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Efficient and Large Scale Monitoring of Retaining Walls along Highways using a Mobile Mapping System

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Abstract

The safety of highways in mountainous areas is strongly dependent on the stability of the retaining walls, which support either the highway itself or the slopes adjacent to it. Failure of such a retaining wall can lead to death of highway users, to repair works and thus to the closure of highway lanes.
An early detection of negative changes of these retaining walls is therefore of high importance. Due to the large number of retaining walls in alpine areas, it is impossible to equip every retaining wall with a monitoring system. The usual approach is to monitor only the walls, which are known to have problems. This leaves most of the walls uninspected. Thus, an efficient method is needed which is capable to monitor all retaining walls along a highway.
In this paper, we present a new approach based on a mobile mapping system (MMS). We use a measurement platform consisting of two laser scanners, an inertial measurement unit (IMU), a differential GNSS sensor and multiple cameras. This platform is mounted on a standard commercial car. Whilst the car travels with up to 100 km/h along the highway, the data of the multi sensor system is continuously recorded with high frequency. For instance, each laser scanner records 1 million points per second. As a result, georeferenced high resolution point clouds of all retaining walls along the highway are obtained. We further analyse the point clouds to derive safety critical parameters like tilt changes of the retaining walls. We demonstrate that it is possible to determine the tilt of retaining walls with an accuracy of better than 0.1°. Furthermore we can reliable detect the movement of individual blocks of the retaining wall and identify areas where material fell off.

1. Introduction

Retaining walls are frequently used to construct highways in mountainous regions to support either the highway itself or the slopes adjacent to it. Failure of these retaining walls can lead to the death of highway users and the repair works may cause delays due to closures of highway lanes. For instance, in 2012 a truck driver was killed on the Austrian Highway Brennerautobahn (A13) because of a collapse of a retaining wall (Die Presse, 2012).
An early detection of negative changes of these retaining walls is therefore of high importance. With respect to geotechnical structures, the Eurocode 7 (EN 1997-1, 2004) distinguishes between serviceability limit state (SLS) and the ultimate limit state (ULS). The SLS defines the limit of the functionality of the structure whereas the safety of the users and the stability of the structure are in danger if the ULS is exceeded. Tilt changes of the structure are an important parameter to define the current state of the structure. The maximum allowed tilt changes for retaining walls are between 0.057° and 0.382°for the SLS and 0.764° for the ULS. These tilt changes are usually monitored

with manual or automatic total stations (TS) or tilt sensors (T) as depicted in Fig. 1. Total stations measure horizontal (Hz) and vertical angels (V) as well as distances (D) to reflective targets (retroreflective foils or glass prisms). These measurements can be used to calculate 3D positions of the targets on the retaining wall. Usually, several targets are placed at different heights in one cross section. Therefore, the tilt of the retaining wall (α) can be derived. On the other hand, the tilt of the wall can directly be measured with a tilt sensor.
However, it has to be noted that in both approaches the behaviour of the structure is only monitored at a few single points. Damages (d) which occur between the measurement positions remain undetected, see Fig. 1.

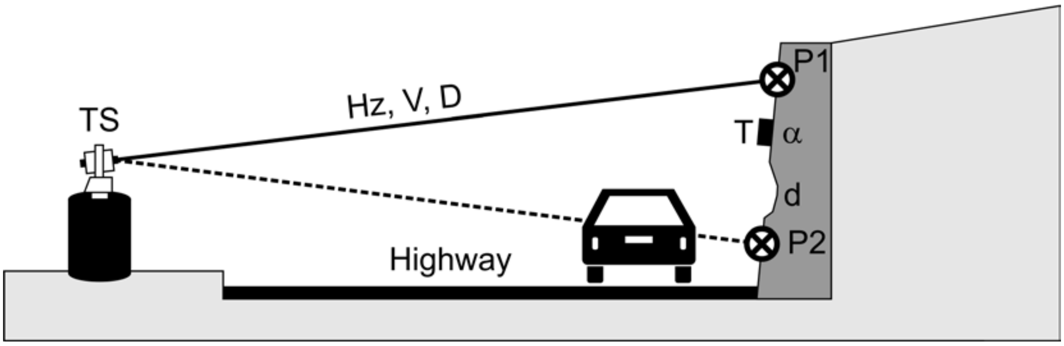

Fig. 1 Conventional monitoring of position and tilt changes of a retaining wall using a total station (TS), reflective targets (P1 and P2) and a tilt sensor (T). Undetectable damage (d)

