



# Towards an Early Warning System for Instable Slopes in Georgia: The Large Tskneti-Akhaldaba-Landslide

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## Abstract

In June 2015 a flash flood caused by a failure of a natural dam originated by a hazardous debris flow in the Vere valley hit Georgia's capital Tbilisi. 23 persons lost their lives and property damages were USD 24 mio. Along with the planning of the reconstruction of two destroyed roads an early warning system shall be developed and implemented for the safe use of the new roads. Therefore, some detailed geological investigations were carried out or are still in progress. This includes detailed engineering-geological mapping, hazard and risk mapping, geophysical measurements as well as planning and execution of exploration boreholes. Furthermore, a setup of a multi-sensor network was designed and is already installed in large parts. First data is providing some evidence of geological, hydrogeological and geotechnical setting in the Tskneti region as well as the occurring deformation. Further monitoring combined with numerical modelling will ultimately lead to the implementation of an early warning system, which is the main goal of this research. This paper tries to give an idea of the general geomorphological and geological setting as well as the occurring processes. It shows, the setup of the monitoring system and how it already delivers safety relevant data.

## Keywords

Early warning system • Rock slide • Geomorphology • Monitoring network

## Introduction

On the night of 13–14 June 2015 a very large landslide of reportedly 1 mio m<sup>3</sup> occurred in the Vere valley west of Georgia's capital Tbilisi (Gaprindashvili et al. 2016). The landslide mass temporarily blocked the Vere river and a flash flood impacted in Tbilisi after failing of the dam (UNDP 2015a; Gaprindashvili et al. 2016). More than 700 citizens were directly affected, direct physical damage was estimated to be at least USD 24 mio and most tragically it caused 23 fatalities (UNDP 2015a). The catchment area is a region of high landslide susceptibility with a range of active and expectable processes with differing intensities and volumes. The event of 2015 must be seen as megaevent with a recurrence period of several 1000 s of years or even more. However, the landslide has created even more unstable conditions and weakened an already semi-stable system. As conclusion, the likelihood for medium to large subsequent events has risen significantly.

As part of the reconstruction of two damaged roads in the landslide area an early warning system (EWS) is to be developed based on detailed geological and geotechnical investigations. While some EWS for dams, mainly of hydropower plants, already exist in the country (e.g. CAE S. p.A. 2018) and the UNDP is currently developing a climate-based regional multi-hazard EWS for the whole country (UNDP 2015b), this is the first local EWS in development for a single landslide in Georgia.

A joint-venture of the local construction company Caucasus Road Projects (CRP), the Austrian manufacturer of retention structures Trumer Schutzbauten and the geological-geotechnical consultants of Baugeologisches Büro Bauer (Munich, Germany) is working on this project and developing the EWS in cooperation with Technical University of Munich, Engineering Geology.

Being located between the two main mountain ranges of the Caucasus, the Greater Caucasus in the north and the Lesser Caucasus in the south, about 65% of Georgia's

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landmass is mountainous. Therefore, it is not surprising that the country has a broad landslide inventory with all major landslide processes occurring. Yet, a concept for landslide mitigation is only just developing in the country, partly as a response to the 2015 disaster (UNDP 2015b). Even though the potential for landslide processes becomes clear just by looking at the country's geomorphology the first ever rock fall protection fence in Georgia has been installed as part of this project.

The goal of the research presented in this article is to develop and implement a local early warning system for the mountain range west of Tskneti. It shall provide the highest safety possible for the newly reconstructed roads.

