Contributions of geodesy to the safety of dams in Switzerland

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ABSTRACT: Geodetic deformation measurements have been used successfully in Switzerland for over 100 years to survey and monitor dams. They make it possible to determine any displacements and deformations of the dams as well as the surrounding terrain with high precision and reliability in relation to an absolute reference frame. Combined with other instruments for deformation measurements, geodetic methods contribute considerably to the determination of dam behaviour and to the assessment of exceptional situations or behavioural anomalies of dams and thus to their safety.

This article specifies the tasks and requirements of dam surveys. Established methods of geodesy, their evaluation as well as recent instrumental developments are described and possible methodological and technological developments are pointed out.

The article published in German in the journal «Wasser Energie Luft» 3-2023 as well as other publications by the working group on dam surveying of the Society for the History of Geodesy in Switzerland (GGGS) can be accessed on the website of the GGGS (www.gggs.ch > Virtuelles Museum > E-Expo Schweizer Talsperrenvermessung). Also available are an extensive bibliography of relevant technical publications beginning in 1920 and a picture gallery from different time-epochs categorized in 17 topics.

RÉSUMÉ: Les mesures géodésiques de déformation sont utilisées avec succès en Suisse pour la surveillance des barrages depuis plus de 100 ans. Elles permettent de déterminer avec une grande précision et fiabilité, par rapport à un cadre de référence absolu, les éventuels déplacements et les déformations des barrages ainsi que du terrain environnant. Associées à d'autres dispositifs de mesure de déformations les méthodes géodésiques contribuent de manière décisive à la détermination du comportement des barrages et à l'évaluation des situations exceptionnelles ou des anomalies de comportement des ouvrages d'accumulation, et donc à leur sécurité.

Cet article explique les tâches et les exigences des levés de barrages. Les méthodes éprouvées de la géodésie, leur évaluation ainsi que les développements instrumentaux récents sont décrits et les développements méthodologiques et technologiques possibles sont soulignés.

L'article publié en allemand dans la revue « Eau énergie air » 3-2023 ainsi que d'autres publications du groupe de travail sur la mensuration des barrages de la Société pour l'histoire de la géodésie en Suisse (SHGS) sont disponibles sur le site web de la SHGS (www.gggs.ch > Virtuelles Museum > E-Expo Schweizer Talsperrenvermessung). On y trouve également une vaste bibliographie de publications spécialisées depuis 1920 et une galerie d'images sur 17 thèmes couvrant toutes les époques

1 TASKS AND REQUIREMENTS OF DAM SURVEYS

According to the "Directive on the Safety of Water Retaining Facilities" issued by the Swiss Federal Office of Energy, geodetic measurements are an integral part of dam surveillance. Used in combination with other means and instruments for detecting deformation, they contribute to:

- the determination of the behaviour of dams (as part of the ongoing assessment of the impacts and conditions of the structure);
- rapid assessment in case of extraordinary situations or following an extraordinary occurrence;
- clarification of causes of anomalous behaviour detected by other measurement instruments.

Geodetic measurements can be used as a stand-alone method to determine the deformation and displacement behaviour of dams and reservoirs and their surroundings. However, they are usually used in conjunction with other measurement systems, such as pendulum systems, to determine changes in the position and height of selected points on a dam, thus providing redundancy in the overall monitoring concept. The control points included may be located on the crest and at different elevations at the airside surface (downstream face) of the dam; and, if accessible through galleries, within the structure (e.g. reference points of pendulum measurements or of traverses in the galleries), on the banks and in rock formations in the immediate vicinity, as well as in the wider environment of the dam outside its pressure zone. Finally, critical terrain features such as landslide slopes or glaciers in the danger zone of the dam can also be monitored. The magnitude of the accuracy requirements can be summarised as follows:

Table 1. Accuracy requirements for dam surveys.

