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The monitoring of slow-moving landslides and assessment of stabilisation measures using an optical–mechanical crack gauge

Abstract It is possible to monitor slow-moving landslides and assess landslide stabilisation measures over protracted periods using an optical–mechanical crack gauge called a TM-71. This technical note outlines the theoretical background to the gauge and illustrates its practical application through a number of case studies. These studies are drawn from a range of landslide types and stabilisation measures. In terms of monitoring slow-moving landslides, three studies of deep-seated deformations are presented. The Taukliman coastal landslide on the Black Sea Coast is characterised by vertical and horizontal displacements of up to 0.2 mm year^{-1} and sudden earthquake-induced dilations of up to 6 mm. The Parohy ridge spreading landslide in the Malá Fatra Mountains is characterised by gravitationally induced vertical displacements of 0.7 mm year^{-1}. The slope deformation that formed Cyrilka Cave in the Beskydy Mountains is characterised by very slow sinistral strike–slip movements of 0.8 mm year^{-1}. In terms of assessing landslide stabilisation measures, two studies are presented from Orava Castle in Slovakia and Tetín in the Czech Republic. The data recorded at these sites demonstrate that the constructed stabilisation measures have successfully alleviated the potential landslide hazard in both localities. These case studies clearly demonstrate that the gauge represents an important tool with which to monitor slow-moving landslides and assess landslide stabilisation measures. It is able to provide a precise three-dimensional record of deformation, withstand harsh environmental conditions, and record reliable data over protracted periods.

Keywords Long-term monitoring · Optical–mechanical crack gauge · Deep-seated landslides · Gravitational–tectonic slope deformations · Stabilisation measures

Introduction

The long-term monitoring of slow or extremely slow landslides, defined as those that move less than 18 mm year^{-1} (Varnes 1978), can be performed using traditional or modern techniques. Traditional techniques include rod dilatometers, wire or steel tape extensometers, and geodetic surveying (Hartvich et al. 2007; Hartvich and Mentlík 2010). Modern techniques include GPS (global positioning system), EDM (electronic distance meter), InSAR (interferometric synthetic aperture radar), and OTDR (optical time domain reflectometry) (Gilli et al. 2000; Petley et al. 2005; Cappa et al. 2006). Irrespective of whether traditional or modern techniques are used, such slow movements often require monitoring equipment to operate close to its sensitivity limit. This poses serious difficulties in relation to the reliability and interpretation of the derived measurements.

It is now possible to send the results of sophisticated on-site monitoring to a remote server equipped with software that analyses velocity changes. These results may then be used to form the basis of a landslide early warning system (Hartvich et al. 2007; Reid et al. 2008; Ying et al. 2010). This type of solution is expensive, both in terms of equipment and operating costs, and requires regular maintenance. It is, therefore, only justifiable if inhabited areas or valuable assets such as industry or infrastructure are endangered. Furthermore, this type of solution is liable to malfunction due to the large number of electronic components that maybe be affected by, for example, energy supply failure, corrosion, or moisture.

During the 1960s, Dr. Košťák developed an optical–mechanical crack gauge at the Czechoslovakian Academy of Sciences. The original purpose of the gauge was to monitor the three-dimensional development of cracks within man-made constructions such as tunnels and bridges. Subsequent studies have demonstrated that the gauge is far more versatile than was originally intended. For example, it is now used as the principal recording device across an entire fault displacement monitoring network in central Europe (www.tecnet.cz). It is also used to monitor slow-moving landslides and to assess landslide stabilisation measures. This technical note focuses on the theoretical background and practical application of the gauge in relation to landslide monitoring. Its application is illustrated by a number of case studies.

Theoretical background: moiré patterns and the crack gauge

The optical–mechanical crack gauge developed by Dr. Košťák has come to be called a TM-71 (Fig. 1a). It is manufactured by Gestra CZ, s.r.o., Czech Republic. The gauge uses moiré patterns to quantify displacement or deformation (Košťák 1969). A moiré pattern is produced whenever two periodic structures are overlapped. Generally, these structures comprise lines with solid and open regions. For a typical moiré pattern, the moiré effect occurs when two sets of straight lines are superimposed so that they intersect at a low angle. If the superimposed lines are nearly parallel, a tiny displacement in one of the figures will give rise to a large displacement in the elements of the moiré pattern. In other words, the displacement is magnified. A moiré pattern may be regarded as the mathematical solution to interference of two periodic functions (Oster and Nishijima 1963).

