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MONITORING OF TILTS AND MICROTREMORS FOR DETECTION OF SLOPE FAILURE IN THE FOREFIELD OF AN OPEN PIT MINE

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ABSTRACT. Tilt changes and microtremors were measured in the exploration gallery and on the surface of the slope in the forefield of a deep open pit mine in connection with the slope stability monitoring. Pendulum tiltmeters with the resolution limit of 0.5 nrad were installed in a free block near the surface and deep in the stable rock mass. Two vertical short–period seismographs in the gallery and on the surface and one horizontal intermediate–period seismograph with the resolution limits of 0.1 μm and 1 μm, respectively, were in operation simultaneously. The Earth's tides course on the stable block corresponded to the theoretical one for the given geographical latitude but was about three times greater in amplitude and of an opposite phase in the free block. The non–tidal part of tilt changes contained long–term drift with some seasonal variations. In the free block short–term tilt loops with several days duration were accompanied by local tremors which were probably generated by slope failures. Step change of tilt with following intermediate–period seismic noise observed in the free block was excited by seismic loading of usual size induced by quarry blasting.

KEY WORDS: tilts, microtremors, slope failure, Northwest Bohemia

1. INTRODUCTION

There are extensive brown coal open pit mines in the basin along the Krušné hory Mts. in the northwest part of the Czech Republic. One of these mines, the Czechoslovak Army Mine (CSA), has a depth of more than 100 m and according to the first project the coal reserves should be worked out close to the slopes of the mountains. The coal seam is stretched out to the height of 20 m up to the slope. The adjacent slope of the Jezerka Hill composed of orthogneiss has a maximum inclination of 35° but under the basin fill, the surface of the crystalline basement dips at an angle of up to 50 – 60°. At the same time, the peak of the hill overtops the open pit bottom by 550 m. Under the slope of the Jezerka Hill, a safety pillar was left and the excavation of the coal seam overburden strata of Tertiary sediments and Quaternary debris have occurred only in adjacency. Unfavourable engineering–geological conditions lead to the classification of the slope of the Jezerka Hill among the so–called "hazardous" slopes. Its stability was recommended to be monitored during mining operations [Rybář 1987].

Relative deformations of parts of the slope are usually checked on the surface or in boreholes in discrete intervals of several hours, days or months. The main purpose of our special tilt and seismic measurements was to record continuously extremely small motions in the exploration gallery driven into the hill long before the potential mass movement along the crystalline surface may develop. In this case the non-tidal tilts could be detected in the frequency range of $0-0.01$ Hz and seismic waves in the range from 0.05 to 15 Hz. It means that the tiltmeters record direct components of the local long-term drift and surface waves of strong distant earthquakes, seismographs record ground motion of near and local earthquakes and local seismic emissions connected with rock failures as well as the disturbing seismic signals of blasting operations. Tilts were detected with high resolution of 0.5 nrad, i.e. 0.0001 second of arc, which corresponds to the relative vertical displacement of 0.5 nm at the distance of 1 m. The limits of the seismic ground displacement amplitudes resolution are about $0.1-1\,\mu$m. The disturbing Earth's tides with the maximum semi-diurnal term are filtered with the aid of numerical filter. Some seismic phenomena as extensive quarry blasts and seismic vibrations from the near mining operations limit the possibility of evaluation of the analog seismograms. Air pressure waves excited by blasts and sonic booms from aircraft flying at supersonic speed make difficult interpretation of local seismic events of natural origin. On the other hand seismograms help us to monitor continuously the time of intensive dynamic loading of slopes by seismic waves.

In the present paper, first results of long-term tilt and seismic measurements on the slope of the Jezerka Hill in the forefield of the CSA mine are described: the first one deals with the correlation of tilt velocity and its direction with the occurrence of local seismic microtremors and the second with the initiation of tilt and long-period seismic noise by average charge of blast in the CSA mine. Both field measurements were provided by the gravimetric and seismic departments of the Geophysical Institute. Regular quarterly reports about tilts and seismic motions and problems of their measurements and interpretations that were prepared for particular methods were used in the following common analysis.