Objects of the survey Deformations	arch or gravity dam (VA or PG) (concrete dam) mm	earth or rock fill dam (TE or ER) (embankment dam) mm	environment, critical terrain zones (e.g. landslides) mm
Horizontal	0.5 – 1	2 – 5	5 – 10
Vertical	0.1 – 0.2	0.5 – 5	5 – 10

The Subgroup Geodesy of the Working Group on Dam observations of the Swiss Committee on Dams has developed detailed recommendations for the use of geodetic deformation measurements at dams (Schweizerisches Talsperrenkomitee STK/CSB, Arbeitsgruppe Talsperrenbeobachtung 2013). Long-term reliable deformation measurements with millimetre accuracy are a complex and challenging field of application for engineering geodesy; and the observations are time consuming. They must be carried out and evaluated by specialists with the necessary competence and experience, using high quality and tested instruments (Walser 2014). Furthermore, in addition to civil engineering knowledge of the possible dam behaviour, an understanding of geological and geotechnical aspects is required. Geodesy provides the basis for determining the deformations and displacements of the dam in combination with the control procedures and measurement methods of the dam operators, such as the visual inspections, clinometer, extensometer and pendulum measurements, which monitor the geometric behaviour of the structure itself. The results are used by the civil engineering and geology experts to judge the slide safety of the dam and to verify its stability. As part of the dam safety inspection, geodetic measurements are usually carried out at least every five years. The reports of the geodetic deformation measurements are therefore kept as part of the file collection on the dam facility.

2 PROVEN METHODS AND INSTRUMENTS OF GEODESY

Geodetic deformation measurements on dams have a history of more than 100 years in Switzerland (Wiget et al. 2021, Wiget 2022). The oldest method of monitoring dams is geometric alignment. Starting from a stable pillar assumed to be fixed, a vertical plane is established by aiming the alignment instrument at a reference mark (target). Using the instrument's telescope, the horizontal deviations of the alignment points on the crest of the dam (signalled by alignment target marks or by means of a measuring rod) are measured from this vertical plane.

The accuracy and reliability of alignment observations were limited by refraction phenomena and uncontrolled stations or pillars (assumed to be fixed). On the occasion of the construction of the *Montsalvens* dam (canton FR) in 1921, which was the first double arch (horizontally and vertically curved) dam in Europe, engineers of the Swiss Federal Office of Topography (swisstopo) proposed the application of trigonometric methods used in national surveying: direction and angle measurements (triangulation) and precision levelling. For this purpose, theodolites were used for repeated bearing intersections (forward intersections, see Figure 1) from (at least) two observation pillars outside the dam to target control points on the crest and on the downstream airside surface of the dam, in combination with more distant reference points ("fixed points"). To determine the grid scale, the distance between the observation pillars had to be measured. In addition to the horizontal position observations, the target points could also be monitored vertically by means of height angle measurements. The first measurements were made at Montsalvens in January 1921, before the initial filling of the reservoir, and in November 1921, when the lake was full.