Furthermore, the conventional approaches are costly and require access to the retaining walls. Because of this and due to the large number of retaining walls in alpine areas, it is impossible to equip every retaining wall with a monitoring system. The usual approach is to monitor only the walls, which are known to have problems. This leaves most of the walls uninspected. Thus, an efficient method is needed which is capable to monitor all retaining walls along a highway.

2. Proposed Approach using a Mobile Mapping System

In order to overcome the aforementioned problems, we propose a new approach based on a mobile mapping system (MMS) which delivers high resolution point clouds of the retaining walls. The whole system should not require physical access to the retaining walls and shall not influence the traffic flow. For a working system the position and orientation of the vehicle has to be known continuously and the measurements to the wall have to be performed with high frequency and high precision.

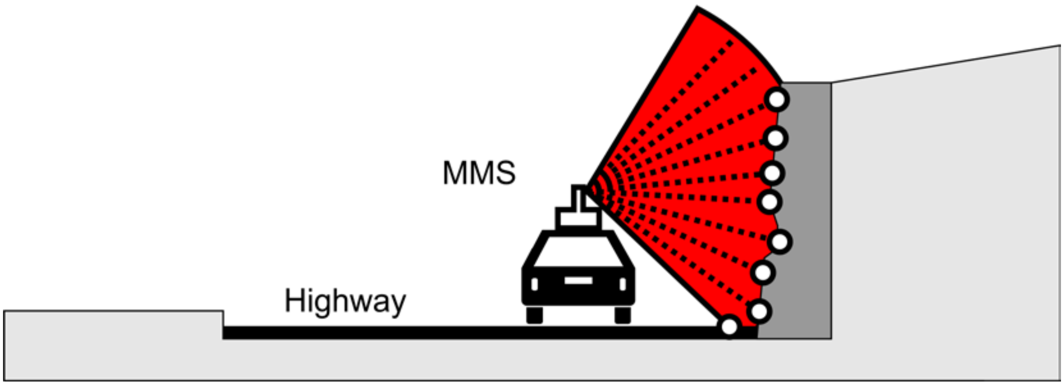

Fig. 2 Mobile mapping approach for monitoring retaining walls

2.1 Hardware

Based on the requirements, our used MMS consists of a geodetic GNSS antenna and a receiver, an inertial measurement unit (IMU), an odometer, several cameras and two laser scanners, see Fig. 3. All sensors are calibrated with respect to each other. The whole platform is mounted on a standard commercial car. The position and orientation of the vehicle are determined using the GNSS in combination with the IMU and the odometer. The distances and angles from the platform to the wall are recorded with the two profile laser scanners. To acquire high density point clouds also at high speeds, each laser scanner measures 1 million points per second. The cameras are used to provide true colours for the point clouds and to validate the results of the automated defect classification.

Fig. 3 Mobile mapping system for monitoring retaining walls

3. Field Study

To evaluate the proposed approach and our developed data processing algorithms, several different retaining walls were measured with the MMS along the Austrian highways. The retaining walls were passed several times with different velocities (60, 80 and 100km/h) in order to verify the repeatability of the results. In this article we discuss the results of two gravity walls (Fig. 4 left and centre) and three anchored walls (Fig. 4 right and Fig. 5). The maximum height of the gravity walls is 8m and the maximum length 255m.