The fundamental underlying principles of the gauge remain the same as they were when it was first developed, although elements have been refined over time. The displacement or deformation is recorded on two identical optical glass plates, referred to as the combined indicator (Košťák 1991) (Fig. 1b). Etched onto each glass plate are three grids: one spiral grid (Fig. 1c) and one pair of rectangular grids. The spiral (or alternatively circular) grid produces a moiré pattern in the form of hyperbolical lines (Fig. 1d). The rectangular grids produce a

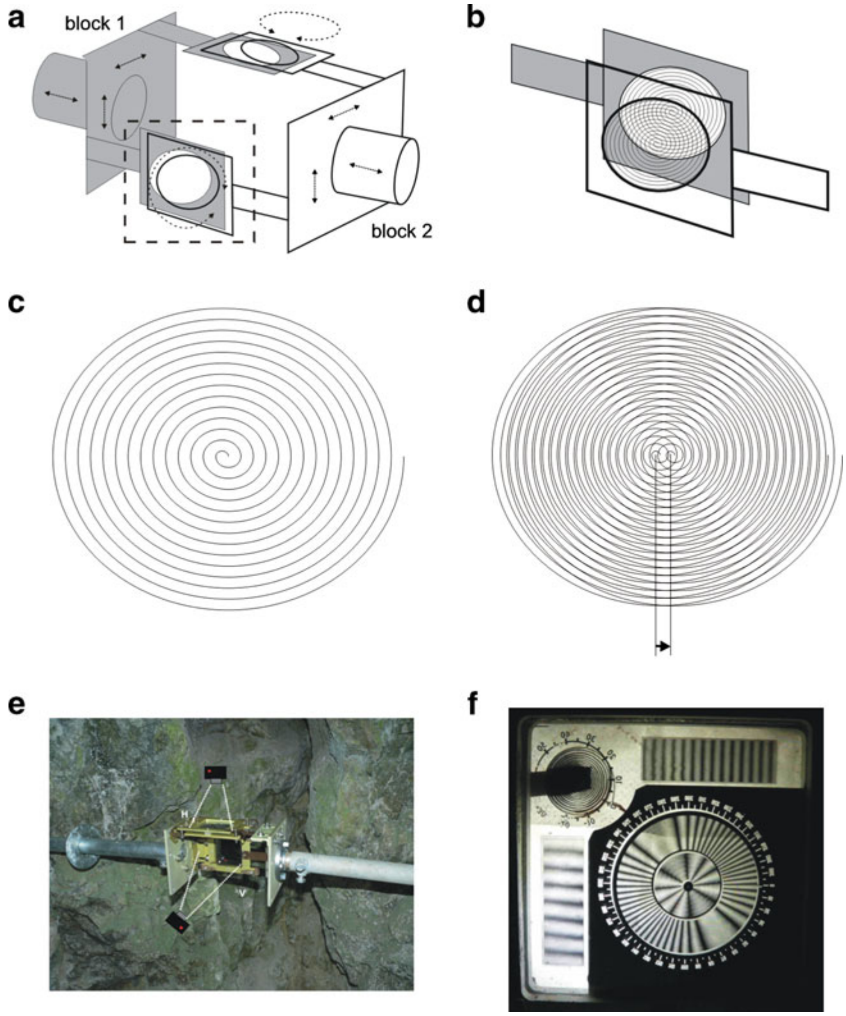


Fig. 1 The optical–mechanical crack gauge set during a reading and an explanation of the moiré principle (see text for details)

moiré pattern in the form of oblique parallel lines. The moiré patterns recorded on the spiral grid are only affected by the displacement of the device and are indifferent to rotations. In contrast, the moiré patterns recorded on the rectangular grids are only affected by the rotation of the device and are indifferent to displacement.

The mathematical principles behind the grids used for the combined indicator are described in Košťák and Popp (1966) and Košťák (1968; 1969). The sensitivity of the device is governed by the density of the applied grids. The grids usually range from 8 to 100 lines per millimeter (Košťák 1995). With high density grids, the device is able to record relative displacements or deformations in three coordinates (*x*, *y*, *z*) with precision of better than ±0.007 mm (Stemberk et al. 2010). It also records horizontal and vertical rotations (*xy* and *xz*) with precision of better than ±0.00016 rad (Košťák et al. 2011). However, in many monitoring situations, such high precision is not required and the density of the applied grids is lower. The device is best suited for sites where the total expected displacement does not exceed 2 mm year^{-1}. However, the total amount of displacement that can occur before the moiré pattern becomes indecipherable depending largely on the quality of the initial installation. It is possible that the total amount of displacement can exceed 8 mm before the glass plates need to be reset, if only a few lines were visible when the plates were installed. Nonetheless, the device can be adjusted to measure movements of up to 30 mm year^{-1}. These adjustments may be necessary at sites that require protracted monitoring or if unexpected sudden movements occur (e.g., Stemberk and Košťák 2007). The procedure for resetting the device does not adversely affect the continuity of the derived results.