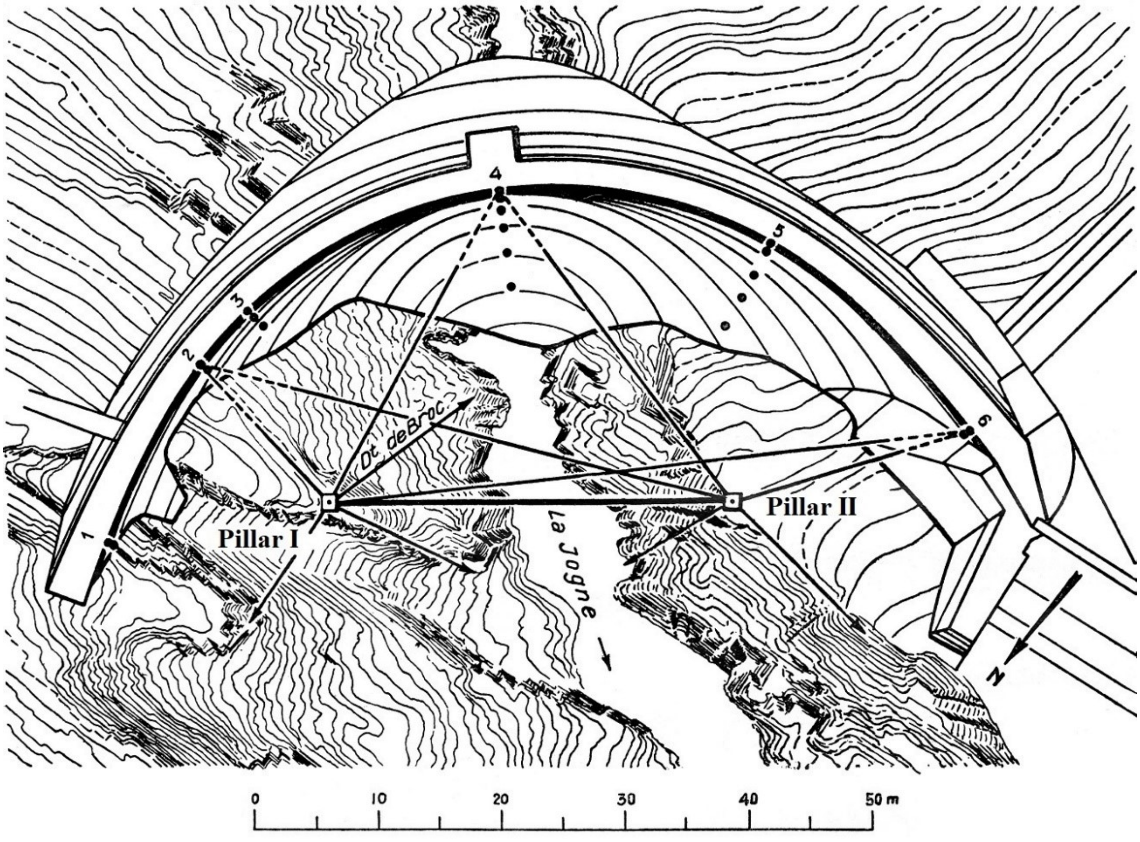

Figure 1. Forward intersections using angle measurements at Monsalvens dam, 1921.

Geodetic deformation measurements were also used at the *Pfaffensprung* dam (canton UR) as early as 1922. In order to be able to measure dam deformations and movements in real time during filling or emptying of the reservoir, all points were measured simultaneously by two observers from two pillars by means of forward intersections.

During the first epoch of Swiss dam construction until the middle of the 20th century, swisstopo was the only institution in Switzerland to carry out geodetic deformation measurements on dams. With the upswing in Swiss dam construction from 1950 onwards, the geodetic methods of dam monitoring were further developed and taught at the Swiss Federal Institutes of Technology in Zurich and Lausanne (ETHZ and EPFL). As a result, engineers from private surveying offices were increasingly commissioned to carry out this work, which eventually also became essential due to the large number of objects to be monitored.

Geodesy has been used for surveillance of all major dams in Switzerland from the very beginning. The methods, of course, have been continuously improved and adapted to technological developments. The measurement networks have been extended and the number of well-founded observation pillars has been increased, partly because of the increasing size of the dams, but also in order to be able to better monitor the stability of the pillars and reference points. Therefore, some of the observation pillars are located up-stream and down-stream of the dam, outside the zone of load influence (pressure bulb). Measurements are taken from the 'fixed' to the 'moving' and give 'absolute' displacements in relation to the chosen reference frames. Whereas in the early days the focus was on short-term differential movements between two epochs, today's measurements are designed for long-term studies.

In addition to the trigonometric measurements already mentioned, precision levellings are measured in order to monitor the changes in height (subsidence, rise) of the dams or of individual parts of the structure, as well as the foundation and the banks in their vicinity, which are also of great interest (Fig. 2). The levellings provide even higher accuracies than trigonometric height differences. They usually run from reference points on one side of the valley over the crest to the other side, but are also measured in the galleries within the dam. Wherever possible, the height reference points are located in stable areas that are not subject to the pressure effects and load influences of the reservoir's varying water volumes, and if necessary in geologically stable areas further away.

Figure 2. Precise levelling in the vicinity of Contra dam (canton TI).