Fig. 4 Gravity walls (left and centre) and one of the anchored walls (right) used in the field study

The anchored walls are higher and also longer (maximum height >23 m and length >300m). The wall A6 is also equipped with a conventional monitoring system. As can be seen in Fig. 5, glass prisms (P) are placed in two different heights in different profiles.

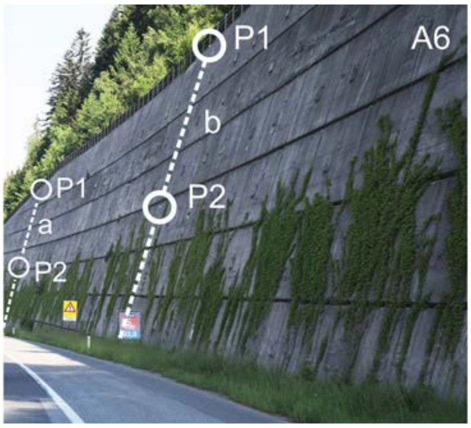

Fig. 5 Anchored walls used in the field study, Left: Retaining wall A6 with total station targets at heights 1 and 2 in profiles a and b. Right: Dissolved anchor wall A9

3.1 Data Acquisition and Data Preparation

Whilst the car travelled along the highway, the data of the MMS was continuously recorded with high frequency. Based on the raw data of the individual sensors we developed following methodology to determine tilt changes and to detect deficiencies.

In a first processing step, high accurate GNSS positions are determined using the recorded GNSS data together with reference station data from the nation-wide permanent reference GNSS network APOS (Austrian Positioning Service). Together, with the odometer and IMU data, the position and orientation of the platform and thus the trajectory are known at any time

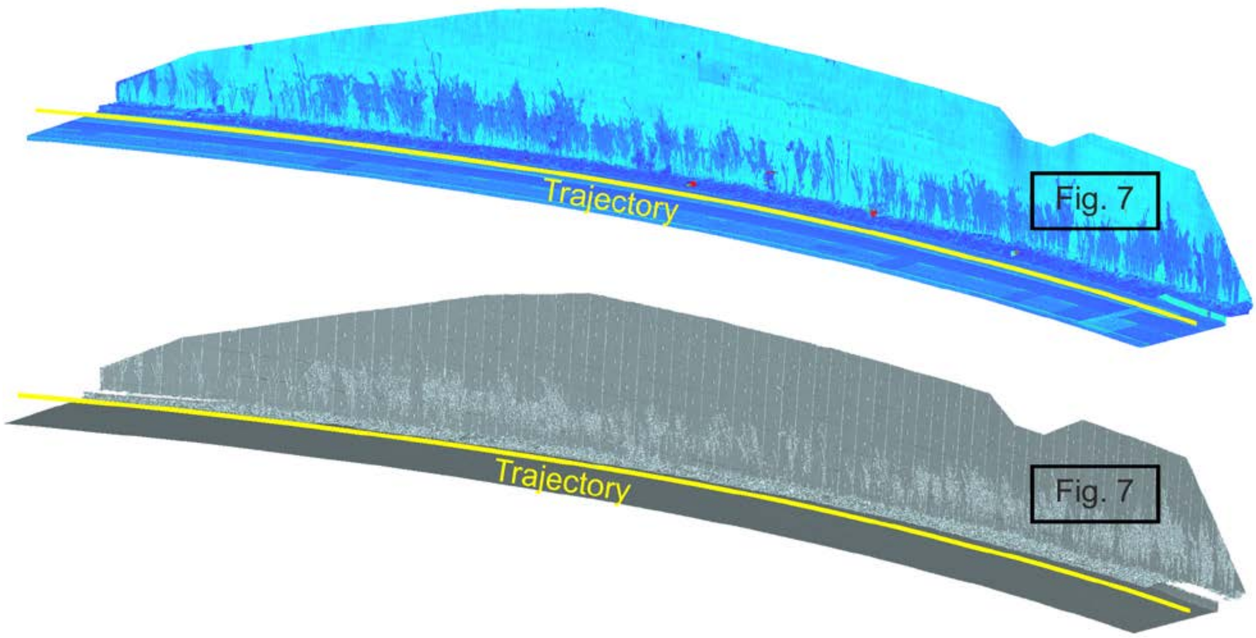

Fig. 6 Trajectory and georeferenced point cloud of retaining wall A6 collected at a travel speed of 80km/h (top). Colors represent intensity values of the reflected laser distance beam. Modelled surface using a TIN (bottom). The black rectangle indicates the area which is shown in more detail in Fig. 7

