PHOTOGRAMMETRIC MONITORING OF AN ARTIFICIALLY GENERATED LANDSLIDE

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ABSTRACT:

According to pre-planned schedules, a series of two artificial rainfall events were applied to a forested slope in Ruedlingen, northern Switzerland. The experiments were conducted in autumn 2008 and spring 2009, the second of which resulted in mobilising about 130 m^3 of debris. Both experiments were monitored by a photogrammetric camera network in order to quantify spatial and temporal changes. A 4-camera arrangement was used for the image acquisition. The cameras operated at a data acquisition rate of circa 8 frames per second (fps). Image measurements were made using the Least Squares image matching method, which was implemented in an in-house developed software package (BAAP) to compute 3D coordinates of the target points. The surface deformation was quantified by tracking the small (ping-pong and tennis) balls pegged into the ground. The average 3D point-positioning precision of ±1.6 cm was achieved in the first experiment and ±1.8 cm in the second experiment.

1. INTRODUCTION

TRAMM (Triggering of Rapid Mass Movements in Steep Terrain) is an inter-disciplinary project conducted in cooperation of

- Swiss Federal Research Institute WSL (Research Unit of the Mountain Hydrology and Torrents, Research Unit of the Avalanches, Debris and Rock Fall, and Research Unit of the Snow and Permafrost Research),
- ETH Zurich (Institute of Geotechnical Engineering, Institute of Geodesy and Photogrammetry, and Institute of Terrestrial Ecosystems), and
- EPF Lausanne (Engineering and Environmental Geology Laboratory, Soil Mechanics Laboratory, and Environmental Hydraulics Laboratory).

The primary goal of the project is to improve the quantification and predictability of hazardous mass movements including landslides, snow avalanches, and debris flows. The project aims to conduct laboratory and field experiments, spatial analyses of hill-slope failures, development of new modeling approaches and new measurement methodologies. The following research tasks are emphasized: spatial characterization of hazard prone slopes, improved understanding of triggering mechanisms and mass dynamics.

The TRAMM project has six test sites. An artificial landslide was generated at one of them near a small town in the north of Switzerland, Ruedlingen, and the mass dynamics were studied numerically.

According to pre-planned schedules, a series of two artificial rainfall events were applied to a forested slope in Ruedlingen. The experiments were conducted in autumn 2008 and spring 2009, the second of which resulted in mobilising about 130 m^3 of debris. Parameters such as pore water pressure, volumetric water content, horizontal soil pressure, temperature, piezometric water level, surface and subsurface deformations were monitored during this sprinkling experiment (Askarinejad et al., 2010a; Askarinejad et al., 2010b; Springman, et al., 2009; Springman, et al., 2010).

This paper covers the details of the photogrammetric image data processing work of the Ruedlingen experiment. Photogrammetry is an accurate and affordable method for measuring geometry of both static and dynamic objects. Three dimensional coordinates are determined by measurements made in two or more images taken from different standpoints. In the TRAMM project, the goal of the photogrammetric work is to quantify spatial and temporal changes of the landslide surface. Points were signalized with markers and their movement was tracked during the landslide, while their 3D coordinates were estimated at each instant of the image acquisition frequency.

The photogrammetric work itself is not the ultimate goal of the project. Rather, it provides input of the geotechnical analysis for better understanding of the landslide characteristics, and also provides external data for validation of other field instruments.

Travelletti et al. (2008) monitors a controlled landslide area during 5 days using a long range terrestrial laser scanner with a one scan per day data acquisition rate. They measure an average displacement rate of 3.2 cm per day.

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The photogrammetric method provides a higher frequency of data acquisition rate than the laser scanning device. The phenomena can be observed continuously. Ochiai et al. (2004) determined the motion of the surface of an artificial rainfall induced landslide using ten low resolution video cameras. In the first TRAMM experiment, four cameras continuously collected 350 GB of image data on four days.

The next chapter introduces the test site area. The third chapter explains the first TRAMM experiment with the details of the photogrammetric network design, network simulation, equipments and installation, camera calibration and orientation, point positioning aspects. The fourth chapter refers to the second TRAMM experiment, which resulted in a landslide.

2. TEST SITE IN RUEDLINGEN

The test site is located on a steep slope next to the River Rhine in Ruedlingen, a small town in the north of Switzerland (Figure 1).

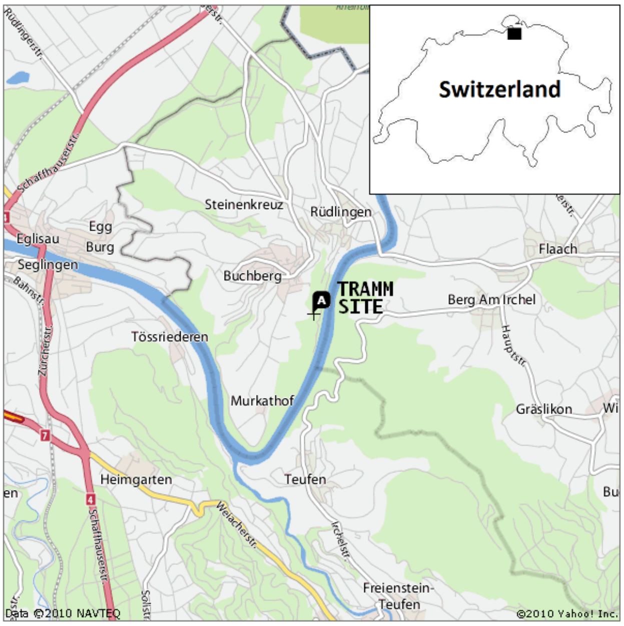


Figure 1. The TRAMM test site in Ruedlingen, Switzerland.

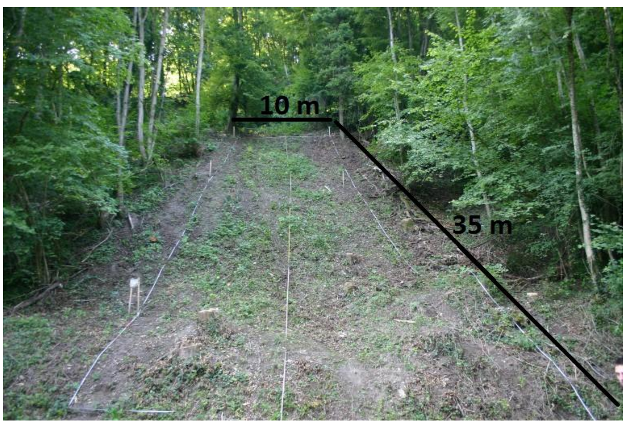


Figure 2. The test site has dimensions of 10 m by 35 m.