Today, the "classical" methods (trigonometry and levelling) still form the backbone of geodetic deformation measurements on dams. However, the geodetic methods have undergone continuous development in terms of measuring stations (e.g. pillars and target bolts) and instrumentation (theodolites, levelling instruments, forced centring, etc.). Since the 1970s, developments in electronics and instrumentation have contributed to a significant increase in the accuracy of geodetic deformation measurements. The biggest step forward was the development of electro-optical distance measuring devices. Previously, distances were measured between the survey pillars by precision invar subtense bars. In polygonal traverses over the dam crest and in galleries invar wires are still used today. Since 1973, electro-optical distance-measuring instruments of the highest accuracy class have been on the market (e.g. Kern Mekometer ME3000 and ME5000). These allowed distances to be measured in the sub-millimetre range in the immediate vicinity or inside the dam, and in the millimetre range over several kilometres in the outer extended network, provided that the representative meteorological parameters are carefully recorded. These instruments were convincing not only because of their high measurement accuracy, but also because of the relatively short measuring time of a few minutes. Today, modern electronic total stations, i.e. theodolites with built-in distance meters, provide similar accuracies with even shorter survey times.

The introduction of electronics brought further important innovations to geodetic instruments: Automatic levelling of the instruments, considering the inclination of the vertical axis; electronic readings of the circle of the theodolites or total stations; automated reading of the staff for digital levels; support of the data acquisition and preprocessing on site by means of external software; digital recording of measurement data on internal or external data carriers, etc. Thanks to developments such as motorisation and automatic reflector alignment, the latest generation of instruments allow faster and more convenient measurements, which in turn can have a positive effect on accuracy. They also enable automated measurement systems for continuous monitoring of dams and their surroundings, known as geodetic monitoring systems (see Geomonitoring in chapter 4).

Since the late 1980s, terrestrial measurements have been supplemented by GPS measurements, today known as GNSS measurements, incorporating all available Global Navigation Satellite Systems. As these do not require line-of-sight between the stations or points to be measured, the external measurement networks can be extended to more distant reference points in geologically stable zones, unaffected by the water retaining facility and its load influences. Thus, long-term displacements of the dam and the surrounding area can be monitored in the well controlled three-dimensional reference frames in the range of a few millimetres.

Especially for large dams, geodetic measurements are used in combination with other measurement systems such as pendulum measuring systems, extensometers, joint meters or deformation meters, etc. These usually provide relative displacements and deformations, whereas geodesy measures absolute displacements in position and height with respect to the above-mentioned reference frames. For the interpretation of the behaviour of the dam and its surroundings, an optimal linking of the so-called "inner" and "outer" measuring systems is therefore essential. The analysis must take into account the local position as well as the temporal execution of the measurements (time, frequency), with careful registration of the respective environmental conditions such as water level or air and concrete temperatures. For example, pendulum system reference points (set plates and suspension or anchor points) should be connected directly or indirectly to the geodetic measurement network. Finally, geophysical and geotechnical instruments such as sliding micrometers or deformation meters, borehole extensometers, etc. can also be linked carefully and precisely to the geodetic network.

Table 2. Advantages and qualities of geodetic deformation measurements.

- Geodetic measurement methods are very adaptable, from the installation of the network, the instrumentation, signalisation and execution of the measurements, to the evaluation; they can be well adapted to the different types of dams and local conditions.
- Geodesy makes it possible to determine the absolute deformations and displacements of dams and their surroundings in relation to the immediate and wider environment and, if the measurement networks are extended accordingly, also to regional or national reference frames in geologically stable or well-studied areas.
- Movements of dams can be recorded even if they are not associated with changes in slope, strain or stress.
- Measurements are made in one, two or three dimensions (horizontal and vertical) and deformations can be analysed accordingly.

- Short-term (elastic) changes, e.g. during the initial accumulation of the reservoir, can be determined as well as long-term phenomena (e.g. subsidence, rise due to concrete changes) or permanent deformations and trends in the measurement series over decades, even with changed methodology and renewed instrumentation.

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3 EVALUATION AND DEFORMATION ANALYSIS

The goal of geodetic deformation measurements is to monitor and record the kinematic behaviour of dams, its foundation and surrounding by taking "snapshots" of its geometry at different time epochs, calculating changes of control points in position and height together with their corresponding accuracy, and describing the differences or movements in an appropriate way. The kinematics to be studied may vary. For example, relatively short-term movements or reversible deformations of the dam in the context of filling or emptying of the reservoir may be of interest, or the long-term stability of the dam over decades may be to be investigated. The questions to be answered also influence the conditions under which the measurements must be carried out and how they are evaluated.