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## Study Area

### Geological Setting

The large landslide is located about 10 km west of Tbilisi between Tskneti and Akhaldaba on the northern edge of the so-called Lesser Caucasus (Fig. 1). The Lesser Caucasus is part of the Alpine-Himalayan mountain belt and is characterized by complex thrust tectonics and strong volcanic activity (Sosson et al. 2010; Danelian et al. 2011). After Sosson et al. (2010) and Danelian et al. (2011) it can be divided into four major units:

The South Armenian Block (1) in the south of the mountain range is a remnant of the former Gondwana continent and is known for its Middle to Upper Paleozoic sedimentary rocks. The active Eurasian continental margin (2) is mainly characterized by Jurassic and Cretaceous volcanic deposits and follows to the northeast. In between lies the ophiolite complex of the Sevan-Akera zone (3), which reflects the area of the subduction zone during the continental collision. In addition, some 1,000 m thick molasse deposits (4) can be found. They were formed by the erosion of the young mountain range from the Paleocene to the Miocene and they are accompanied by a variety of volcanic deposits (Adamia et al. 2010; Sosson et al. 2010).

Two sedimentary rock formations of tertiary age occur in the study area, which belong to the Molasse deposits (4) (Gudjabidze 2003; Sosson et al. 2010). On the one hand, very thin-bedded alternating Oligocene sandstones and claystones appear in the lower part of the slope. The portion of sandstones within this formation increases from the bottom to the top (Gaprindashvili et al. 2016). On the other hand, there are flyschoid Eocene alternating deposits of thick-bedded to massive conglomerates and sandstones with very thin-bedded clay- and siltstones (Gaprindashvili et al.

2016). Both formations are, partly strongly, folded and tectonically stressed. In general, the rock layers are dipping very unfavorably with about 25–50° parallel to the slope. See Fig. 3 for an impression of the thick bedded formation.

The upper scarp of the large landslide is located at an altitude of about 1410 m.a.s.l. directly at the top of the mountain range west of Tskneti, which forms the southern valley flank of the Vere valley (see also Fig. 2). The average slope angle is 29° and therefore very steep between the main scarp (1410 m) and the Akhaldaba road (910 m). Below the Akhaldaba road, the terrain is significantly shallower at an average of 6.5° until the Vere river.

### The Tskneti-Akhaldaba Landslide

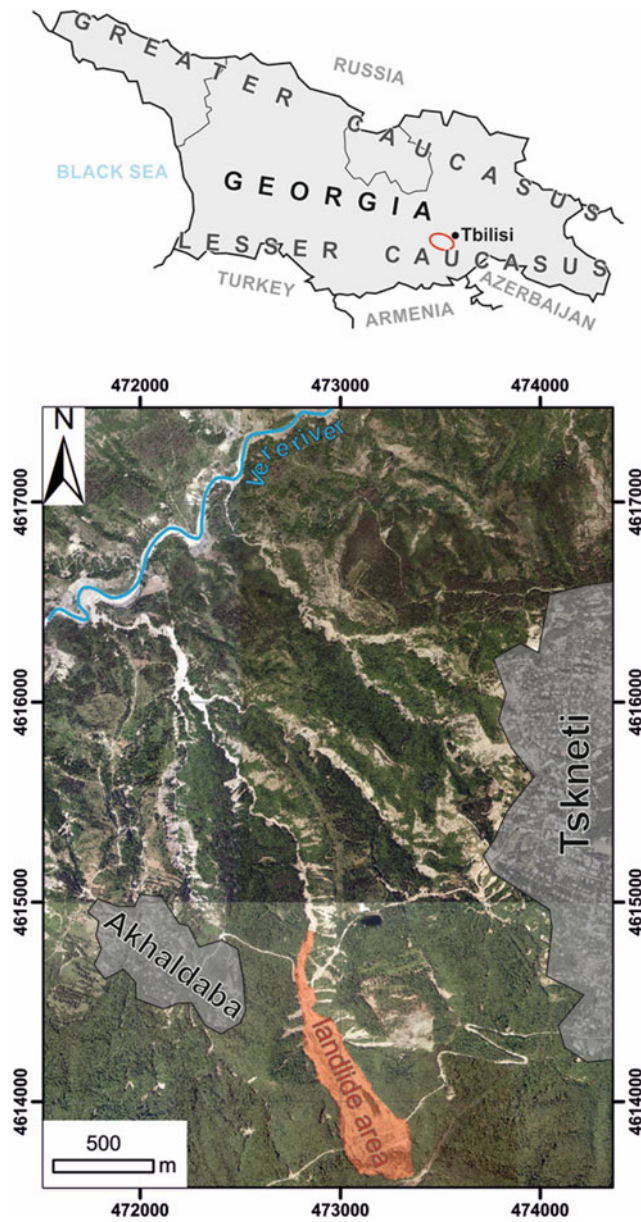
The landslide leading to the blockage of the Vere river occurred between Tskneti and Akhaldaba south of the Vere river west of Tbilisi (Fig. 1) and was a highly complex process of different types of landslides, such as rock slides, debris slides, earth slides and debris flows (UNDP 2015a; Gaprindashvili et al. 2016). In the landslide area two important roads were completely destroyed by rock slide (upper Samadlo road) and debris flow (lower Akhaldaba road), isolating Akhaldaba from Tskneti, which is the villages main source for supplies, water and food (UNDP 2015a; Gaprindashvili et al. 2016).