2. LOCAL CONDITIONS FOR MONITORING OF TILTS AND SEISMIC EVENTS AND THEIR EVALUATION

2.1. Location of instruments

The assessment of potential tilts and seismic emissions, before the first indubitable deformation of the slope surface will be discovered, is based on the engineering-geological data estimation. A simplified scheme of the cross-section of a part of the slope and the Jezerka exploration gallery drawn after the report of [Kolektiv Stavební geologie 1985], is shown in Fig. 1. The portal of the gallery is at the height of the safety pillar. The top of the hill is at the height of 690 m above sea level and the average inclination of the slope is about 35°. Up to the distance of 65 m the gallery is driven through debris and gravel followed by about 5 m of clay and by weathered and sound gneiss. Starting at the distance of 80 m gneiss is deformed by dislocations which mostly dip towards the open pit. From here to the

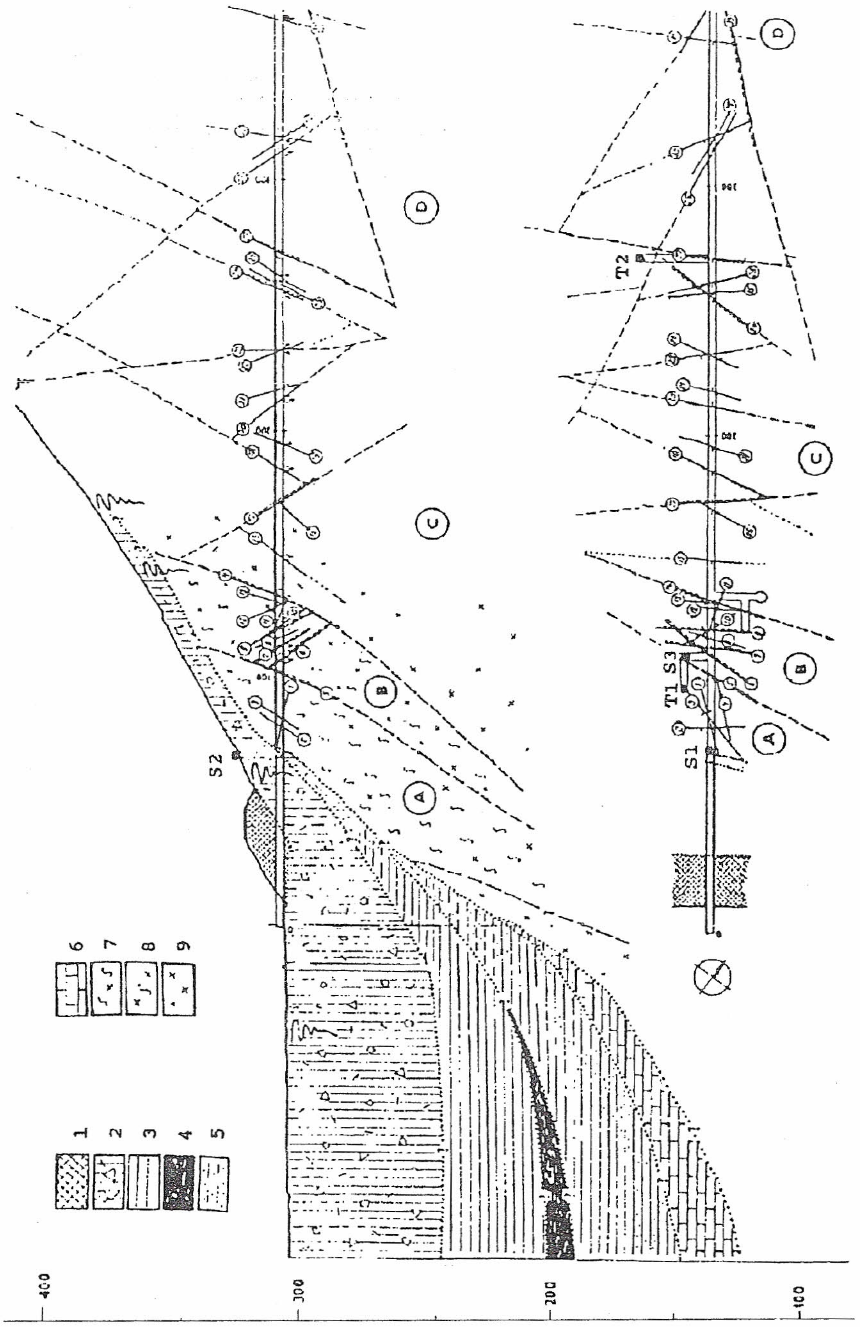

FIG. 1. Geological scheme of the Jezerka exploration gallery. A – D: geological blocks, T1 and T2: tilt stations, S1 – S3: seismic stations. 1 – talus material, road embankment, 2 – debris and gravel, deluvial and proluvial sediments, 3 – overlying clay-dominated units, 4 – coal seam, 5 – underlying sand-dominated units, 6 – Cretaceous deposits, 7 – tectonic breccia, 8 – altered gneiss of dislocation zone, 9 – weathered and/or sound gneiss.

gallery face, there are more than 35 dislocations, several of them over 0.5 m thick. The supposed geological boundaries are marked by dotted lines and the supposed course of dislocations by dashed lines.

The rock mass along the gallery was divided in four big blocks A – D with different internal fault patterns. The boundary between the first block A (beginning at 70 m) and the second block B at 102 m is not so clear due to the strong failures of both. The boundary between blocks B and C at 132 m is well defined. The stresses measured on both sides are distinctly different. According to the stress measurements in situ the shear forces cannot be permanently transferred over this failure. On the other hand the dislocation between blocks C and D, which is located deep in the massif at a distance of 269 m from the portal, has high cohesion and rocks behave here like a continuum. This is in good agreement with seismic velocity in the rock mass between the hinder part of the gallery and the slope surface that verifies block D as homogeneous for the seismic wave velocities [Hrách et al. 1984]. Variations of seismic velocity in the front part of the slope show complicated geological structure near the surface and fine dislocations found in the gallery were not traced in the cross–section by this method.

