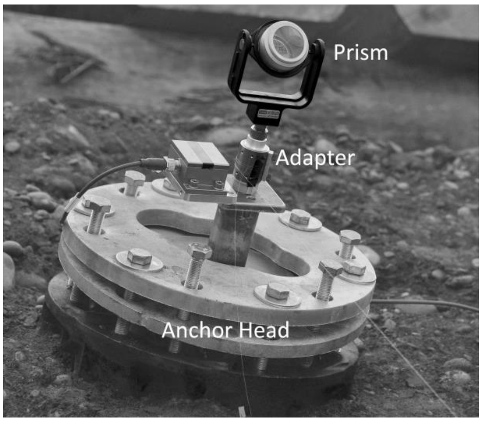

Figure 3. Detail view of monitoring point on Spideranchor head

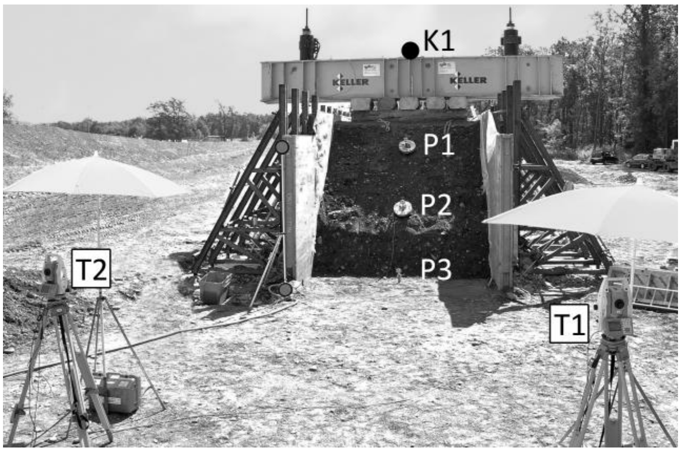

Figure 4. Measurement setup for the continuous monitoring of the anchor heads with two tracking total stations (T1, T2) and location of the inclination sensor (K1) on the steel traverse

The overall measurement setup is shown in Fig. 4. The prism P1 was tracked by total station T1 (Leica Geosystems TS15) and the prism P2 by total station T2 (Leica Geosystems TCRA1201). A third point P3 was installed as a reference point at the foundation plate of the dam and sporadically observed for stability. The total stations were remotely controlled with Matlab programs developed by EGMS. As a third total station the new scanning total station Leica Geosystems MultiStation MS50 was used for scanning the dam surface. This instrument has full total station functionality, fast direct drives and can measure up to 1000 points per second [4]. During all measurements meteorological data were collected for meteorological distance reductions. On top of the steel traverse a KELAG inclination sensor (K1) was installed to monitor inclination changes of the steel traverse during the load application.

1) Local Reference Point Network

A local reference network was established to analyze all total station data in a common coordinate system. Fig. 5 displays the position of the network points, the location of the foundation plate and the instrument positions for the experiment on August 30th, 2012. The center and orientation of the local coordinate system were aligned to the foundation plate of the dam. The positions of all total stations were determined by free stationing at the beginning of each experiment and verified again at the end of the experiments.

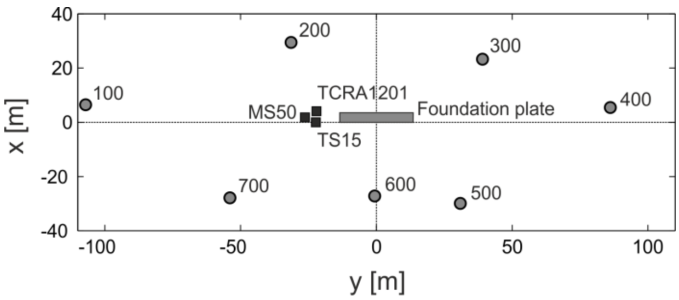

Figure 5. Local reference point network

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2) Static Single Point Measurements

Static total station measurements are more precise than continuous measurements. However, the attainable measurement resolution and precision are typically not fully specified by the manufacturer. To verify the results of the two tracking total stations the scanning total station MS50 was used to measure the prism positions on the dam in the static measurement mode after each loading step. The EDM and ATR precision for measurements in the standard measurement mode are specified as 1mm (1σ) for the distance measurement and 1mm (1σ) for the ATR measurement [5] for the given short distance. However, since only deformations are of interest in this application a higher relative precision can be expected.