The Rüdlingen experiment is a sub-project within TRAMM. The express purpose is to trigger a rainfall induced landslide, having characterized the slope, instrumented it with a range of state of the art sensors to observe its response to the environmental loading and exposed it to 24 hour observation using high resolution cameras to witness the slide. Rüdlingen village (Figure 1) was chosen following an extreme event in May 2002 in which 100 mm of rain had fallen in 40 minutes, leading to 42 landslides around the local area (Springman et al., 2010).

The test area is about 10 m by 35 m in size and has an average slope of 38 degrees. The ground was cleared from trees and bushes prior to the experiment (Figure 2).

3. THE FIRST TRAMM EXPERIMENT

3.1 Photogrammetric Network Design

Two tall trees on the front side of the experiment area (shown as Tree1 and Tree2 in Figure 3), both of which are approximately 25 meters in height, were selected to set up the cameras based on a site visit of 7 August 2008. It was decided to use a 4-camera arrangement (2 cameras per tree) for adequate photogrammetric coverage of the experiment area. The baseline of the cameras is 5.1 m along the trees, and 6.2 m across the trees.

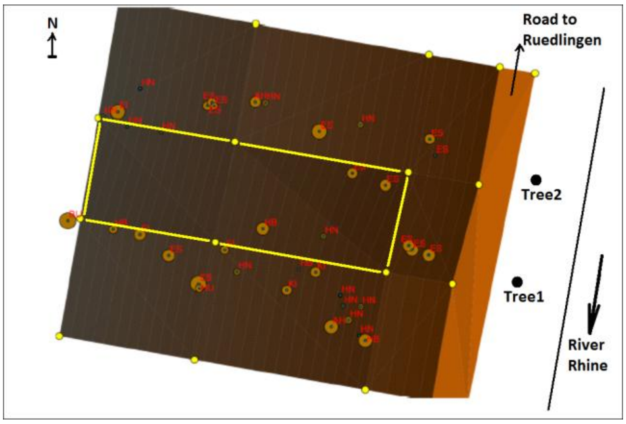


Figure 3. The test site is delineated by yellow border lines. Tree1 and Tree2 are located on the opposite site of the road to Ruedlingen.

An initial map of the area was generated using basic geodetic equipments (Figure 3). This information served as input to an in-house developed photogrammetric network simulation software tool, called PanCam. The proper camera formats and lenses were interactively examined in the simulation environment.

Table 1. Technical details of IDS uEye UI-6240 C video cameras.

Feature	IDS UI-6240 camera
Sensor type	CCD
Sensor size	½ inch
Image format	1280 x 1024
Shutter	Global shutter
Frame rate	14 fps
Pixel pitch	4.65 microns
Data transmission protocol	Gigabit Ethernet

Accordingly, 1.3 Megapixel IDS uEye UI-6240 C (IDS - Imaging Development Systems GmbH, Germany) video cameras were chosen for the image acquisition (Figure 4). Technical details of the cameras are given in Table 1. Intentionally, a CCD type of sensor is preferred over the CMOS sensors, since radiometric quality and light sensitivity is a concern especially for the night time images.

Figure 4. IDS uEye UI-6240 C Gigabit Ethernet video camera.

Using the in-house developed network simulation tool, a priori point positioning accuracy of the signalized targets was estimated to ± 10.3 mm in the horizontal direction and ± 3.5 mm in the vertical direction (Figure 5). A priori standard deviation of the image point observations was given as ± 0.1 pixel. The design consideration for the project is to track the points during the landslide within a positional accuracy of ± 1-2 cm. According to the simulation results, the photogrammetric network, as designed, meets this requirement quite well.

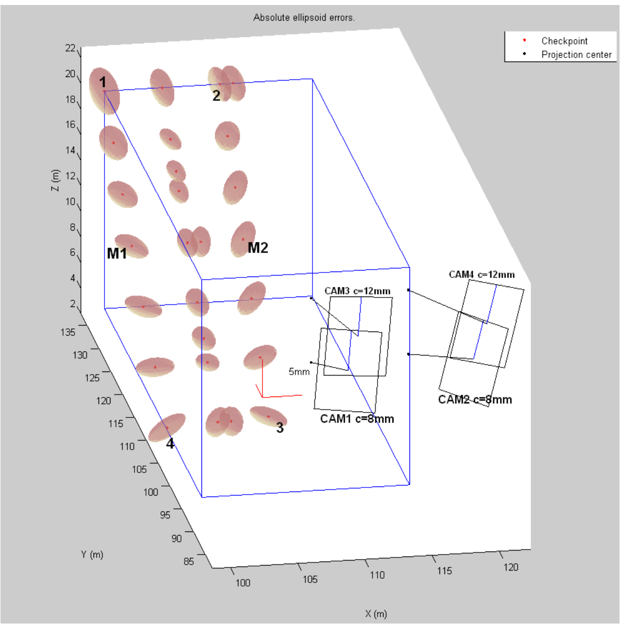


Figure 5. The a priori estimated error ellipsoids of some representative signalized targets.

3.2 Equipments and Installation

The four IDS cameras were equipped with two 8.0 mm and two 12.0 mm C-mount lenses. The two 8.0 mm lenses equipped cameras (CAM1 and CAM3 in Figure 6) were directed towards the bottom-side of the experiment area, and the other two cameras with 12.0 mm lenses (CAM2 and CAM4 in Figure 6) were directed towards the upper-side of the experiment area. The two lower cameras (CAM1 and CAM3) and the two upper cameras (CAM2 and CAM4) are 13 m and 18 m above the ground, respectively.