Both landslide and flash flood were caused by exceptionally long and heavy rainfalls in the previous ten days to the event resulting in an already high discharge of the Vere river. After the landslide mass temporarily blocking the river and ultimately causing the flash flood after failing of the dam peak discharge during the event has been estimated to be 468 m<sup>3</sup>/s (UNDP 2015a; Gaprindashvili et al. 2016). This almost doubles the discharge during the catastrophic flood in 1960 (259 m<sup>3</sup>/s discharge; UNDP 2015a). Following a flood recorded on 4 June 2015 (155 m<sup>3</sup>/s discharge) this were the highest consecutive floods ever recorded in the Vere river (UNDP 2015a). Vere river flows into Mtkvari river in Tbilisi.

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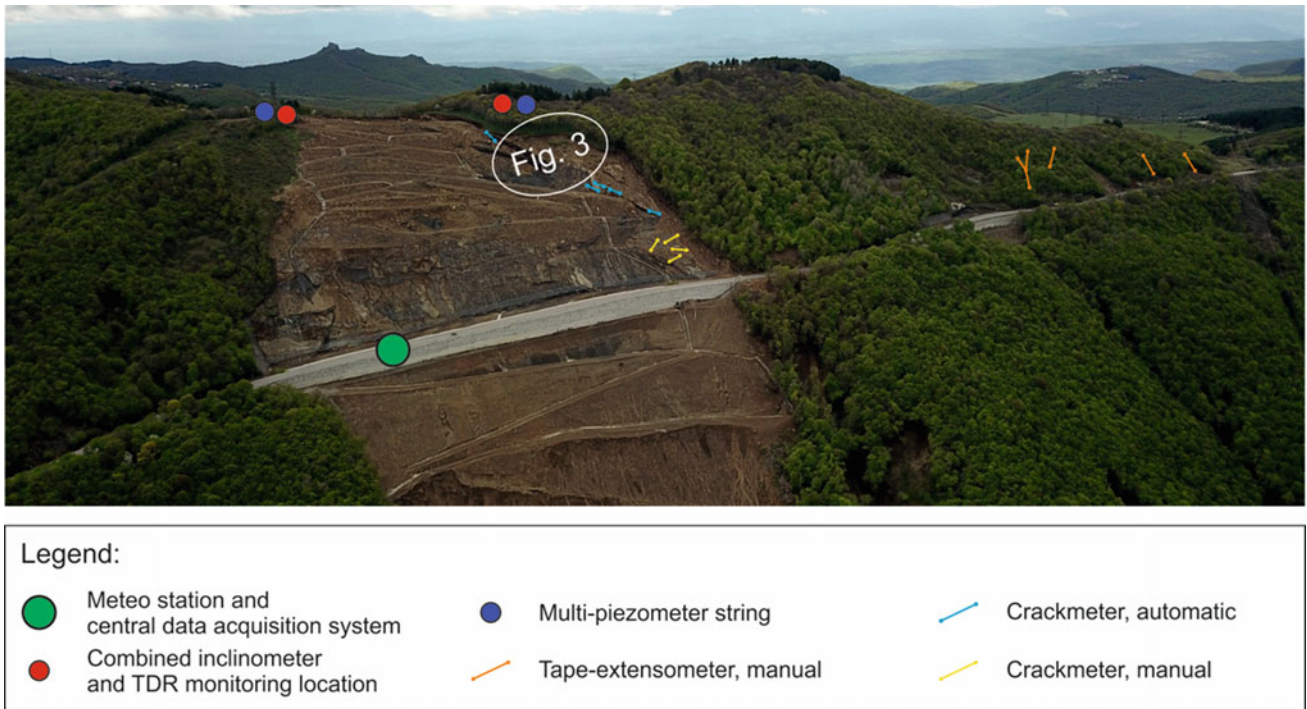
### Field Investigation