The first trigonometric measurements were evaluated "by hand" using relatively simple functional models or graphical methods. Today, digital recording or on-line data transfer to the analysis software in the case of automatic measuring systems and electronic data processing allow faster and less error-prone evaluation of geodetic measurements and the adjustment of extensive measurement networks. This and the subsequent deformation analysis can be roughly divided into the following phases:

1) Verification of the measurements carried out by specific processing of the raw measurements according to the measurement procedures (directions, angles, distances, levelling, GNSS), taking into account calibration values, meteorological conditions as well as geometric corrections such as instrument heights, etc.; modelling and correction of systematic error influences; determination of stochastic key figures for parametric estimation.
2) Network adjustment of all measurements of an epoch to calculate the epoch-specific geometry (coordinates, heights) of the permanently marked control points on the structure and in the terrain; "fixed point analysis": i.e. testing of fixed point hypotheses and reasonable selection of fixed points in the chosen reference frame. The calculated coordinates and heights of the control points, as well as their accuracy, refer to the selected fixed points.
3) Overall adjustment of all measurements and point calculations over several epochs or adjustment of all previous measurement epochs, considering the above mentioned fixed point analysis (the aim is to achieve a spatial reference frame as uniform as possible in the long term); calculation of the epoch-specific coordinates and heights in all epochs in relation to the selected reference points, considering their accuracies.
   In addition to point coordinates and heights, the adjustment provides a great deal of additional information which is important for assessing the quality of the measurements and for analysing displacements and deformations (see also Table 3):
   - Accuracy in the form of empirical standard deviations and confidence ellipses: The values are "absolute" with respect to the fixed points, but "relative" between the determined points in the same epoch or in different measurement epochs;
   - Information on the geometric reliability of the coordinates and heights;
   - Estimation of the achieved overall accuracy of the different types of observations (so-called variance component estimation).
4) Deformation analysis: Calculation of the position and height differences of the control points over one or more periods (difference between two epochs), including their accuracy and reliability; i.e. calculation of short-term differences, displacements or deformations, e.g. between the last two measurement epochs, as well as comparison and determination of long-term trends over all epochs; reporting of relative accuracies compared to the selected reference points as well as between the measurement epochs; clarification of the significance of the changes for the selected confidence level (e.g. 95% or 99%) for the detection of real displacements.
5) The measurements carried out (including measurement programme, personnel, instruments and measurement conditions), the evaluation procedure, the fixed point analysis and the results of the deformation analysis are documented in a technical report as part of the long-term

monitoring of the dams. The results are presented in clear tables and descriptive graphs and are evaluated from a geodetic point of view (including choice of control points, significance, special conditions before and during the measurements) as a basis for the technical assessment by the experts (Fig. 3).

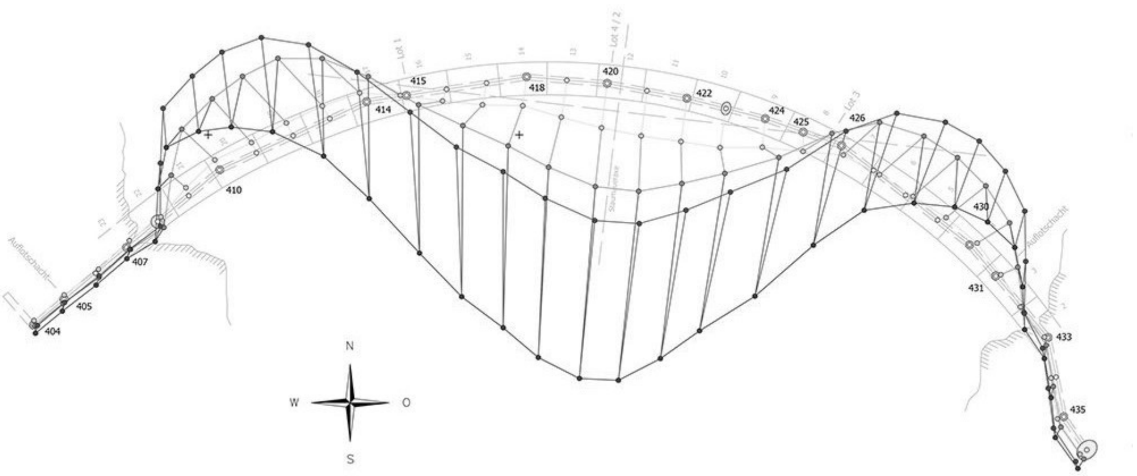

Figure 3. Horizontal displacements over four epochs.