The cameras were placed in housing shields (Figure 7a) which protect them against snow, rain, dust and other kind of environmental effects. The four cameras were fixed on the two trees by a professional climber (Figure 7b). If the image block is defined as two strips (CAM2-CAM4 and CAM1-CAM3), each of which consisting of two photographs, the photogrammetric block has 100% overlap along strip direction and 75% overlap across strip direction.

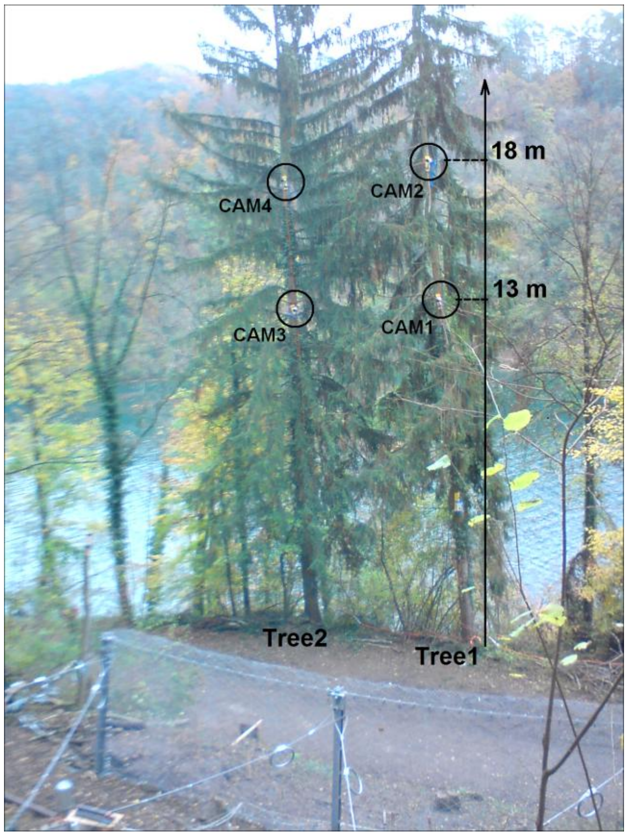


Figure 6. The four cameras are fixed on two trees at 13 meters and 18 meters height, respectively.

All cameras were connected to a central computer using approximately 100 m Cat-6 Ethernet cables. The control computer was a Supermicro server with an Intel Xeon QuadCore 2.33 GHz CPU, 4 GB DDR2 RAM memory, 16x 250 GB 7200 rpm SATA II harddisks and MS Windows Server 2003 R2 Enterprise operating system. An Intel Pro/1000 PT Quad Port Network Interface Card (NIC) was used for the Ethernet protocol communication.

The cameras were set to operate at 10 frames per second (fps) data acquisition rate. The imaging frequency of the four cameras was synchronized by in-house software, which is a MS Windows multi-threading application, developed using C# programming language and IDS SDK (Software Development Kit) library functions. The standard MS Windows software are single-threading applications, where the instructions are executed serially. The multi-threading is a software programming concept where multiple instructions can run synchronously in parallel. The in-house image acquisition software enables the four cameras to shoot (and to store) the frames simultaneously at the same instant.

The synchronization of the cameras is extremely important when monitoring such dynamic events. Otherwise, we could have bought cheaper cameras with larger image format, and would thus have obtained even better results.


(a)

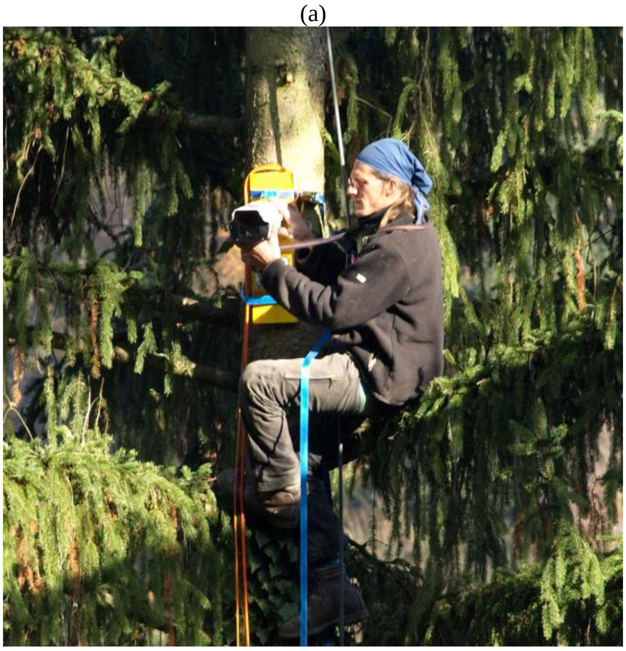

(b)

Figure 7. (a) The housing shield. (b) The cameras are fixed on the trees by a climber.

Approximately 250 white ping-pong balls (with 40 millimeter diameter) were glued on 20-30 centimeter wooden sticks. The sticks were pushed vertically to the ground in a 1 m regular grid arrangement. 21 well distributed ground control points (GCP) were established on the surrounding stable trees. The 3D coordinates of the GCPs were measured with a Leica TCR407 reflectorless electronic theodolite with a standard deviation of ± 2.0 mm for the X,Y and ± 1.0 mm for the Z coordinates, respectively.

The GCPs and the ping-pong balls were illuminated using strong halogen lamps during night time. The radiometric settings (brightness, contrast, gain and exposure time) of the cameras were altered periodically for the day time and night time by our in-house developed software. The same software was also used for automatic image shooting and storing the images into appropriate harddisk locations.

3.3 Calibration and Orientation

The camera calibration was performed in the field. The calibration procedure determines the interior orientation parameters and the systematic errors caused by the lenses and other system components. Ten consecutive image frames were measured for each of the four cameras. The collected image measurements were input to a self-calibrating bundle block adjustment procedure. The estimated camera calibration parameters were considered as constant over time in the following point positioning computations.

Since the camera stations on two tall trees were not stable platforms and were moving with the wind, the exterior orientations of the cameras were calculated for each camera/image frame individually, by use of the GCPs.

3.4 Point Positioning

The TRAMM-I experiment started on 28.10.2008 and ended on 31.10.2008. The four cameras continuously worked on four days with an average (actual) image acquisition rate of 8 fps, and gathered approximately 350 GB of image data. Although the cameras can provide 24-bit color images, 8-bit grey scale images were acquired for faster data transmission and processing purposes.