Tiltmeters were located at station T1 in block A (near the boundary with block B) at a depth of 35 m and at station T2 (approximately on the dislocation between blocks C and D) in a depth of 150 m below surface. Seismic measurements were executed at stations S1 and S3 situated in blocks A and B in the gallery and at station S2 situated on the slope surface near the central laboratory at a distance of about 530 m from the gallery. Measurements at particular places were started in 1985, simultaneous measurements have been taken at T1, T2, S1 and S2 since 1988. Regular operation at S3 started later in the fourth quarter of 1991. All stations are still in operation without any interruption. Additional data on regional seismicity were regularly supplied by the nearby temporary seismic station at Vysoká Pec at a distance of about 2 km and by the nearest seismic station of the international seismic network at Berggiesshübel (FRG).

2.2. Tiltmeters and seismometers

Basic parts of tiltmeters were composed by the photoelectric instruments of Ostrovsky [Ostrovsky 1961] which were later substituted by modern ones with capacitance pick up [Anonymous 1989]. They were adjusted at both posts to monitor the components of tilts in the astronomical directions NS and EW (with the orientation error less than $\pm 5'$ and the resolution of 0.5 nrad. The output current of tiltmeters was recorded in the central laboratory located on the surface. The compensating two–channel recorders were used for analog recording with the speed of 9 mm per hour on paper chart with 250 mm width. Every channel was equipped with automatic remote calibration and the pendulum position adjustment in the range of $\pm 25\,\mu$rad. To keep down the short–period variations with frequencies higher than 0.005 Hz additional filters – passive RC filters with photoelectric transducers and active Butterworth filters with capacitance transducers – were applied [Anonymous 1989].

The tiltmeters are highly sensitive to vertical deformations and air temperature variations in the immediate proximity (the static temperature coefficient is about 5 μrad per 1° C). Therefore, they were placed under special covers from polystyrene in rooms separated by two heat-proof doors. The temperature variations were measured by all pendulums with the sensitivity of 10^{-4} °C and their daily changes were in the limits of ±0.01° C. The so-called thermoelastic tilts excited by irregular warming of the Earth's surface are spread easily to a depth. The daily temperature deformations did not exceed ±34 nrad at station T1 and the value of ±73 nrad at station T2.