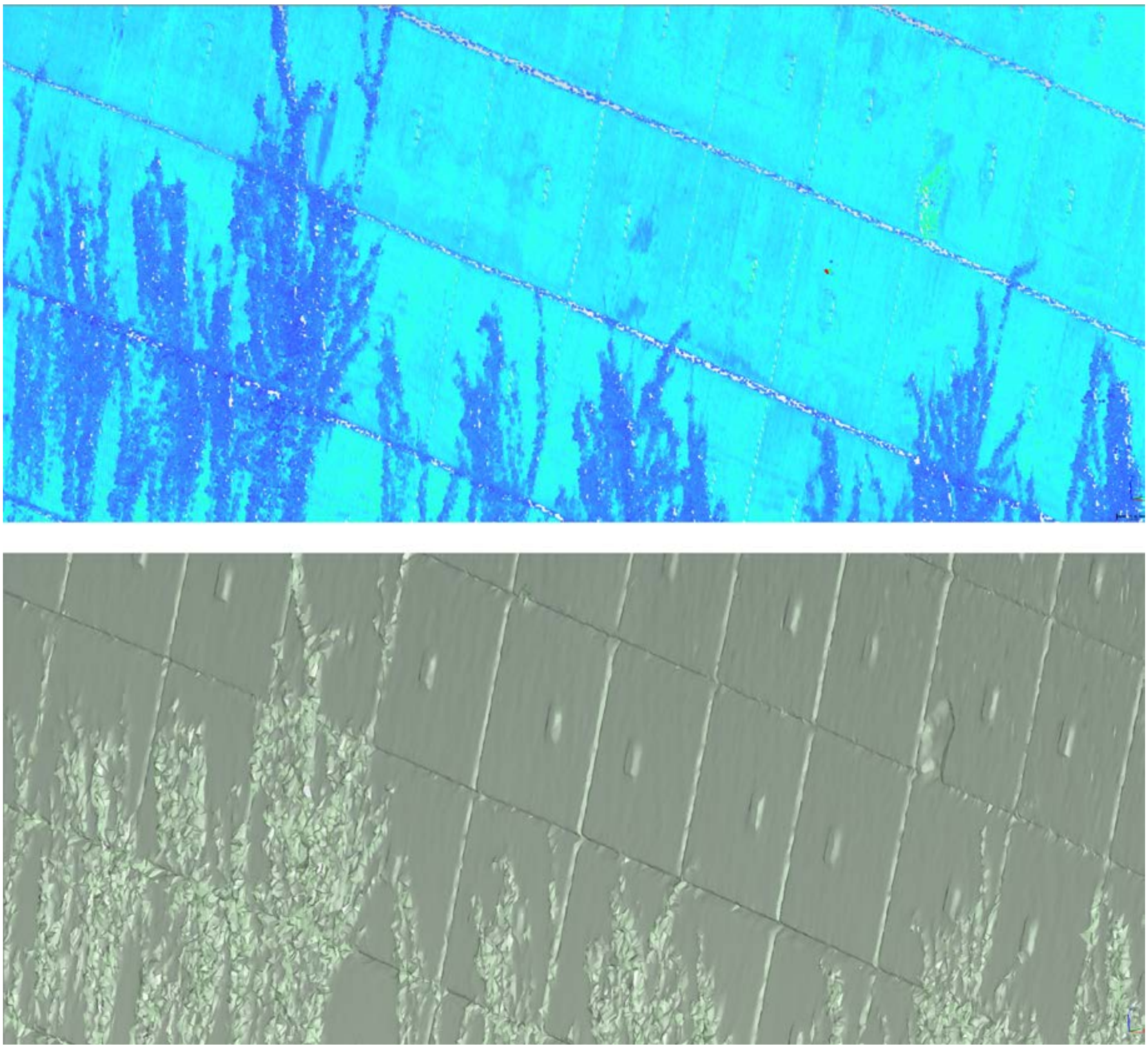

Fig. 7 Detail of point cloud (top) and modelled surface (bottom) of retaining wall A6