A total of 1.7 m of rainfall, calculated as an average over the slope area, was supplied over 3.5 days. Some deformations were measured in the top right quarter of the field, but the landslide did not occur. Only three epochs of the entire image set were processed to show the surface deformations:

- 28.10.2008, at 15:12 o'clock,
- 30.10.2008, at 15:16 o'clock, and
- 31.10.2008, at 15:00 o'clock.

In the network design step, the ping-pong balls were assumed to appear 3-4 pixels in diameter in the images. The assumption is appropriate when the background has sufficient contrast. This a priori consideration did not apply here due to the leaves on the ground (Figure 8). They produced spurious artifacts on the images, and confused the identification of some points, especially the ones on the right side of the area.

In addition, at the more distant locations of the field, there were some visibility problems with the ping-pong balls in the images, which were not considered in the network simulation.

The automatic tracking algorithm did not work because of the identification and visibility problems. All image measurements were done semi-automatically using the Least Squares image matching method, which was implemented under an in-house developed software package BAAP (Figure 9). The BAAP is a GUI based MS Windows software, and it was specifically designed for close-range photogrammetric applications.

Subsequently, the image coordinates were entered into another in-house developed software package SGAP, where 3D coordinates of the ping-pong balls were computed. The SGAP software has a command-line interface and offers sophisticated photogrammetric bundle adjustment modules.

Figure 8. An example of the CAM4 day time images. The ping-pong balls are hardly visible and are easily confused with the leaves on the ground at some locations.

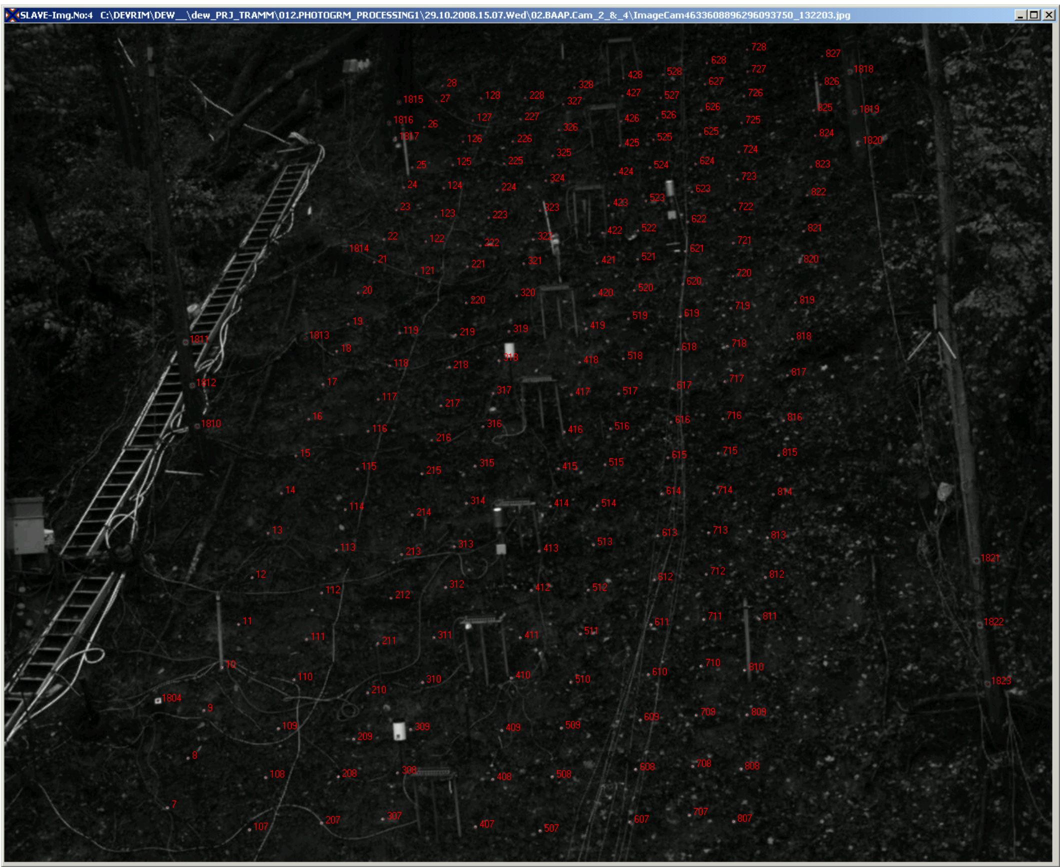


Figure 9. Image measurement result of the image shown in Figure 8.

Table 2. Point-positioning precisions of the ping-pong balls.

Epoch	**Sigma naught (micron)**	**STD-X (mm)**	**STD-Y (mm)**	**STD-Z (mm)**
Day 28	0.61	7.2	14.2	3.4
Day 30	0.60	7.1	14.0	3.3
Day 31	0.65	7.4	14.7	3.5
Mean	0.62	7.2	14.3	3.4

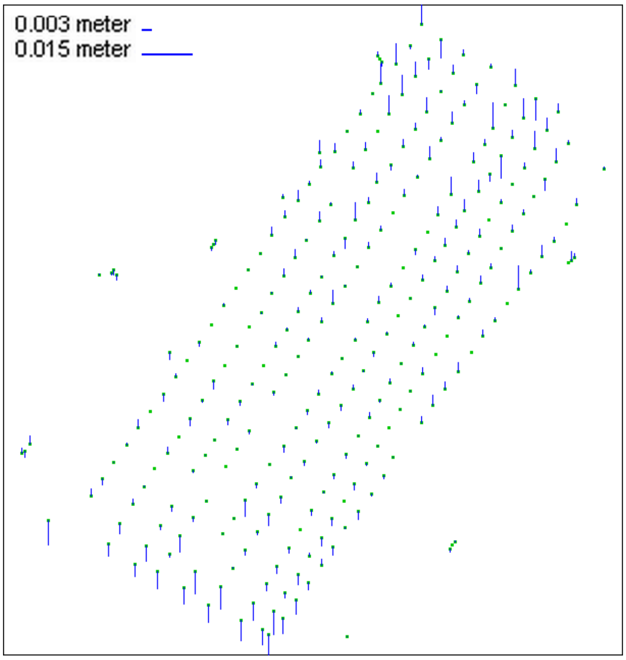


Figure 10. The vertical displacements between the 28.10 and 29.10 epochs. Upward arrows show rising and downward arrows show lowering points.