Practicalities of the optical–mechanical crack gauge

Choosing suitable locations and mounting the device

The device is mounted across a discontinuity using two connecting arms, which are normally solid steel bars with a diameter of 45 mm. These connecting arms are drilled into the rock walls on both sides of the discontinuity to a depth of at least 0.4 m and secured with cement mortar. If the discontinuity is flanked by unconsolidated material on one or both sides, the appropriate arm has to be set into a sufficiently large concrete block to ensure the stability of the device. The device is mounted across the crack in such a manner that one pair of glass plates records the horizontal movements in two perpendicular directions (*x*- and *y*-coordinates). At the same time, it records rotation in the horizontal plane (*xy*). The second pair of glass plates records vertical movements (*z*-coordinate) and rotation perpendicular to the horizontal plane (*xz*).

The correct placement of the gauge within the landslide is crucial for obtaining results that are able to constrain landslide kinematics. Therefore, detailed landslide maps should be generated prior to the installation of the device or devices. The following assessments must be made with regard to the suitability of a specific site. First, consideration must be given to the size of the block that is to be monitored and the processes likely to be responsible for the development of the specific crack. These are important to ensure that the measurements represent movement on a significant part of the landslide. Second, consideration must be given to the width of the specific crack. The metal arms can easily span a crack with a width of less than 2 m. However, if the distance is greater, they need to be supported by additional arms or fixed concrete blocks to prevent bending due to the weight of the instrument. Third, consideration must be given to the geometry of the block that is to be monitored and the strength of the rocks on either side of the crack as highly fractured or deeply weathered rocks are not stable for installation. In soft rocks and soils, the arms must be fixed into concrete blocks on both sides of the crack. Fourth, consideration must be given to the accessibility of the device as this is required to record the data. However, some devices continue to be monitored despite difficult accessibility. Fifth, consideration must be given to the protection of the device from the environment and vandalism; sites with frequent and unrestricted access, for example, those in tourist areas, are best avoided.

Temperature effects

The use of steel components in the manufacture of the device means that changes in temperature will be reflected as dilation in the direction of the connecting arms. For this reason, many of the devices are located in deep joints or caves where the temperature is more stable. Nonetheless, it is possible to apply the steel expansion coefficient in order to correct the measured data. In a normal situation, in which the opposing holes have been drilled 1 m apart, then dilation of 0.012 mm will be registered if the temperature decreases by 1°C. Conversely, the registered dilation will be negative if the temperature increases. A standard correction procedure may be applied to compensate for this steel dilation with respect to the actual temperature and span of the connecting arms. Rock expansion is frequently more complex as it is more dependent on local conditions including structure and mass conductivity. Therefore, the displacement graphs are usually left without correction for expansion and show a seasonal effect. Such a simple approach is usually satisfactory (Košťák 1969). The effect of temperature variations on monitoring results at the surface has been examined in detail and a method of data filtering has been suggested in order to eliminate temperature effect on the measurement (Kontny et al. 2005; Vlčko et al. 2005). More recently, Briestenský et al. (2010) demonstrated that the influence of seasonal temperature induced by rock dilations decreases sharply with depth below the surface.

Recording measurements

Measurements are usually recorded photographically from the horizontal and vertical moiré units (Fig. 1e). This requires the use of either photographic paper and a flash or a digital camera and, preferably, backlight panel. An example photograph is presented on Fig. 1f. The two photographs contain all the information needed for data evaluation. The frequency of reading depends generally on the purpose of the monitoring, the expected rate of displacement, and cost considerations. The incremental vector of the space displacement is then defined by its components that are simply found from increments of the readings compared with the last measurement period (Košťák 1969).

In addition to manual measurements, the crack gauge can be equipped with automatic reading and data storage. This is designed to be easy to install, resistant against humidity, and cost effective. The automatic reading and storage equipment consists of two digital video cameras, infrared diode lights, a timer, and data loggers (Fig. 2). The timer is user defined and the cameras take photographs of the horizontal and vertical moiré units. Initial trials have been successful. However, the disadvantage of this system is that it requires a relatively high power supply (1,200 mA). Therefore, at present, automated readings are usually only possible at sites with an external electricity supply. The images are either stored in the data loggers or can be sent to a remote location via GSM.