The air pressure variation is the second disturbing meteorological factor in addition to temperature changes. Unlike temperature variations the air pressure variations cannot be conspicuously eliminated because the real underground tilts (local or regional) dominate. Barometric pressure was measured by a digital barograph with a sensitivity of 0.025 hPa/digit. Tilts excited by air pressure changes have local and directionally dependent variability which makes difficulties with the application of a single correction term. E.g., the barometric mean correction was the maximum in the NS component at station T1 having a value of 28 nrad/hPa.

At station T2 ground water issued at several places. Its movement in the neighbourhood of tiltmeters could excite local tilts and therefore a special drainage system based on the principle of connected vessels was constructed. It ascertains stable and at the same time the lowest water level near the tiltmeters.

Seismometers at S1 and S2 were standard short-period vertical VEGIK models [Aranovich et al. 1974] with exchanged transducer coils and additional amplifiers and filters. Pendulum of seismometer adjusted to the free period of 1 s was sufficiently long-term stable in the environment of the gallery as well as under polystyrene cover at the surface stand. Seismometer at S3 was a horizontal type seismometer SKD with the free period of 30 s [Kirnos et al. 1969] where the original coils of electrodynamic transducer were replaced for more powerful ones and amplifiers and filters were added [Tobyáš, Soukup 1992]. It was installed to be the most sensitive to the horizontal ground displacement parallel to the gallery axis in the NW-SE direction and had a constant sensitivity up to periods of 20 seconds. Simultaneously the pendulum was sensitive to tilts along the horizontal axis that is perpendicular to the axis of maximum displacement sensitivity. Due to the electrodynamic transducer of pendulum motion the frequency response for tilts was the same as for the ground displacement; displacement sensitivity per 1 μm was twice higher than the tilt sensitivity per 1 μrad. The recorded trace on seismogram was an integral result of both components – tilt change and ground displacement – which could not be separated. For the static tilt of 5 μrad the pendulum position on the scale was shifted by 1 mm. As the voltage output of all seismometers was proportional to the velocity of pendulum motion no problems with records of long-term disturbances have arisen.

The ink-pen drum recorder with recording speed of 1 mm/s was used for the most time with the short-period seismographs and 0.5 mm/s with the long-period seismograph. Recording instruments were installed in the central laboratory by the side of ink pen recorders of tiltmeters. Daily remote control of the complete seismograph channels by means of standard electric pulses was regularly applied from this laboratory.

2.3. Standard evaluation and interpretation of records

All observed tilt data are evaluated by the same method. Relative tilts of particular component at the every whole hour of the Universal time (UTC) are measured. After the interpolation of missing values, removal of "steps" due to the adjustment of the tiltmeter in new working position, determination and introducing non–linearity of record and sensitivity, the continuous hour set of observed tilts in seconds of arc is obtained. Adjoining sets, separated by interruptions of record, are linked up with the aid of the well–known compensating current. This way the courses of both components of tilts in directions NS and EW related to the beginning of measurements are derived at each station.

In the recorded set of data the periodic part of tilts visible at the first sight is excited by gravitational attraction of the Moon and the Sun. These variations are for the further study of local non–tidal deformation processes removed by means of the Pertzev 36 hour's filter [Pertzev 1957]. It means that each uninterrupted set of data is shortened by 18 hours at the beginning and at the end. The resulting filtered data called as "non–tidal tilts" are used as a basic set for the interpretation of long–term as well as daily tilt rate in the gallery.

According to the published data about rock failure in situ the release of seismic energy is initiated if the stress exceeds about 50 % of the breaking strength. The value of the released seismic energy depends on the volume of rock failures. We were interested in "mega" processes with failures on large areas or with relative motions between geological structures [Hardy 1975a]. These can originate by particular cracks in crystalline rocks at a depth of the slope, their successive interconnection into a slip surface that should propagate upwards to the surface at the top of the slope [Košťák 1987]. Due to higher absorption of seismic signals in the range from several tens Hz to tens kHz only near sources of seismic emissions can be detected [Bláha et al. 1978; Hardy 1975b; McCauley 1975]. In our case of the observation of an extent slope area we tried to monitor seismic signals in lower frequency range 1 – 20 Hz at stations S1 and S2 to detect failures at distances from several tens of metres to a few hundreds of metres. We expected that such signals are associated with cracks from several decimetres to several metres in length and with the fracture zone up to several square metres in area. Such seismic sources correspond to tectonic ultramicroearthquakes with magnitudes of about zero. We intended to look for a correlation of long–period seismic signals recorded by the seismograph at station S3 and the tilt changes at the rate of warning state.