3) Continuous Single Point Measurements

As described before the prism P1 was tracked with a TS15 and prism P2 with a TCRA1201, both from Leica Geosystems. The EDM precision in tracking mode is specified as 5mm (1σ) for the TCRA1201 [1] and as 3mm (1σ) for the TS15 [3] for the given distance. The ATR precision is specified as 2mm for the TCRA1201 [1] and 1mm for the TS15 [3]. Again, a higher relative precision can be expected. The measurement update rate is specified as better than 6Hz [1], [3]. These, theoretical values will be compared to empirically determined values in section IV of this paper.

4) Scanning of the Dam Surface

At the beginning of each experiment and at the end of every loading step the whole dam surface was scanned with the MultiStation MS50. The duration of one scan was about 2min using the highest possible distance measurement rate of 1000Hz. After completing a scan, the total station was used to measure the prisms P1, P2 and P3 to assess the tracking performance of the other two total stations.

5) Scanning of Single Scan Lines

During the loading steps the MultiStation MS50 was also used to continuously scan one specific vertical cross section of the dam surface with a distance measurement rate of 1000Hz. These data can be used to obtain detailed deformation information during loading steps.

B. Fiber Optic Monitoring

A fiber optic monitoring system was used for the early detection of a possible dam failure and the investigation of potential creeping behavior of the dam. The development of the monitoring system and the calibration of the fiber bragg grating (FBG) sensors is described in detail in [6]. Using FBG sensors the distance changes between the anchor points P1 and P2 (FBG1) and between P2 and the reference point P3 (FBG2) can be measured with micrometer resolution.

FBG sensors are sensitive to strain and temperature changes, see e.g. [7]. Therefore, the local temperature was measured in the vicinity of the FBG sensors using electrical temperature sensors (thermocouples), see Fig. 6. Thus, strain and temperature could be separated using the calibration functions determined in the laboratory and the on-site temperature measurements.

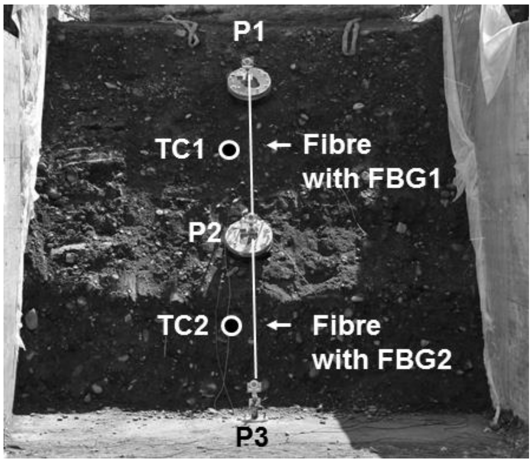

Figure 6. Position of two fiber bragg grating (FBG) sensors and termocouples (TC)

Due to the expected large deformations of several centimeters and the short distances of about 1.3m between the anchor points the measurement concept had to be prepared for high strain values. As a consequence draw tower gratings (DTG, FBGS International) were used and high pre-strain was applied with the developed mounting adapters.

IV. Measurement Results

In this article we focus on the results of the experiment on August 30th, 2012. In this experiment Spideranchors were used as stabilization method and the load was gradually increased up to 650kN/m^2 as shown in Fig. 7. The initial goal was to increase the load until the dam fails. However, as will be discussed later, the experiment was aborted due to deformations of the steel traverse caused by the high loads in combination with the high stability of the dam.