Results

For nearly 40 years, various slow-moving landslides and landslide stabilisation measures have been monitored using optical–mechanical crack gauges. The results are usually presented graphically as *x*, *y*, *z* coordinates. The *x*-coordinate represents crack dilation (the opening or closing of the crack), the *y*-coordinate represents relative horizontal shear displacement, and the *z*-coordinate represents relative vertical displacement (Fig. 3). The measurements reflect the relative changes in distance between the three coordinates. Furthermore, the relative angular rotation of the adjacent blocks can be calculated for both the horizontal (*xy*) and vertical (*xz*) planes. These are not presented here as the main focus of the paper is displacement monitoring. The following section outlines a number of case studies in which data have been recorded over protracted periods. The location of the monitoring sites is presented in Fig. 4.

Deep-seated landslides

The optical–mechanical crack gauge has been used to monitor various types of landslides including deep-seated compound rock slides in a range of geological settings (Rybář and Košťák 2003). This monitoring describes the relative movement between two rigid blocks; one of the blocks may be stable and one active or both blocks may be active as part of a large deforming landslide mass.

Taukliman, Black Sea Coast, Bulgaria

The deep-seated coastal landslide at Taukliman on the Black Sea Coast in Bulgaria was monitored for nearly 20 years, between October 1973 and August 1992 (Fig. 5). Three devices were installed on this landslide after attempts to characterise its movements using geodetic techniques were found to be unsuccessful (Košťák 1977). Data recorded along the main tension crack of the landslide are presented in Fig. 3a. The results show that the overlying limestone blocks are moving across the underlying claystones (Košťák and Avramova-Tacheva 1981). This slow creep may reach rates of up to 0.2 mm year^{-1}. The far larger movements are associated with earthquake events in the seismogenic area of

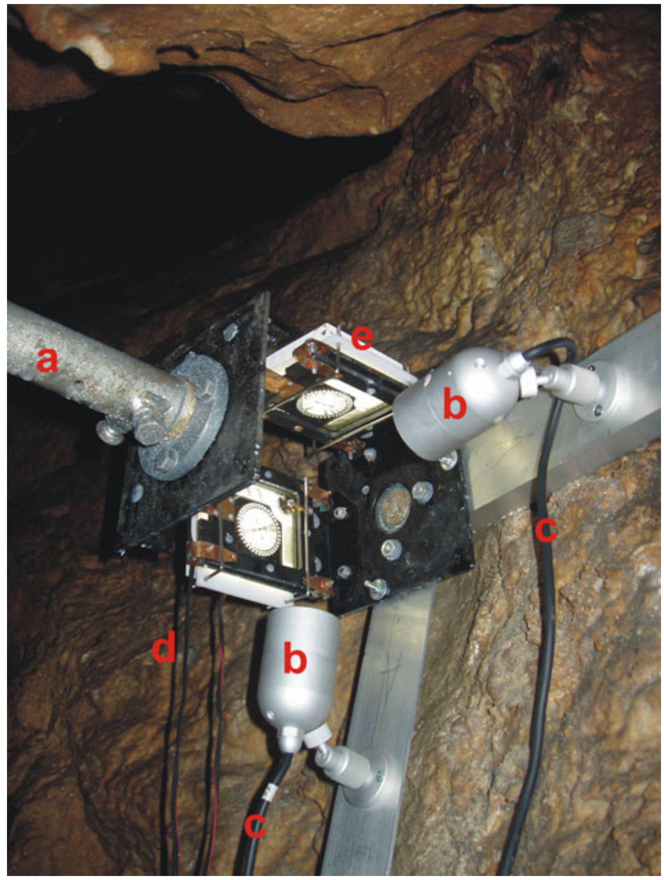


Fig. 2 The optical–mechanical crack gauge equipped with automatic reading and data storage technology. *a*: metal arms, *b*: digital cameras, *c*: power supply and video signal cables, *d*: power supply cables for backlight panel, *e*: backlight panel. The datalogger is outside the photograph

Vrancea. For example, the tension crack recorded ~1.5 mm of vertical displacement and ~4 mm of dilation following an event in 1977 (USGS Earthquake Hazards Program 2010). Similar effects are observed following events in 1986 and 1990 (Vlad and Vlad 2008; USGS Earthquake Hazards Program 2010). The data also reflect cyclic annual temperature fluctuations, seen most clearly in the horizontal and vertical displacement data (*y*, *z*).