This information is now combined with the data of the two profile laser scanners which results in a high resolution georeferenced point cloud of the whole retaining wall Fig. 6 top and Fig. 7 top. Next, the surface of the retaining wall is reconstructed e.g. as a TIN, Fig. 6 bottom and Fig. 7 bottom. We generate vertical profiles of the retaining walls by intersecting the surface model with planes orthogonal to the trajectory of the vehicle. Fig. 8 left demonstrates the principle. Displayed are the intersecting lines for profiles with 5m separation. For our detailed analysis a profile was generated every 5cm along the trajectory (Fig. 8 right). Thus, more than 6000 profiles were obtained for the more than 300m long retaining wall A6.

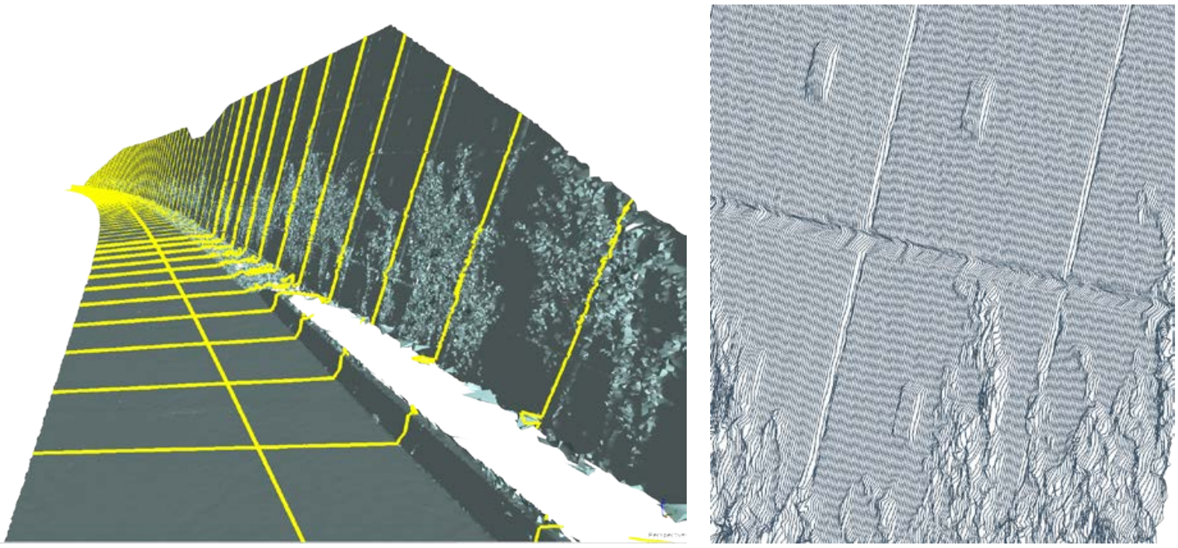

Fig. 8 Intersection lines between vertical planes every 5m along the trajectory and the surface model (left). Profiles with 5cm spacing for detailed analysis (right)

3.2 Detailed Analysis and Interpretation

Robust adjustment methods are finally used to extract the retaining wall from the vertical profiles and to subsequently determine the tilt of the retaining walls without outliers. It has to be noted that the threshold values for outlier determination have to be adapted to the roughness of the retaining walls. If the threshold values are too small, too many valid measurements will be excluded whereas if the threshold values are too large, other elements like vegetation will be used for the tilt calculation and incorrect tilt values will be reported.