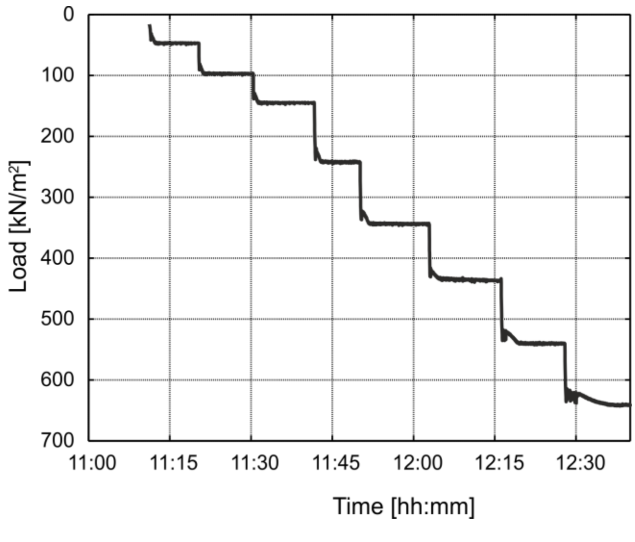

Figure 7. Stepwise increase of load on August 30th, 2012

A. Static Single Point Measurements

The precision of static single point measurements was determined on site by repeated measurements to a stable point of the reference point network. From these measurement data a coordinate precision of 0.2mm (1σ) was derived. As expected the precision of repeated measurements to one target under the same environmental conditions is significantly better than the specified precision which is derived from measurements to several targets at different distances and different directions.

As explained before, static single point measurements were performed after each loading step. The derived movements of the anchor heads are displayed in Fig. 8. It is apparent that the anchor head movements are much smaller than expected. The movements of the anchor points do not exceed 5mm and prove a high stability of the Spideranchors. A detailed analysis reveals that P1 and P2 experience different deformation behavior. The movements of P1 are predominately horizontal whereas P2 moves almost the same amount horizontally and vertically. The total movements are about 4.8mm for P1 and 3.2mm for P2. Furthermore, the static single point measurements confirm the stability of the fixed reference point P3 at the toe of the dam. The measured coordinate variations of this point are within the measurement noise.

B. Continuous Single Point Measurements

The results of the continuous single point measurements using the two robotic total stations are shown as grey dots in Fig. 8. The continuous measurements follow the trend of the static measurements but with high measurement noise. For P1, high measurement noise is only present for the y-coordinate, whereas all coordinate directions of P2 show high measurement noise.

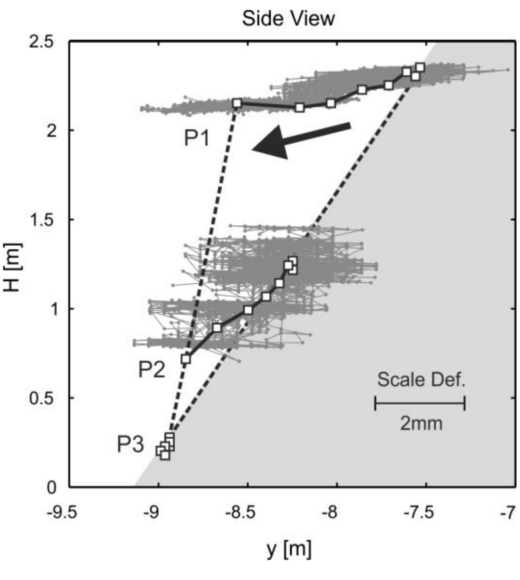

Figure 8. Static single point measurements (black squares) and continuous single point measurements (grey dots)

This aspect can be investigated by analyzing the data of a stable period without any load applied. Fig. 9 displays the coordinate variations in y-direction and height for both total stations for a 4 minute time period. Thus, it appears that the y-coordinates have larger variations which result in a standard deviation of 1mm. These variations are caused by the noise of the distance measurements which correspond to the y-direction in our setup. Furthermore, it can be seen that the distance resolution in tracking mode is only 1mm for both instruments.