Parohy, Malá Fatra Mountains, Slovakia

The deep-seated ridge spreading landslide at Parohy in the Malá Fatra Mountains of Slovakia has been monitored for nearly 40 years, starting in August 1973. The landslide mass comprises marlstones, sandstones, and claystones of Mesozoic age. It is predominately represented by sagging of the mountain slopes ('sagging' used in the sense of Hutchinson (1988)). The device was installed in the extension crack behind the mountain ridge, away from the main scarp of the landslide (Fig. 6) (Košťák 1993). The recorded data show extremely slow and steady, gravitationally induced, vertical displacement of 0.07 mm year^{-1}. Over the same period, the overall horizontal displacement has been negligible (Fig 3b). It is interesting to note that the recorded vertical displacement is not associated with dilation and no pronounced periods of accelerated displacement have been observed over the monitoring period. The three distinct peaks in the vertical displacement data appear to relate to increased water infiltration during spring snow thaw (Košťák 1993); this process is discussed further by Briestenský et al. (2011). However, these peaks do not influence the overall vertical displacement trend.

Tectonically induced gravitational slope deformations

Cyrilka Cave, Beskydy Mountains, Czech Republic

The slope deformation that caused the development of a large fissure cave near the ridge of the Beskydy Mountains in the Czech Republic has been monitored for around 10 years. The cave has a length of 370 m, and formed as a result of gravitational movements within gently inclined rigid sandstone strata interbedded with thin claystone layers. It is part of a large deep-seated landslide (Fig. 7) and follows a fault that trends NNE–SSW. Two crack gauges show very slow sinistral strike–slip movements of 0.08 mm year^{-1} (Fig. 3c). This result corresponds well to those derived from other studies of recent tectonic movement in the area (Krejčí et al. 2004). The dilation and vertical displacements, which would have resulted from gravitationally driven movements, were negligible until the end of the 2005. Since then, the vertical component shows a very slow movement trend. This suggests that the tectonic influence has prevailed during the first part of the monitored time period. It is seen that the crack dilation is strongly affected by seasonal variations, which reflect the amount of moisture in the fractured claystones and sandstones within which the cave has formed.

Assessing the performance of stabilisation measures

Orava Castle, Slovakia

The landslide stabilisation measures constructed at Orava Castle in Slovakia were assessed for more than 17 years, between July