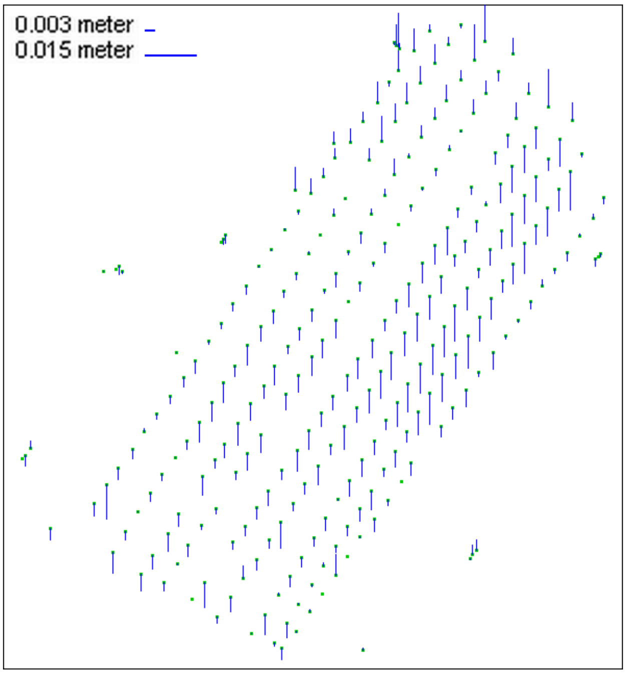


Figure 11. The vertical displacements between the 28.10 and 31.10 epochs.

A posteriori (mean) point positioning precisions obtained from the SGAP bundle adjustment are ± 16.0 mm along the horizontal plane and ± 3.4 mm along the vertical direction (Table 2).

From 250 ping-pong balls, 48%, 4% and 48% of them appeared in 2-fold, 3-fold and 4-fold images, respectively. The actual horizontal precision number (± 16.0 mm) slightly deviates from the simulation result (± 10.3 mm), whereas the actual (± 3.4 mm) and simulation result (± 3.5 mm) of the vertical direction are in close agreement.

The Z-components of the point coordinates were differenced among the day 28, 29 and 31 epochs. The displacements are visualized graphically (Figure 10 and 11). Most of the ping-pong balls maintain a steady condition (Figure 10). A large number of balls are seen to be moving down by almost 1.5 cm (Figure 11), whereas a small area close to the upper-left corner is rising. Although the right side of the area was beginning to deform, a landslide did not occur on this occasion.

4. THE SECOND TRAMM EXPERIMENT

The research team concluded that failure had not occurred on two accounts: (1) because of the leaky base rock in the lower half of the slope, where the greatest part of the water had been supplied, so that a groundwater table could not rise, and (2) root reinforcement from a tree stump in the lower left quadrant of the slope (Springman et al., 2010).

There was less permeable base rock underlying the top of slope that would probably permit a groundwater table to rise during the rainfall event. Therefore, the area of interest was moved approximately 5 meters up the slope in the second sprinkling experiment.

4.1 Photogrammetric Network

A very similar photogrammetric set-up to the first experiment was adopted. The cameras were set to the same locations on the two tall trees by the professional climber, but with the new exterior orientation angles towards the new location of the field. This new arrangement gave 100% imaging overlap of all four cameras. Note that the camera naming has been changed compared to the case given in Figure 6. Now, the two lower cameras at 13 m ground height are CAM1 and CAM2, and the two upper cameras at 18 m ground height are CAM3 and CAM4.

The field computer was replaced by a Fujitsi-Siemens Celsius W-360 PC with an Intel Core 2 Quad 2.4 GHz CPU, 4 GB DDR2 RAM, 1x 250 GB and 2x 500 GB 7200 rpm SATA II harddisks, and MS Windows Server 2003 R2 Enterprise OS.

In order to make the targets more discernable in the image space, the ping-pong balls were replaced by 76 yellow tennis balls with 80 mm diameter, which are now imaged into 5 to 7 pixels in diameter. 13 tennis balls were occluded by a textile strip (right side of Figure 13a). The remaining 63 tennis balls were effectively used in the continuation of the experiment. 12 GCPs were established on the stable trees in the immediate vicinity. Their 3D coordinates were measured with a Leica TCR 407 Power reflectorless electronic theodolite.

4.2 Calibration

A laboratory testfield calibration was performed on the cameras and their set up. The photogrammetric 3D calibration field at the Institute of Geodesy and Photogrammetry at ETH Zurich was used. It is 3.4 m x 2.0 m x 1.0 m in size (Figure 12). The room has stable temperature (22^{o}C) and humidity (40%) by means of air conditioning. The 3D coordinates of 87 well distributed control points were measured using a Leica Axyz system. The average theoretical precision values of the control points are ±0.03, ±0.05 and ±0.03 mm for the X, Y and Z axes, respectively.