The development and implementation of an early warning system is an interdisciplinary and complex task. For a successful execution, extensive investigations are necessary in order to finally obtain a coherent geological and geotechnical model of the slope and to install the appropriate monitoring devices at the right locations.



**Fig. 1** Geographical overview of the study site





**Fig. 2** Overview on the sensor network installed in the upper part of the landslide area. Extent of Fig. 3 is indicated



**Fig. 3** Large cliff in the upper part of the landslide that is being monitored with an inclinometer

## Geological-Geotechnical Investigation

The area of the large landslide, in particular the upper scarp area, as well as the closer vicinity have already been mapped in large parts from a geological-geotechnical point of view. In addition to the spatial distribution and the geotechnical properties of the rocks, geomorphological features of slope movements were recorded in order to draw conclusions about the different movement processes. The mapping has been carried out on a scale of 1:1.000 and forms the basis for the development of a geological model and the construction of a sensor network. It will also provide important information for further investigations.

In addition to the exploratory drillings along the roads, which are to be rebuilt as part of the construction work, further drillings were carried out on the basis of the first mapping results. The aim was, on one hand, geological exploration in other areas of the work area and, on the other hand, to install monitoring equipment into the boreholes.

Representative rock samples were taken from both boreholes and the surface to determine geotechnical parameters such as uniaxial compressive strength, tensile strength and durability in the laboratory.

Additionally, a very detailed characterization of discontinuities based on ISRM (1978) was carried out. This was done with special attention to spacing, persistence and roughness of sets of different discontinuities in order to create statistically relevant input data for future numerical stability calculations.

## Optical Investigations

Optical methods are used in order to observe the development of the slope. UAV surveys are used to create digital elevation models (DEMs) by the photogrammetric reconstruction of the terrain surface. This is done using the commonly used “structure from motion—multi-view stereo” (SfM MVS) workflow (Carrivick et al 2016). Multiple DEMs can be compared following the approach of Wheaton et al. (2010) in order to detect areas with geomorphic changes.

Terrestrial laser scanning (TLS) is used to monitor particularly susceptible areas such as the 12 m high reinforced earth construction (as seen in Fig. 2) or the main cliff in the upper part of the study site (Fig. 3).

## Monitoring Network

After the geological-geotechnical mapping was largely completed, numerous monitoring devices were installed in the project area in the summer of 2018. An overview of the installed sensors and monitoring location is shown in Fig. 2.

### Ground Deformation

In order to observe movements in the unstable rock mass or between larger blocks, several crackmeters were installed in the project area. With these devices the aperture of discontinuities can be measured. In order to keep the costs for the instrumentation as low as possible, a very simple construction was chosen. This construction consists of two common rock bolts, which are installed on both sides of a discontinuity or crack. The distance between these bolts can be manually measured with a caliper. If the aperture of a discontinuity changes, so does the distance between the screws. Advantages of this easy to apply method are the extremely low costs and the robustness against damage. Additionally, a total of five automatic vibrating wire crackmeters were installed in particularly dangerous areas which were also very difficult to access. Just as the simple rock bolt construction, this monitoring device is fixed on both sides of a discontinuity and by detecting frequency changes of the vibrating wire, deformations can be detected at sub-mm range.