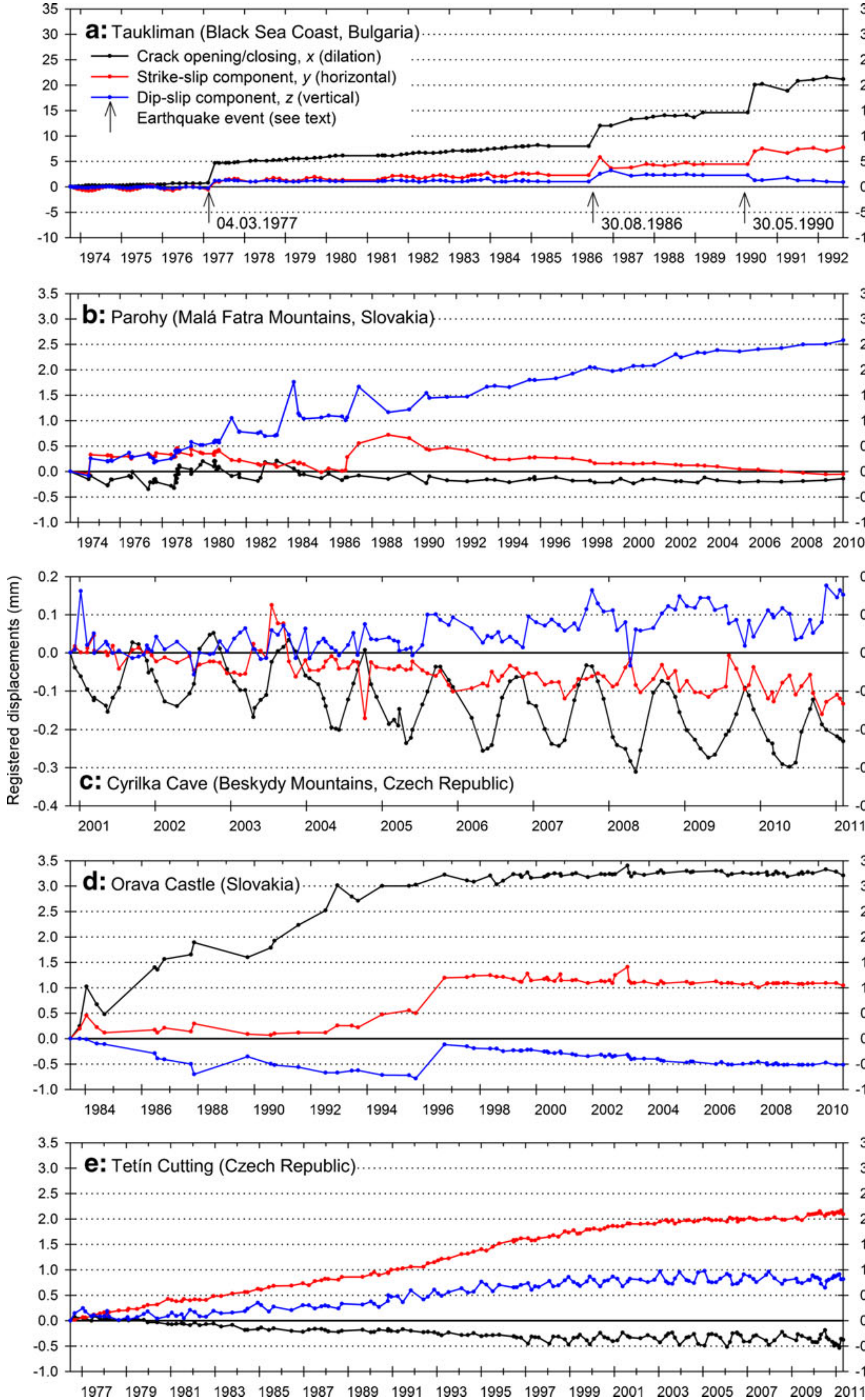


Fig. 3 The optical–mechanical crack gauge measurement results at the selected sites. Note the changes in scale on both the x- and y-axes

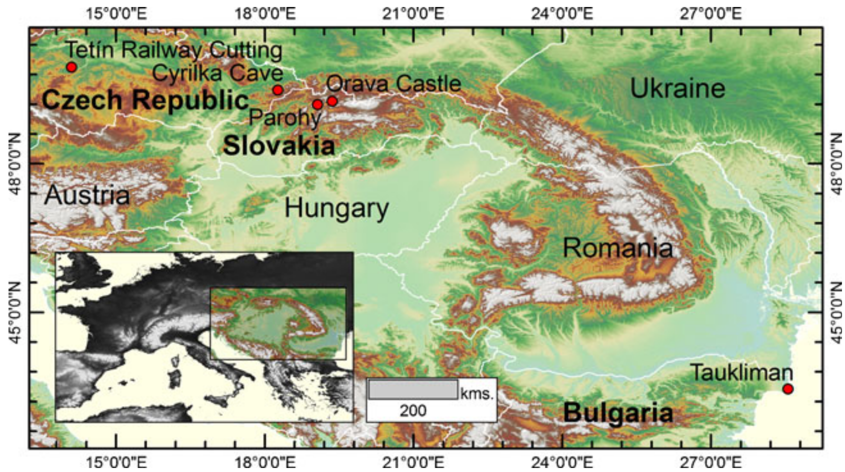


Fig. 4 The location of the study sites in the Czech Republic, Slovakia, and Bulagria. The *inset map* shows western and central Europe

1982 and October 1999. These measures were constructed following an extensive geotechnical investigation undertaken between 1980 and 1982. The investigation revealed progressive slip within the marlstone and claystone bedrock underlying the southern wing of the castle (Košťák and Sikora 2000). The installed optical–mechanical crack gauge demonstrated that dilation continued at a rate of 0.3 mm year^{-1} for more than 4 years after the completion of the remedial works (Fig. 3d). This dilation ceased suddenly in 1996 (Košťák and Sikora 2000). The delay is explained by the amount of time it took for the measures to become effective in stabilising the progressive slip (e.g., anchor tightening). Nonetheless, the data confirm that these measures have been successful (Košťák 2006).

Tetín Railway Cutting, Czech Republic

The landslide stabilisation measures constructed on a railway cutting at Tetín in the Czech Republic have been assessed for more than 35 years, starting in June 1976. The bedrock hereabouts comprise tectonically loosened marlstones of Silurian age, which is characterised by creep movements along its joints. A geotechnical investigation undertaken close to a local archaeological site revealed a large planar discontinuity dipping at 35° into the adjacent railway line that runs between Prague and Pilsen (Fig. 8) (Košťák 1995). In 1975, this discontinuity was stabilised using a set of anchors and their effectiveness has been monitored using a crack gauge (Košťák 2006). Following the completion of the remedial works, the data reveal that the discontinuity has actually closed by about 0.4 mm (Fig. 3e). Whilst some horizontal and vertical displacements have occurred, these are very small (y=~0.6 mm year^{-1}; z=~0.02 mm year^{-1}). The data again confirm that these stabilisation measures have been successful.

Discussion

The case studies described above point to certain advantages of the optical–mechanical crack gauge. In this section, these advantages are outlined explicitly along with the known limitations of the device.