The performance in vertical direction differs between the instruments. The precision of height values is 0.4mm (1σ) in case of TCRA1201 measurements and better than 0.1mm (1σ) for TS15 measurements. The observed height variations are a result of the precision and resolution of the automated target recognition (ATR) sensors of the instruments. It has to be noted that the TCRA1201 and TS15 use different hardware and firmware for the ATR. The ATR sensor of the TCRA1201 is based on a CCD sensor whereas the TS15 uses a CMOS sensor which Leica Geosystems introduced first with their TPS1200+ series [2]. By analyzing the raw measurement data it was found that the ATR resolution of the TCRA1201 is only a full CCD pixel in the tracking mode. For the TCRA1201, this corresponds to about 40cc and results in jumps of the data. The resolution of the ATR of the TS15 is one tenth of a pixel and therefore a higher precision and smoother data is gained.

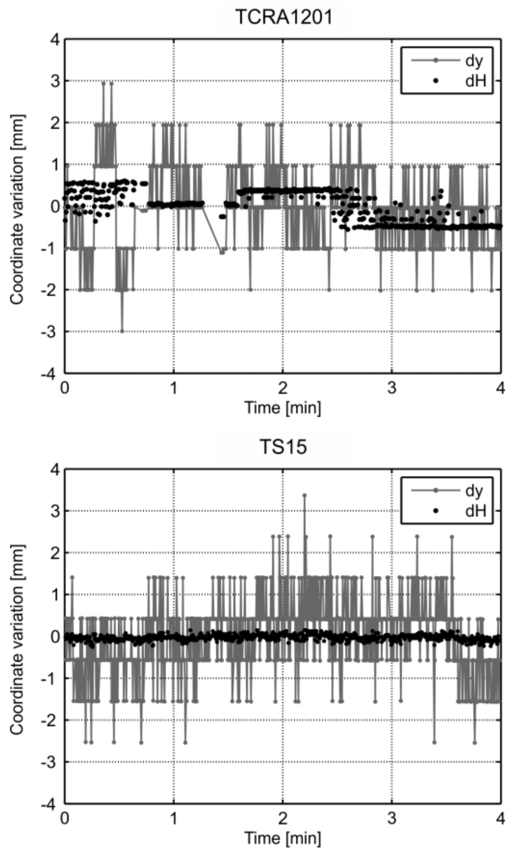

Figure 9. Coordinate variations during a stable 4 minute period of TCRA1201 (top) and TS15 measurements

C. Scanning

The whole dam surface was scanned after each loading step with a distance measurement rate of 1000Hz. Fig. 10 displays the measured point cloud of one scan with 50 000 points.

1) Deformations along a Scan Line

First we concentrate on the deformation analysis of one single vertical scan line. The selected scan line is indicated in black in Fig. 10. Deformations of points along this scan line were calculated with Matlab using scan data from different loading steps. The deformations between the last loading step (650kN/m^2) and the initial unloaded state are shown in Fig. 11. For better visibility the deformations are exaggerated by a factor 5. It is apparent that the area above the Spideranchor SP1 bulges out several centimeters. The area below the Spideranchor SP1 is almost stable, thus confirming again the high stabilization capabilities of the Spideranchors. It can also be seen that in some areas material slides down and accumulates at the toe of the dam.