Furthermore, several monitoring locations with tape-extensometers were equipped to detect deformations at longer distances e.g. between large blocks and/or trees and a main slide scarp. This also represents a cost-effective and simple device, but subsequent manual readings are necessary. The measurement accuracy also is in the sub-mm range and can provide important insights into the movement patterns.

At the moment, preparations are under way for the installation of reflectors, which are to be regularly surveyed geodetically with a tachymeter.

### Deep Deformation

Two boreholes (42 m and 50 m) above the main scarp of the landslide were equipped in order to perform inclinometer measurements. This allows to detect and quantify movements

perpendicular to the borehole axis. In order to be able to carry out continuous deformation monitoring in case of movement acceleration without the high investment costs of a chain inclinometer, a coaxial cable was installed additionally in the boreholes. Time domain reflectometry (TDR) uses a transceiver to transmit electrical pulses into the cable and measure the reflection. If the cable is kinked by shearing movement, this can be detected in the reflected signal (Singer et al. 2006, 2009). In addition to the continuous measurement, another advantage is that also with large deformations, measurements can be made even if the inclinometer tube has already been squeezed and the inclinometer is not able to be lowered in the borehole (Singer et al. 2006, 2009; Thuro et al. 2010).

### Hydrological Measurements

In five boreholes with 30–50 m depth, a multi-sensor chain of five piezometers was installed to measure water pressure at different elevations. The alternation of impermeable clay layers with more permeable sandstones suggests that non-correspondence aquifers exist at different depths. On the one hand, this hypothesis should be checked with the chosen installation. On the other hand, possible connections between pore water pressures and deformation measurements can be recognized.