Fig. 5 View of the Taukliman deep-seated landslide (Black Sea Coast, Bulgaria). Note the main scarp that forms the upper rim of the slope. The location of the optical–mechanical crack gauge is indicated by an arrow (photo: B. Košťák)

Fig. 6 View of the Parohy deep-seated landslide (Malá Fatra Mountains, Slovakia). The location of the optical–mechanical crack gauge is indicated by an arrow (photo: P. Blaženín)

Advantages of the optical–mechanical crack gauge

The optical–mechanical crack gauge has very high precision compared to both traditional and modern landslide monitoring techniques (Tab. 1). It has also been demonstrated that seasonal and climatic variations can be detected and separated from the results following protracted observation periods (Kontny et al. 2005). The device is unique in that it is able to record high precision displacement in three dimensions. From these data, it is then possible to determine the angular deviations. As the device is permanently installed, data obtained over periods of several decades are directly comparable. Moreover, large displacements or deformations recorded by the optical grids are visible to the eye. This is very useful if the device is monitoring a potential landslide hazard as the relevant authorities can be contacted immediately. It is also robust and can withstand harsh environmental conditions for many decades. If it is not equipped with an automatic reading system, the device has no electrical parts and is, therefore, not susceptible to problems associated with power failure. Furthermore, it does not require any form of wireless connection or signal coverage. In situ measurements have been used to compare the optical–mechanical crack gauge and the Bragg Grating Extensometer (BGX). These measurements demonstrated that the moiré gauge is better able to record very small displacements. It also has fewer attributes that may introduce errors into the recorded data (Maniatis 2006).

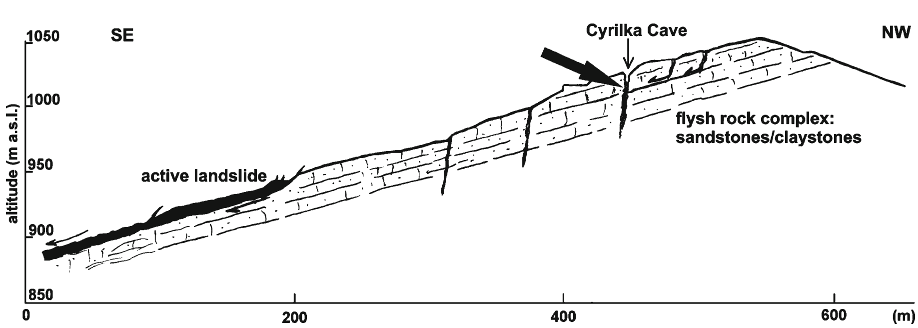
Limitations of the optical–mechanical crack gauge

The main limitations of the device are that personnel are required on-site and that monitoring is relatively time-consuming. It is, therefore, beneficial to have a number of instruments located within a comparatively small area such as at Taukliman on the Black Sea Coast. In addition, data cannot always be recorded regularly. For example, it is not possible to record data manually during the winter due to poor weather conditions and deep snow cover at Parohy in the Malá Fatra Mountains. To overcome this problem, long-term monitoring is required in order to establish the overall trend. Nevertheless, successful automatic reading trials show that these drawbacks may soon be overcome (see below).

Future developments

Recently, difficulties in automatic data acquisition and transmission have been resolved. The relatively high power supply demand for the automatic station can be resolved by using fuel cells. However, automated data processing and interpretation is needed in order to further develop this functionality. The possibility of transferring the recorded data via satellite or mobile phone network so that it could then be processed automatically would allow the device to be incorporated into landslide early warning systems. However, early warning systems are not required at the sites presented in this paper because the rates of movement are far too low to pose a threat. Clearly, given its initial aim, developing the instrument so that it requires an electrical supply for automated data reading and interpretation reduces some of its particular advantages (i.e., to work in remote locations and withstand harsh environmental conditions). Unfortunately, these problems are associated with virtually all modern monitoring and warning systems. However, as demonstrated in Table 1, the precision of the device is still better than the majority of the alternative instruments and it is unique in that it can record both displacements and angular rotations.

Fig. 7 A cross profile of the deep-seated landslide that includes Cyrilka Cave. The fissure cave is located in the upper part of the landslide (Beskydy Mountains, Outer Western Carpathians, Czech Republic)