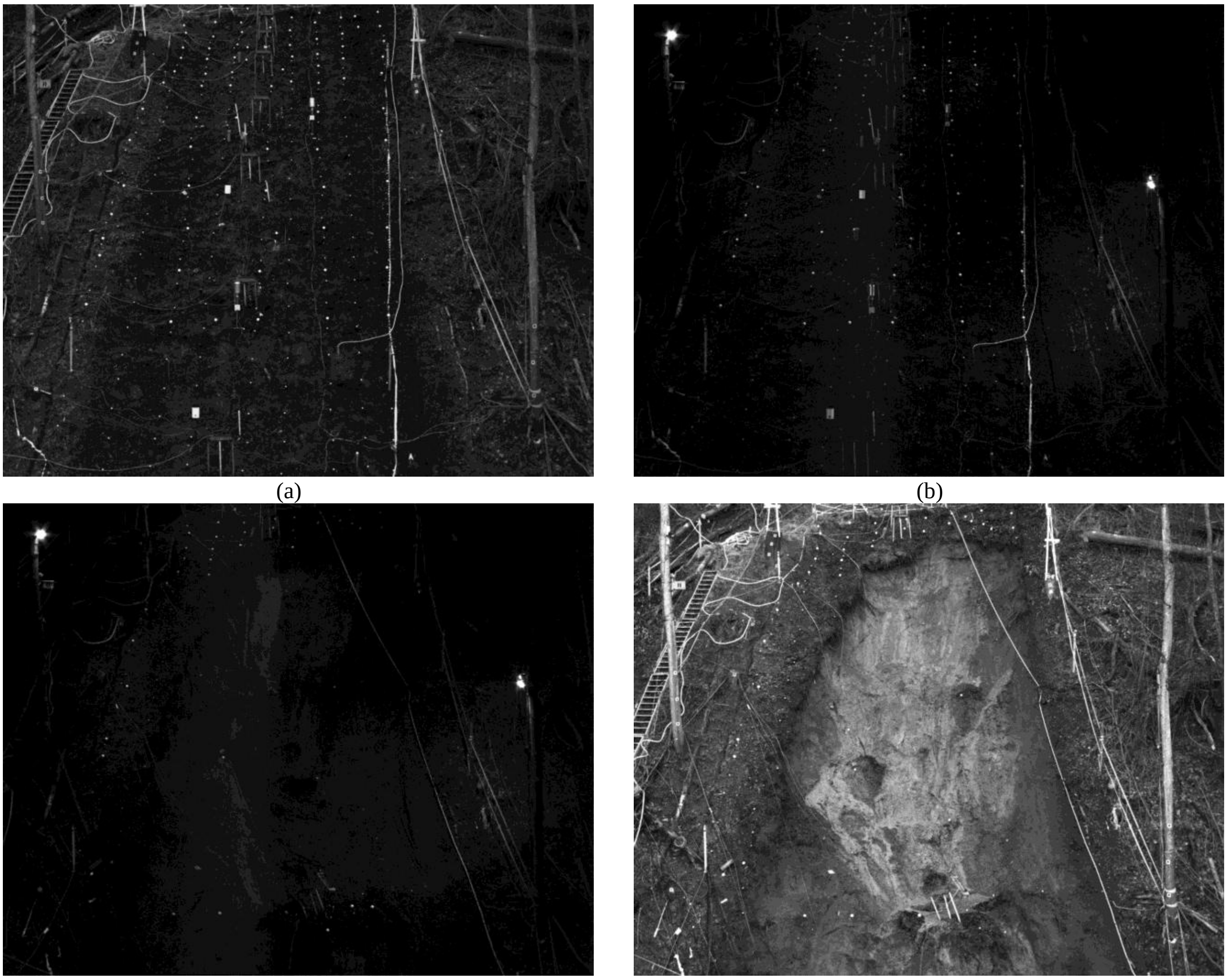
Figure 12. The photogrammetric 3D calibration field at the Institute of Geodesy and Photogrammetry at ETH Zurich.

Nine images were taken for each of the four cameras from three locations (each of which has three stations, down, middle and up) in a convergent geometry mode. Six images were taken in normal mode and the remaining three images were rotated in order to de-correlate the interior and exterior orientation parameters.

All tie point and control point measurements were carried out interactively using the Least Squares image matching method implemented in the BAAP software. The self-calibrating bundle adjustment, implemented in the SGAP software, was used for the final estimation of the parameters. The average of the standard deviation of image point observations (sigma naught) is 0.36 microns, which translates to 1/13 of a pixel of the CCD sensors. Some parts of the results are given in Table 3.

Table 3. Results of the 3D testfield camera calibration.

Cam. Name	**Cam. Constant (mm)**	**Sigma naught (micron)**	**STD-X (mm)**	**STD-Y (mm)**	**STD-Z (mm)**
CAM1	8.286 ± 0.001	0.40	0.14	0.33	0.11
CAM2	8.296 ± 0.001	0.35	0.14	0.36	0.12
CAM3	12.047 ± 0.001	0.34	0.22	0.48	0.15
CAM4	12.098 ± 0.001	0.34	0.19	0.33	0.13
Mean		0.36	0.17	0.38	0.13



(a) (b) (c) (d)

Figure 13. Images taken from CAM3 in the evening at 6:00:00 pm (a), just before the landslide at 3:23:00 am (b), just after the landslide at 3:24:18 am (c), and in the morning at 7:00:00 am (d).

4.3 Point Positioning

Image acquisition of the TRAMM-II experiment was started on 16.03.2009 at 3:28 pm and ended on 17.03.2010 at 11:58 am. The photogrammetric system worked continuously for 20 hours and 30 minutes, and collected approximately 2.5 million grey-level images of the scene (Figure 13).

With newly aligned sprinklers, the rainfall was adjusted to an average distribution of 15 mm/h. There was an instant response in the upper part of the field as the saturation degree increased, suctions dropped and then the water table rose over 5 hours to about 1.5 m below ground level, where it stayed for the next 10 hours. 15 hours after the rainfall had begun, at 3:00 am, the upper right quadrant started to creep downslope, with the rate increasing until 3:23 am. It took 36 seconds to mobilize about 130 m^3 of soil and roots, which travelled on a slightly leftward trajectory towards the tree stump in the lower part of the field, which re-directed the flow to accelerate towards the bottom right, whereupon it took only 12 seconds more to impact on the protection net (Springman et al., 2010).

The images were processed in three temporal frequency groups:

- **Hour-by-hour**: 1 frame per hour (1 fph) starting from 6:00 pm until 3:00 am, totally 8 epochs, and 8x4 = 32 images.
- **Minute-by-minute**: 1 frame per minute (1 fpm) starting from 3:01 am until 3:23 am, totally 23 epochs, and 23x4 = 92 images.
- **Original imaging frequency**: 5 frames per second (5 fps) starting from 3:23:00.000 am until 3:24:00.909 am, totally 263 epochs, and 263x4 = 1052 images.