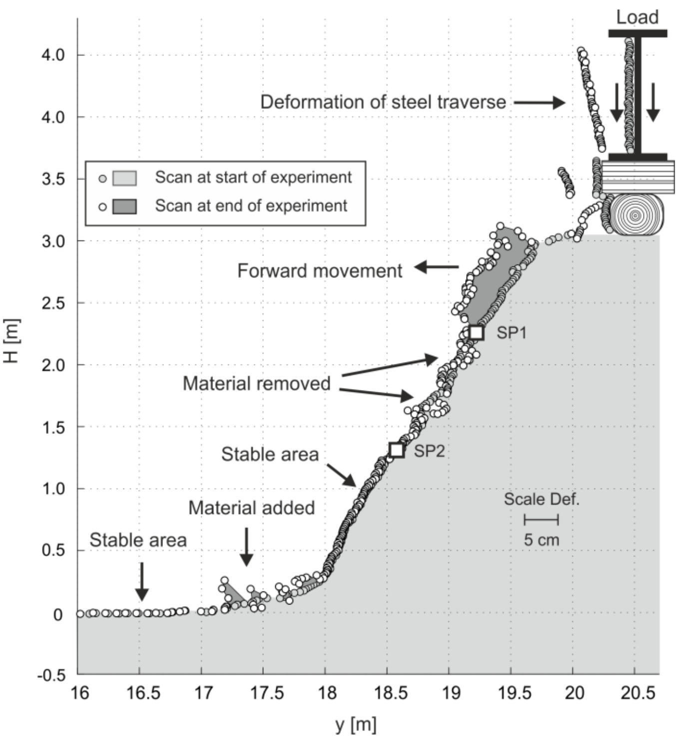

Figure 11. Deformations along the vertical single scan line between the start and the end of the experiment

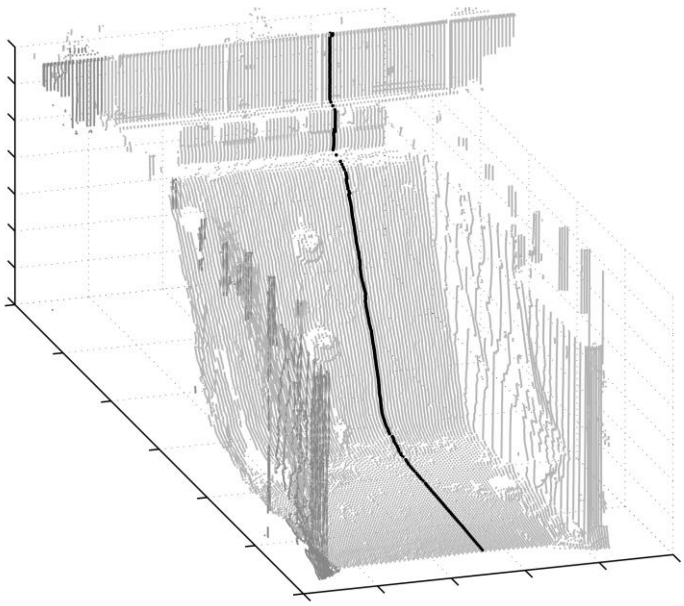

Figure 10. Point cloud of dam surface and single scan line for detailed analysis

2) Precision of Distance Measurements in Scanning Mode

In order to determine the precision of the distance measurements to the dam surface one single scan line was scanned about 30 times during a stable period of the dam. The range noise of the Leica Geosystems MS50 in scanning mode is specified as 1.0mm (1σ) for measurements with 1000Hz orthogonally to a target plane with 90% reflectivity [4]. Field measurements typically result in a lower precision due to inclined measurements to natural targets with rough surfaces and lower reflectivity. In our case measurements with low incidence angles could be avoided due to a high instrument setup on a small hill about 2.5m above the foundation plate. Therefore, the measurements were almost orthogonal to the dam surface.

Fig. 12 displays the distance variations for all 270 points of the line. It can be seen that the mean standard deviation of the distance measurements is 1mm which corresponds well to the specifications of the instrument.

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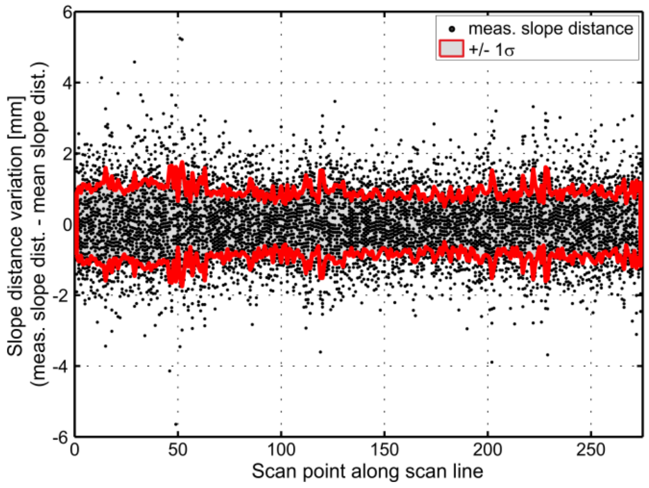