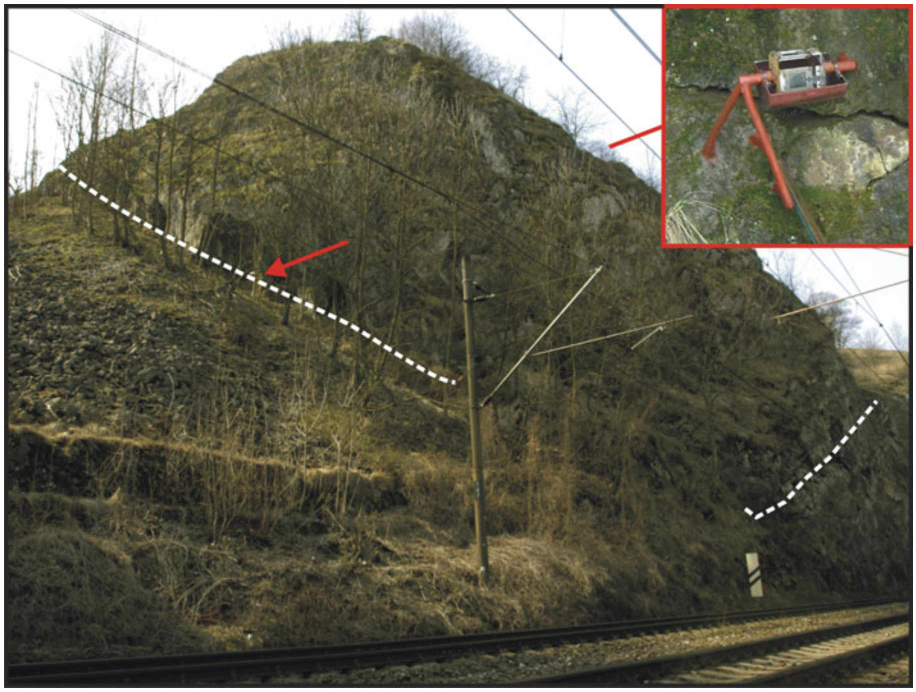


Fig. 8 View of the Tetín Railway Cutting (Czech Republic). The *inset* shows the optical–mechanical crack gauge, in situ (photo: P. Blaženín, T. Nýdl). The *white dashed lines* indicate those parts of the monitored discontinuity that are visible in the photograph

Table 1 A comparison of landslide monitoring techniques (updated after Gilli et al. (2000))

Method	Results	Typical range	Typical precision
Precision tape	Δ distance	<30 m	0.5 mm/30 m
Fixed wire extensometer	Δ distance	<10–80 m	0.3 mm/30 m
Rod for crack opening	Δ distance	<5 m	0.5 mm
Induction extensometers	Δ distance	<10 m	0.001 mm
LVDT	Δ distance	Variable (usually <0.45 m)	0.25 mm
Laser distance meters	Δ distance	Variable (usually <1,000 m)	0.3 mm
Portable rod dilatometer	Δ distance	<0.5–1 m	0.1 mm
Offsets from baseline	Δh Δv	<100 m	0.5–3 mm
Surveying triangulation	Δx Δy Δz	<300–1,000 m	5–10 mm
Surveying traverses	Δx Δy Δz	Variable (usually<100 m)	5–10 mm
Levelling	Δz	Variable (usually <100 m)	2–5 mm/km
Precise levelling	Δz	Variable (usually <50 m)	0.2–1 mm/km
EDM	Δ distance	Variable (usually 1–14 km)	1–5 mm+1–5 ppm
Terrestrial photogrammetry	Δx Δy Δz	Ideally <100 m	20 mm/100 m
Aerial photogrammetry	Δx Δy Δz	H flight <500 m	10 cm
Inclinometer	Δa	±10°	0.01–0.1°
Precision theodolite	Δa	Variable	±10″
GPS	Δx Δy Δz	Variable	5–10 mm+1–2 ppm
LiDAR	Δx Δy Δz	Variable	2.5–30 cm (ground-based) <1 m (airborne)
InSAR	Δx Δy Δz	Variable	10 mm[a] 0.25–0.5 mm for PS InSAR
Crack gauge, TM-71	Δx Δy Δz Δa	<3 m	0.01–0.03 mm

[a] InSAR precision is affected by a number of factors including the type of satellite, radar wavelength, and duration of the research

Conclusions

The monitoring of slow-moving landslides and assessment of landslide stabilisation measures may be undertaken using an optical–mechanical crack gauge called a TM-71. This paper has outlined the theoretical background and practical application of the gauge. In terms of monitoring slow-moving landslides, a range of deep-seated landslides and tectonically induced gravitational slope deformations have been presented from distinct geological and topographic settings. It has been demonstrated that the gauge is able to quantify the rate of movement with a high degree of precision and define the landslide kinematics. This information is important in order to be able to more accurately constrain the underlying cause of the landslide activity. In terms of assessing landslide stabilisation measures, it is possible to determine the length of time it takes for the stabilisation measure to become fully effective. From these case studies, it is clear that the optical–mechanical crack gauge represents a very useful and important tool for monitoring slow-moving landslides and assessing landslide stabilisation measures. It is able to provide a very precise three-dimensional record of deformation, withstand harsh environmental conditions, and record data for protracted periods.

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