All image measurements were performed automatically using an image tracking algorithm implemented as a module inside the BAAP software. In an initialization step, the user measures the tennis balls semi-automatically of only the 6:00 pm images of the 1 fph group, using a cross-correlation template matching. Here, the template image is white circle that is generated artificially on a black background, and is 11x11 pixels in size (Figure 14). Then, the tracking algorithm automatically searches for the same tennis balls in the next frames, recursively. The 11x11 pixel cross-correlation window seeks the sub-pixel matching location inside a circular search area of 15 pixels in radius. The origin of the circular search area is defined by the pixel coordinates given in the previous frame.

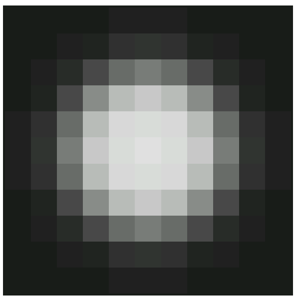


Figure 14. The template image is 11x11 pixels in size.

As a result, (8 − 1) + 23 + 263 = 293 images (or epochs) were measured automatically. This procedure was repeated for all of the four camera image sets.

The image measurements generated (together with their ancillary data) were input into the SGAP software. The SGAP software computed 294 individual bundle adjustments in the batch computation mode. The average sigma naught of the all computations is 0.43 microns, which is equal to 1/11 of a pixel of the imaging system (Table 4).

Table 4. Theoretical point-positioning precisions of the tennis balls.

Groups	Sigma naught (micron)	STD-X (mm)	STD-Y (mm)	STD-Z (mm)
1 fph	0.45	7.0	15.5	6.6
1 fpm	0.43	7.0	15.4	6.5
5 fps	0.41	7.0	15.4	6.3
Mean	0.43	7.0	15.4	6.5

The tracking algorithm produced satisfactory results. Only 4% of the resulting image measurements were erroneous. The outliers were automatically identified and localized in the batch mode bundle adjustments run by the SGAP software. Each individual outlier was inspected and corrected by the user.

Although the new network configuration gave 100% imaging overlap for all four cameras, the field instruments, e.g. sprinklers, deformation probes, acoustic sensors, etc., obscured a few of the tennis balls. 8 of the total 63 tennis balls (13%) were visible in 3-fold images, the remaining 55 tennis balls (87%) were captured in 4-fold images.

The mean theoretical precisions of the estimated coordinates of the tennis balls are ± 16.9 mm along the horizontal plane and ± 6.5 mm along the vertical direction (Table 4).

The relative displacements along the horizontal and vertical directions were illustrated graphically in Figure 15 and 16.

Starting from 6:00 pm till 3:00 am, the 1 frame per hour computations show relatively small planar movements both along the slope and across the slope directions (Figure 15a). At 3:00 am, the right half of the field was only lowered by 1 cm (Figure 16a).

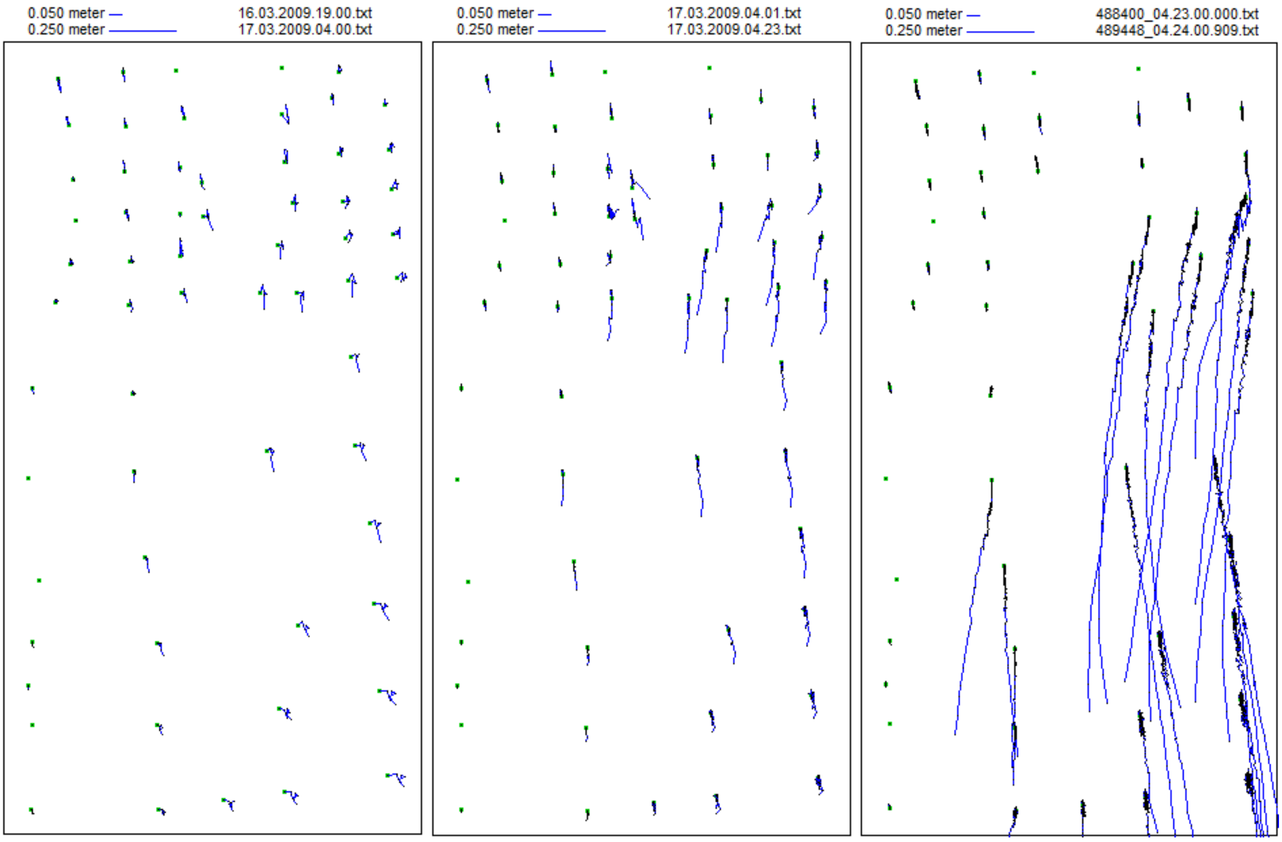
Between 3:01 am and 3:23 am, the upper right quadrant started to move downslope in slow motion, at some points, totally 40 cm in the horizontal plane (Figure 15b) and 30 cm in the vertical direction (Figure 16b). The velocity is 3.0 cm/minutes on average and 11.8 cm/minutes at maximum.