In order to verify the reliability of the MMS based tilt determination, the same retaining wall A6 was measured several times. Two measurement runs were made with 60km/h, two with 80km/h and one with 100km/h. For each measurement run, the tilt of the wall is computed at every vertical profile. Fig. 9 displays the distribution of the tilt differences $\Delta\alpha = \alpha_{t2} - \alpha_{t1}$ of two measurement runs made at t1 and t2. Individual outliers were already excluded in the analysis.

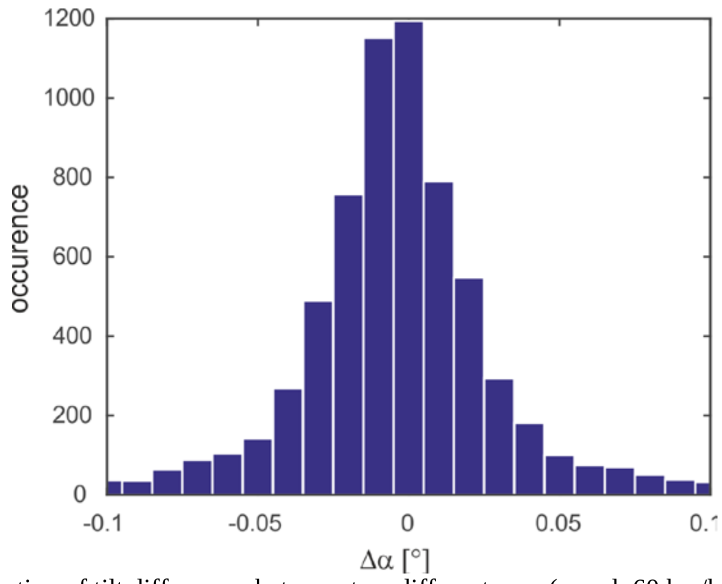

Fig. 9 Distribution of tilt differences between two different runs (speed: 60 km/h and 80 km/h)

Furthermore, the empirical standard deviation $s_{\Delta\alpha}$ of the tilt differences can be calculated to quantify the achievable precision of our proposed approach. It has to be noted that the precision is also dependent on the roughness of the structure. An overview of the results of all five walls is given in Table 1.
The question arises if these precisions are sufficient to detect tilt changes relevant for the SLS and ULS. In deformation analysis, a measured difference is only than stated as significant if the calculated test statistic is higher than the value of the corresponding distribution at a given significance level, usually 5%. Table 1 quotes the minimum size of a tilt change to be detected reliably. In case of the first four retaining walls, it can be seen that tilt changes of less than 0.1° can be detected reliably with the developed approach. Problems only occur with the dissolved anchored wall. For this special construction tilt changes may also not be the relevant parameter to be observed.

Table 1 Standard deviation of tilt change measurements and detectable tilt change at a significance level of 5%

Retaining wall	Type	$s_{\Delta\alpha}$ [°]	Minimal detectable tilt change [°]
A3	Gravity wall with smooth surface	±0.007	0.013
S1	Gravity wall with rough surface	±0.047	0.093
A4	Anchored wall with smooth surface but heavy vegetation	±0.007	0.014
A6	Anchored wall with smooth surface	±0.026	0.050
A9	Dissolved anchored wall	±0.074	0.145

Finally we take a closer look at the outliers which are automatically flagged prior to the tilt calculation. Outliers are caused for instance by vegetation. On the other hand, outliers i.e. deviations from the general shape of the profile, may also give valuable information about structural deficiencies. In first test, we applied artificial deficiencies by placing obstacles on the surface of the retaining wall. After the first successful test, the analysis was extended to all measured retaining walls. An interesting result is displayed in Figure 10.