Figure 12. Precision of the observed slope distances

3) Inclinations derived from Scanning Data

The loading experiment on August 30th, 2012 had to be aborted due to large deformations of the steel traverse. Fig. 13 shows the tilt of the steel traverse at a load of 650kN/m^2. Since deformations of the steel traverse have already been expected prior to the experiments a KELAG dual axis inclinometer SCA124T-D04FA was mounted on top of the steel traverse to observe inclination changes.

Additionally, the deformation of the steel traverse could also be derived from the scanning data. Therefore, regression lines were estimated from the scan data of different loading steps using measurement points of the straight section of the steel traverse, see Fig. 14. The maximum deviation of the scanning points to the regression lines is about 1.9mm and the standard deviation of the estimated inclination is better than 0.1°.

Finally, these estimated inclinations were compared to inclinations measured with the KELAG inclination sensor. The derived inclinations are in good agreement to the measured inclinations as can, see Fig. 15. Maximum deviations between measured and calculated inclinations are less than 0.3°.

Figure 13. Deformations of steel traverse at 650kN/m^2

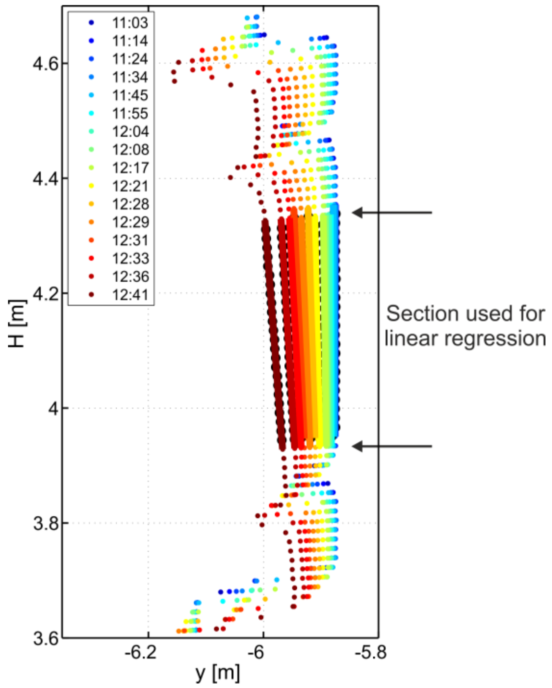

Figure 14. Scanning points on steel traverse from 11:03 to 12:41

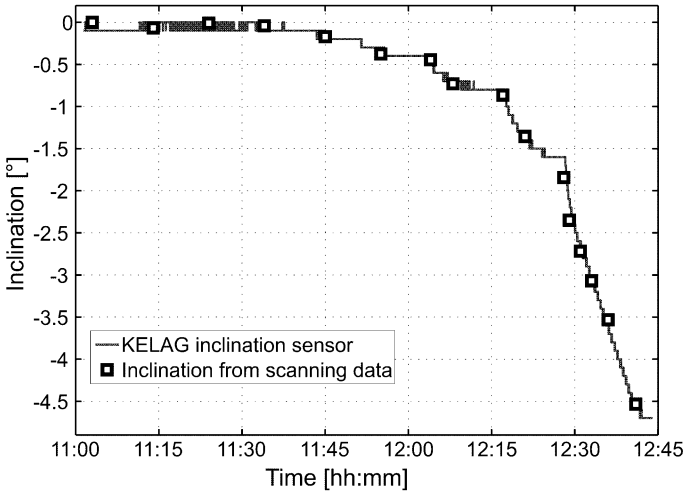

Figure 15. Inclinations measured with inclination sensor and inclinations derived from scanning data

4) Deformation Analysis of whole Dam Surface

Deformations of the whole dam surface using the point cloud data were calculated using Leica Geosystems GeoMoS v6.0. Fig. 16 displays the result of the deformation analysis using point cloud data from the unloaded state of the experiment and from the last loading step (650kN/m^2). It is apparent that the upper part of the dam slope experiences a forward movement of several centimeters. Compared to the movements of the prisms on the anchor heads, these movements are more than ten times higher. In some areas material, mostly stones, was sliding down and causing negative deformations. This material was accumulating at the toe of the dam.