The landslide occurred between 3:23 am and 3:24 am, lasting 48 seconds. In this time span, the upper right quadrant flowed along the slope with an average velocity of 14.0 cm/seconds, and a maximum speed of 100.4 cm/seconds was reached at some locations.

5. CONCLUSIONS

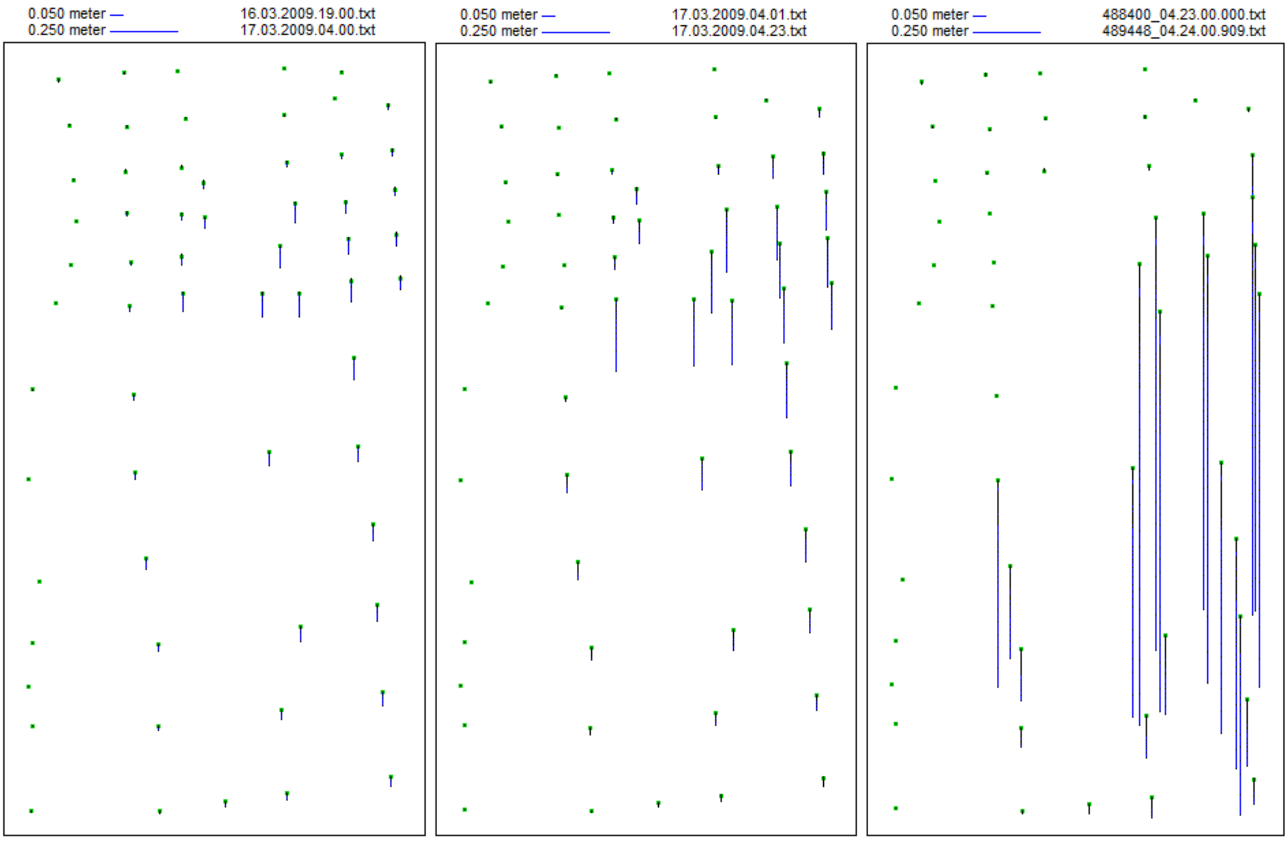
A photogrammetric network was designed and installed to monitor an artificially triggered landslide. Photogrammetry is a cost-effective and accurate method for such tasks. Planning and designing are the key steps when environmental conditions and project specifications have strict limitations.

The simulations, performed by the in-house developed PanCam software, aided the design step. Different photogrammetric network options were simulated; the optimal one was chosen by considering the project requirements and the budget. In this way, just at the beginning of the project, the outputs of the final computations could be predicted and the hardware was purchased accordingly.



(a) (b) (c)

Figure 15. Horizontal displacement of the tennis balls, (a) 1 fph between 6:00 pm and 3:00 am, (b) 1 fpm between 3:01 am and 3:23 am, and (c) 5 fps between 3:23:00 am and 3:24:00 am.



(a) (b) (c)

Figure 16. Vertical displacement of the tennis balls in the same timeframes as Figure 15, (a) 1 fph, (b) 1 fpm, and (c) 5 fps.

Based on the simulation results, 4 IDS cameras with 1280 x 1024 CCD sensors were used. Although the factory specifications of the IDS cameras report a 14 fps image acquisition rate, only a 5 to 8 fps acquisition rate was achieved during the experiments. This deficiency was reported to the Swiss IDS distributor, but no satisfying explanation (and solution) could be given.

Nevertheless, results of the photogrammetric processing fulfilled the project requirements largely because the landslide developed over a long period of time than an earlier example in Japan (Ochiai et al., 2004) which had failed and flowed within about 5 seconds. The surface deformation was quantified by tracking the small (ping-pong and tennis) balls pegged on the ground. The average 3D point-positioning precision of ±1.6 cm was achieved in the first experiment and ±1.8 cm in the second experiment.

In multi-disciplinary field experiments, such as the TRAMM project, transportation and logistics are highly important, and must be planned carefully. The photogrammetric part stands as a work-package in the entire project. Equipment installation, testing, post-processing and other field and office activities were coordinated in the entire project framework.

The results of the photogrammetric work provide a better understanding of surface dynamics of landslides.

6. ACKNOWLEDGEMENTS

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