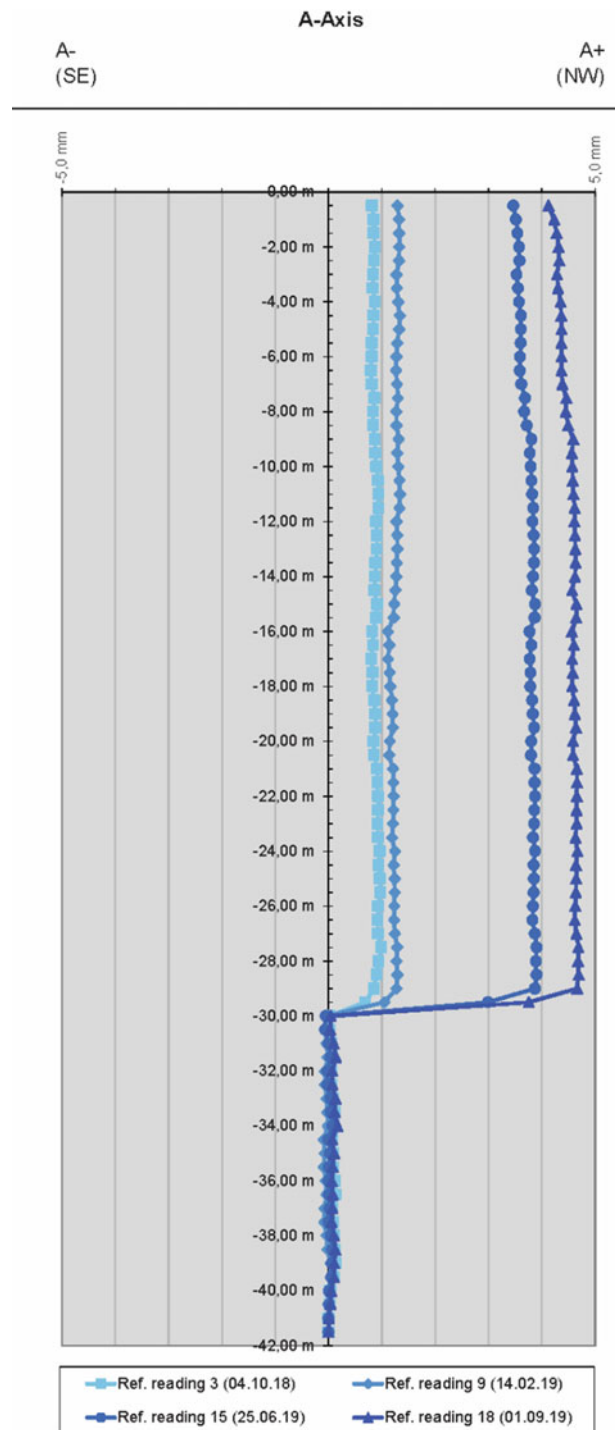
### Meteorological Measurements

In order to be able to correlate measured deformations and pore water pressures with intensity, duration and magnitude of precipitation events, a meteorological station was installed in the project area. This station measures precipitation, temperatures and humidity. It is equipped with a solar cell and thus self-contained.

### First Results and Outlook

First measurement results show active movements in multiple sensors. Figure 4 shows parts of the inclinometer measurements monitoring the large cliff at the main scarp (see Fig. 3). A very defined translational shear movement in about 30 m depth can be detected and quantified. The results prove the ongoing deformation of the slope and provide vital information about the activity, velocity and intensity of the rock slide at the cliff. The results will also play an important role for future numerical modelling by indication the depth and activity of the movement.

Tape extensometer measurements have detected a high acceleration of a shallow slide directly next to the road west



**Fig. 4** Exemplary inclinometer measurements below the main cliff shown in Fig. 3 near the main scarp at the top

of the main landslide. Based on this data the slide was stabilized by a simple wall construction and damage to the road was avoided successfully. Monitoring of this slide continues and movement rates have decreased dramatically after the stabilization.



Overall, the installed monitoring system already proves to be very valuable for the safety of the road and will continue to provide important data for the completion of the EWS.

In the further progression of the project the data acquisition will be optimized with improved radio antennas and updated power supply. Ultimately, data collection and analysis should be carried out simultaneously through an integrated database system, as developed in the alpEWAS project (Thuro et al. 2009, 2010).

To develop a true local EWS, thresholds must be defined that are able to trigger the closure of the affected roads. Such thresholds can be large amounts of precipitation, critical pore water pressures or high deformation rates. To avoid false alarms, a great deal of effort must be made in deriving and evaluating these alarm thresholds correctly. Although there are many different ways in which such thresholds can be determined, the determination of such a value is still a challenge and a constant adaptation to new information is necessary. In most cases, time series analysis and/or numerical modeling are used to identify the thresholds (Nadim et al. 2009; Festl and Thuro 2016). In this project we aim for a multi-level threshold consisting of a threshold for precipitation, pore water pressure and deformation rate. In theory, significant precipitation causes a rising water table and therefore rising pore water pressure, which can result in higher deformation rates. Between each step is a certain time lag, which provides the possibility to both review the data and have a timely and early warning in its true meaning.

The most important task for the near future will be to complement and refine the geological model. These include e.g. the ongoing laboratory tests of geotechnical parameters, further drilling and their equipment to new measurement locations or the implementation and evaluation of planned geophysical measurements like ERT electrical resistivity tomography.

In addition, an application process is currently underway with Georgian colleagues for the promotion of a project aimed at developing a regional EWS for the whole Vere catchment.