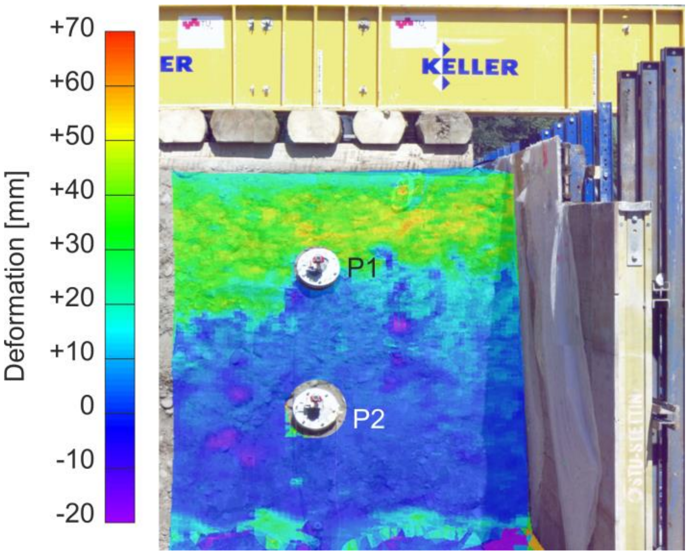

Figure 16. Deformations calculated from point cloud data

D. Fiber Optic Measurements

Relative anchor head movements can be calculated from the geodetic 3D positions or directly be measured with the fiber optic sensors. The measurement noise of the FBG measurements can be determined by analyzing the data of a stable period. Fig. 17 shows the measurement variations within 5 minutes in the unloaded state of the experiment. A standard deviation of better than 7µm can be derived from these data for both sensors which is remarkable keeping in mind the difficult measurement conditions in the field.

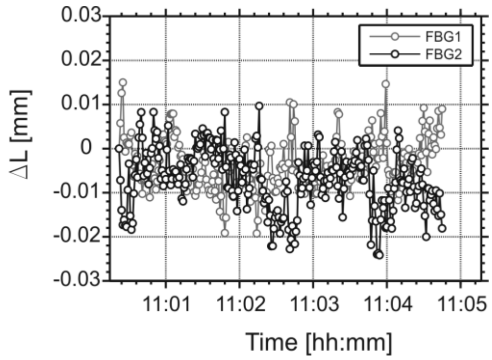

Figure 17. FBG measurements during the initial stable phase showing the measurement noise

The results of the dynamic fiber optic measurements are displayed in Fig. 18. It can be seen that the FBG sensors depict relative movements between the anchor points immediately after the load is increased. Furthermore, the creeping behavior of the movements, e.g. between 12:18 and 12:25, is visible by these measurements.

The distance between the anchor heads P1 and P2 (FBG1) and the distance between P2 and the fixed reference point P3 (FBG2) was decreasing as expected. The length change at the end of the experiment is about 0.8mm (approx. 600µε) for the distance P1-P2 and about 2.7mm for the distance P2-P3 (approx. 2200µε).