Table 3. Quality features of the evaluation of geodetic deformation measurements and results.

- Adjustment of the precisely collected and recorded measurements using high quality functional (physical) models and considering verified stochastic parameters of the measurement methods used.
- Determination of the coordinates and heights of the control points on the dam, inside the structure and in the surrounding area to be investigated, with high precision (relative accuracy) as well as absolute accuracy with respect to the reference points, which can be located at almost any distance from the structure, defining the reference frame.
- Optimal combination with other measurement methods to determine displacements and deformations of the dam and surrounding terrain with respect to the reference frame.
- Controlled high reliability of all results.

4 MODERN METHODS AND OUTLOOK ON POSSIBLE FUTURE TECHNOLOGICAL DEVELOPMENTS

The methods described so far enable surveying of discrete individual points (control points) at periodic intervals and comparing them with previous surveys. Differential, irregular movements in space and time between the surveyed points are usually not determined; they can be interpolated if necessary.

But with today's instruments and software tools, automated, continuous monitoring of the position and height of dams and their surroundings is possible. For permanent monitoring with high accuracy requirements and temporally dense sampling rates, geodetic monitoring systems (so-called geomonitoring) are increasingly being used. A well-known example was the monitoring of the dams above the Gotthard Base Tunnel during its construction. Such geomonitoring applications are conceivable, for example, for monitoring critical terrain zones like slopes and unstable parts of the valley that could damage the dam structure or its auxiliary works directly or indirectly by falling into the reservoir. Dams of pumped storage power plants, which are additionally or increasingly stressed by more frequent and rapid changes in lake levels, are particularly suitable to be automatically and permanently monitored by monitoring systems. Temporary monitoring systems are installed especially when work or construction has to be carried out on, under or in the vicinity of the dam that can endanger its safety.

The monitoring systems can be composed of several different sensors, such as total stations, digital levels, GNSS receivers, electronic inclinometers and hydrostatic levelling, CCD sensors, inertial measurement units (IMU), extensometers, temperature and pressure sensors or other modern measurement methods, which will be mentioned below (TLS, In-SAR, FOS, etc.). The software systems for control, evaluation, analysis and alarms are integrated into the monitoring system. The results are determined in real time, broadcasted or made available for viewing via web browser; alarms and error messages are transmitted at critical moments.

New techniques for area and time continuous measurements of deformations are laser scanning and radar interferometry. They shall be briefly described:

Terrestrial laser scanning (TLS): The scanner measures the dam surface in a freely definable geometric point grid (in horizontal and vertical direction) in three dimensions without contact, providing oblique distances, intensity and possibly RGB colour values (Barras 2014). The rapid measurement of large numbers of points (up to 1 million points/second) is less precise (a few mm to cm) than the conventional, highly redundant but time-consuming multi-point determination (sub-millimetre to mm). However, the mentioned accuracies of the displacements can practically only be determined one-dimensionally in the direction of the laser beam. In addition, the georeferencing and modelling of the point cloud is a challenge. In the future, but probably for some time to come, TLS will increasingly be used in combination with traditional geodetic methods.

Terrestrial and satellite radar interferometry: In the case of high risk potential, terrestrial radar interferometry (ground-based interferometric synthetic aperture radar, GB-InSAR) can monitor surface deformations at dams or in their vicinity, quickly over a wide area or, if necessary, continuously with millimetre precision (Jacquemart & Meier 2014). The range of the sensor is up to 4 km, the area covered is over 5 km^2. Movements can be detected in the millimetre range, under favourable conditions even in the sub-millimetre range, but only in the direction of the axis of the radar beam (line-of-sight LOS). By using several GB-InSAR sensors at different stations, 3D displacements can be determined. So far, the method has only been used experimentally in the vicinity of Swiss dams.