## References

- Adamia S, Alania V, Chabukiani A, Chichua G, Enukidze O, Sadradze N (2010) Evolution of Late Cenozoic basins of Georgia (SW Caucasus): a review, pp 239–259. In: Sosson M, Kaymakci N, Stephenson RA, Bergerat F, Starostenko V (eds) Geological Society, London, Special Publications, p 340: Sedimentary basin tectonics from the Black Sea and Caucasus to the Arabian platform. The Geological Society, London (ISBN 9781862393080), 509 pp
- CAE S.p.A. (2018) Dams: emergency plans, early warning and public safety systems. The case of Zhinvali in Georgia. [https://www.cae.it/eng/news/dams-emergency-plans-early-warning-and-public-safety-](https://www.cae.it/eng/news/dams-emergency-plans-early-warning-and-public-safety-systems-the-case-of-zhinvali-in-georgia-nw-1181.html)
- [systems-the-case-of-zhinvali-in-georgia-nw-1181.html](https://www.cae.it/eng/news/dams-emergency-plans-early-warning-and-public-safety-systems-the-case-of-zhinvali-in-georgia-nw-1181.html). Last accessed 24 Jan 2020
- Carrivick J, Quincey D, Smith M (2016) Structure from motion in the geosciences: new analytical methods in earth and environmental science. Wiley Blackwell, Chichester (ISBN 9781118895849), 197 pp
- Danelian T, Sosson M, Avagyan A, Galoyan G, Asatryan G, Rolland Y, Sahakyan L, Müller C, Grigoryan A, Person A, Corsini M, Jrbashyan R, Melkonyan R (2011) A brief geological outline of the lesser caucasus: new insights on its tethyan-alpine evolution based on recent results of a french-armenian collaboration. Bull Soc Geol Fr 18(2):65–75
- Festl J, Thuro K (2016) Determination of thresholds at the Aggenalm landslide (Bayrischzell, Germany) by time series analysis and numerical modeling. In: Landslides and engineered slopes. Experience, theory and practice: proceedings of the 12th international symposium on landslides, 12–19 June 2016. Napoli, Italy, pp 909–916
- Gaprindashvili G, Gaprindashvili M, Tsereteli E (2016) Natural disaster in Tbilisi City (Riv. Vere Basin) in the Year 2015. Int J Geosci 7 (9):1074–1087
- Gudjabidze GE (2003) Geological map of Georgia 1:500.000. Georgian State Department of Geology and National Oil Company “Saqnavtobi”, Tbilisi
- ISRM—International Society for Rock Mechanics (1978) Suggested methods for the quantitative description of discontinuities in rock masses. Int J Rock Mech Mining Sci Geomech 15(6):319–368
- Nadim F, Cepeda J, Sandersen F, Jaedicke C, Heyerdahl H (2009) Prediction of rainfall-induced landslides through empirical and numerical models. In: Proceedings of the 1st Italian workshop on landslides, 8–10 June 2009. Napoli, Italy, pp 206–215
- Singer J, Schubäck S, Wasmeier P, Thuro K, Heunecke O, Wunderlich T, Glabsch J, Festl J (2009) Monitoring the Aggenalm landslide using economic deformation measurement techniques. Aus J Earth Sci 102(2):20–34
- Singer J, Thuro K, Sambeth U (2006) Development of a continuous 3D-monitoring system for unstable slopes using TDR. Felsbau 24 (3):16–23
- Sosson M, Rolland Y, Müller C, Danelian T, Melkonyan R, Kekelia S, Adamia S, Babazadeh V, Kangarli T, Avagyan A, Galoyan G, Mosar J (2010) Subductions, obduction and collision in the Lesser Caucasus (Armenia, Azerbaijan, Georgia), new insights, pp 329–352. In: Sosson M, Kaymakci N, Stephenson RA, Bergerat F, Starostenko V (eds) Geological Society, London, Special Publications, p 340: Sedimentary basin tectonics from the Black Sea and Caucasus to the Arabian platform. The Geological Society, London (ISBN 9781862393080), 509 pp
- Thuro K, Singer J, Festl J, Wunderlich T, Wasmeier P, Reith CH, Heunecke O, Glabsch J, Schubäck S (2010) New landslide monitoring techniques—developments and experiences of the alpEWAS project. J Appl Geodesy 4(2):69–90
- Thuro K, Wunderlich T, Heunecke O, Singer J, Schubäck S, Wasmeier P, Glabsch J, Festl J (2009) Low cost 3D early warning system for alpine instable slopes—the Aggenalm Landslide monitoring system. Geomech Tunnel 2(3):221–237
- UNDP—United Nations Development Programme (2015a) Tbilisi disaster needs assessment 2015. Part 1 (Final draft), 59 pp
- UNDP—United Nations Development Programme (2015b) Towards a multi-hazard early warning system for Georgia, 25 pp
- Wheaton JM, Brasington J, Darby SE, Sear DA (2010) Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth Surf Proc Land 35(2):136–156