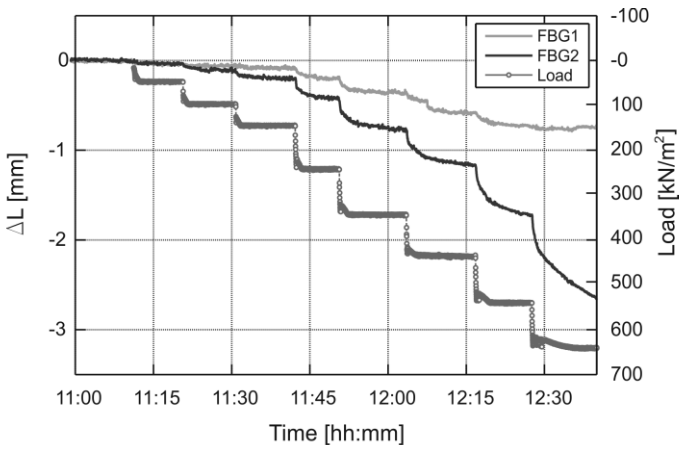

Figure 18. Load steps and results of dynamic fiber optic measurements

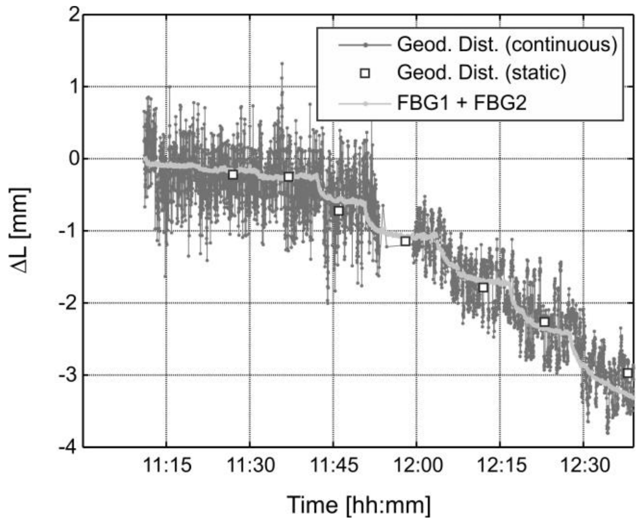

Figure 19. Length changes between P1 and P3 derived from geodetic and fiber optic measurements

To verify the results, we compared the FBG measurements with the TS15 total station measurements. Fig. 19 shows the results of the two different measurement techniques. Displayed are the length changes between the anchor point P1 and the fixed reference point P3. This corresponds to the sum of the two FBG readings. For the geodetic data distances were calculated from the continuously tracked 3D coordinates of P1 and the known coordinates of the fixed reference point P3. Although the precision of the geodetic and fiber optic measurement techniques is completely different, it can be seen that the overall deformation can also be detected with the continuous and static geodetic measurements. However, the deformations caused by the individual loading steps and the creeping behavior are only measurable with the fiber optic sensors.

V. CONCLUSIONS

In this paper we reported about the evaluation of different monitoring methods for the surface monitoring of an earth filled dam with a height of 3m and vertical loads up to several hundred kN/m^2.

Static single point measurements with robotic total stations are a proven monitoring technique and were also well suited for this experiment. The coordinate precision was verified to be 0.2mm (1σ) in our measurement setup. The position changes of two points on the slope could be determined with high precision but not in the continuous measurement mode.

Continuous high frequent measurements are crucial for the observation of sudden dam failure. However, continuous total station measurements in tracking mode were not suitable for this dam experiment due to the small movements of the anchor heads and the low precision and limited resolution of the continuous distance measurements. Furthermore, height changes could only be determined accurately with the ATR measurements of the TS15 due to the low ATR resolution of the TCRA1201.

The data from the scanning total station proved to be valuable for the evaluation of the overall deformation behavior of the slope. Different deformation patterns could be identified by the analysis of the point cloud data. The area above the stabilization experienced movements of several centimeters whereas the area below the Spideranchors turned out to be stable. In our case a distance measurement precision of 1mm could also be achieved in 1000Hz mode scanning the dam surface. Furthermore, the inclination of the steel traverse could reliably be derived from the scanning data.

The fiber optic system was well suited for measuring relative anchor head movements. Creeping behavior of the dam could be detected due to the high precision of 7μm of the FBG sensors. However, only relative deformations can be depicted with fiber optic measurement systems. Therefore, relative fiber optic measurements complement absolute geodetic measurements and enable detailed investigations on small-scale deformations which are critical for early warning systems.

Finally, the Spideranchors significantly increased the stability of the dam and are a flexible method for slope stabilization.

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