Interferometric Synthetic Aperture Radar (InSAR) from satellites can be used to monitor the surface of entire valleys or countries. The areas that can be measured and the periodicity result from the illumination zones of the satellite passes. In Switzerland, for example, subsidence in salt mining areas, landslides, block glaciers and permafrost areas are studied. The accuracy of the average displacement rates is better than 1 mm/year in the LOS direction and better than 4 mm/year for individual measurements.

Table 4. Other methods related to or combined with geodesy.

- Close-range photogrammetry: High quality photographs, if necessary with overlaps for stereographic evaluation, to document and interpret cracks and other surface changes. Today, drones (unmanned air vehicles UAV) are also used as sensor carriers (Fig. 4). Accuracies are in the centimetre range. This area of application is currently developing rapidly and it can be assumed that the use of artificial intelligence will lead to major increases in productivity.
- Deformation Camera: Automatically analyses sequential high-resolution imagery and uses sophisticated image processing techniques to determine two-dimensional deformations of unstable slopes, rock faces or rock glaciers to an accuracy of a few centimetres.
- Monitoring of deformations in dams using integrated fibre optics with integrated sensor systems (FOS) to determine changes in length, e.g. in block joints, with an accuracy of a few micrometres.
- Rockfall radar: Detects rockfall events in all weather conditions, including darkness, and alerts within seconds.
- Digital geotechnical sensors for sub-millimetre fracture measurements (extensometers, telejointmeters, etc.).
- Motion sensors, piezoelectric sensors or MEMS (Micro-Electro-Mechanical Systems).
- Digital level measurements.

Figure 4. UAV for close range photogrammetry of dam surface.

Table 5. Possible future developments.

- Measurement systems with increased networking and integration of geodetic, geotechnical and other, possibly new, sensors (meteorological, inertial, tide gauges, etc.).
- A transition from periodic measurements to continuous time series at selected, permanently installed monitoring stations, thanks to lower sensor prices even in large numbers.
- Integration of the geodetic dam monitoring networks by means of GNSS into the "absolute", well-monitored and long-term stable reference frame of the national survey for inter-regional comparisons, e.g. in case of earthquakes.
- Evaluation and analysis tools with advanced algorithms, i.e. more complex adjustment methods, near real-time 3D time series and strain analysis, trend derivation, cloud services, artificial intelligence, deep learning.
- Use of new Internet of Things technologies for networking and remote control of autonomous multi-sensor systems (machine-to-machine communication via 5G, IPv6).
- Terrestrial positioning systems using pseudolites (pseudo-satellites, i.e. locally mounted microwave transmitters), analogous to Ground Based Augmentation Systems (GBAS) in aviation.
- Technologies from indoor navigation methods.
- Modern representation methods and graphic tools such as augmented and virtual reality for simulating deformation processes or predicting future object states.

High-precision, long-term reliable deformation measurements are an exciting, complex and highly demanding field of application for engineering geodesy. Geodetic monitoring of dams will remain an important pillar in the safety concept of dams, mainly because of its "absolute" results.

REFERENCES

Barras, V. 2014. Lasergrammétrie terrestre – une Solution pour l'Auscultation Surfacique. *Wasser Energie Luft* 106(2): 112-115.

Jacquemart, M. & Meier, L. 2014. Deformationsmessungen an Talsperren und in deren alpiner Umgebung mittels Radarinterferometrie. *Wasser Energie Luft* 106(2): 105-111.

Schweizerisches Talsperrenkomitee STK/CSB, Arbeitsgruppe Talsperrenbeobachtung 2013. Geodäsie für die Überwachung von Stauanlagen. See also publications and contributions to CSB/STK symposia 2014 and 2022. *https://www.swissdams.ch/de/publications/journees-d-etudes.*

Walser, F. 2014. Geodäsie für die Talsperrenüberwachung. *Wasser Energie Luft* 106(2): 101-104.

Wiget, A., Sievers, B., Huser, R. & Federer U. 2021. Beiträge der Geodäsie zur Talsperrensicherheit – Zum 100-jährigen Jubiläum der Talsperrenvermessungen in der Schweiz. *Geomatik-Schweiz* 119(7/8): 170-177 in German, 178-185 in French.

Wiget, A. 2022. Hundert Jahre Talsperrenvermessungen in der Schweiz. *Wasser Energie Luft* 114(1): 39-42.