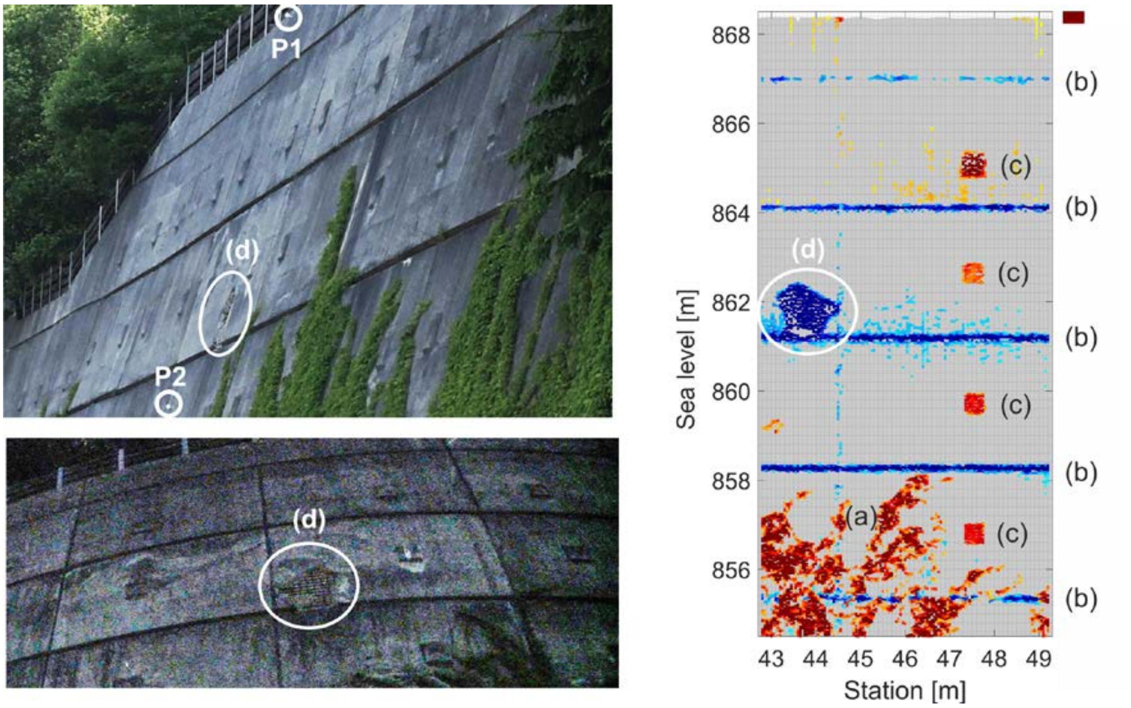

Fig. 10: Position of prism targets P1 and P2 and damage (d) in retaining wall (left), color coded significant deviations from fitted lines with categories (a) vegetation, (b) horizontal joints, (c) anchor heads and (d) damage

Different types of outliers are highlighted in Fig. 10 right. We automatically group the outliers by using the DBSCAN algorithm (Ester et al., 1996) and classify them thereafter. Group (a) belongs to vegetation, group (b) are the horizontal joints and group (c) are the anchor heads. Interesting is group (d). This is a deficiency where material has fallen off and the rebar of the reinforced concrete is visible as can be seen in Fig. 10 left. Interestingly, this retaining wall is also monitored with conventional methods and two target positions are located in the vicinity of the damaged area. However, as stated at the beginning of this paper, conventional methods cannot detect local damages and do not deliver a complete picture of the retaining wall.

4. Conclusions and Outlook

The proposed approach of collecting high resolution georeferenced point clouds proved to be suitable to derive critical deformations like tilt changes and deficiencies like pop outs fully automatically of all retaining walls along the motorway. A detailed analysis confirmed that tilt changes of better than 0.1° can be determined if outliers are automatically removed in the analysis.
The data collection can be performed at high travel speeds and thus does not adversely affect the traffic flow. We are repeating the measurement campaign this year and are planning to assess the absolute accuracy by comparing position and tilt changes derived from total station measurements with the results from the mobile mapping system.

5. Acknowledgements
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