The main task of seismic record evaluation is the determination of real local tremors connected with local failures of brittle and tight orthogneiss pervaded by weakened zones of the slope. They are recorded as simple pulses without distinct wave types and with the recording speed of 1 or 2 millimetres per second. They look like short lines across the quiet trace. Similar pulses are created by air pressure waves excited by quarry blasts and supersonic aircraft. For their discrimination air pulses were recorded separately by electrodynamic microbarograph at the Vysoká

Pec seismic station located at a distance of about 1.8 km from the laboratory at Jezerka [Tobyáš et al. 1988]. The time delay among signal arrivals at S1, S2 and S3 and the direction of the first ground motion helped as independent entries for the discrimination of the source type.

3. TILT RATES AND SEISMIC PHENOMENA

3.1. Long- and short-term tilt rates

High sensitivity of tiltmeters makes possible to evaluate the Earth's tide course in addition to the local non-tidal tilts that are of our main interest. The Earth's tides at T2 corresponded to the standard course at the geographical latitude 50.5 °N where the maximum range is about ±100 nrad. Besides the fact that the attractive forces of the Moon and the Sun at the nearby location T1 do not differ measurably, the recorded semi-diurnal tidal waves were of about three times higher amplitude and nearly the opposite phase there [Skalský 1990; Skalský, Trešl 1992]. It is an independent evidence that blocks C and D are situated in the half-space with the elastic rock massif and blocks A and B behave to a certain extent as "free" ones.

The long-term non-tidal drift of tilt obtained at T2 during the time interval 1988 – 1993 had a stable rate of $(23.6 \pm 4.0)\,\mu$rad per year in the azimuth $186° \pm 6°$ where the azimuth is measured clockwise from the north. The drift at T1 was more complicated with an oscillatory character. The average tilt change was about $(18 \pm 17)\,\mu$rad in the azimuth $14° \pm 16°$ from March to September and $(17 \pm 10)\,\mu$rad in the azimuth $154° \pm 26°$ between September and March. The oscillatory character of tilts at T1 might be the response to seasonal temperature and precipitation variations as well as to different mining activities during summer and winter in the neighbourhood of the safety pillar. The total difference of tilts was about 40 μrad eastward in the period 1988 – 1993 [Skalský, Skalský 1994].

Differences of long-term non-tidal tilts observed at T1 and T2 agree with the different behaviour of the stability of blocks. The continuous long-term drift to the south in the compact massif at T2 might be explained by the recent uplift of the Krušné hory Mts. [Vyskočil 1981] and the oscillatory character of tilts near the border of the mine pit at T1 by the overcompensation of the general regional motion by the effect of pit uploading. These long-term tilts were not accompanied by rock failures with seismic effect (the "aseismic" tilts) and the recorded tilts were the only evidence of the local microdeformations. We have to point out that the tilt change of 50 μrad (i.e. about 10″) corresponds to the relative vertical displacement of 0.05 mm at a distance of 1 m (that is the length of the rigid plate under the tiltmeter). It is not clear to what distance the extrapolated deformations are real.

As a measure of the standard long-term tilt rate relative daily tilt changes are used. Their average and maximum yearly values are given in Table 1 for the time interval 1988 – 1994.

The average tilt changes at T2 had a tendency to decrease in the last four years. The maximum daily tilt changes obtained in 1988 were not reached. Daily tilts as well as their maxima have systematically increased at T1 since 1990. High values

TABLE 1. Non–tidal daily tilts in nrad

Station	T1		T2	
Year	Average	Maximum	Average	Maximum
1988	300	1891	91	572
1989	134	558	94	373
1990	115	674	77	276
1991	213	1517	63	165
1992	288	2317	65	165
1993	329	2094	69	383
1994	488	2666	54	247
1988 – 1994	**266**	**2666**	**74**	**572**

in 1988 were probably affected by the blasting operations right in the gallery where the water reservoir in sound gneiss was built.

There is not yet quantitative empirical measure of a hazard level for the slope stability evaluation based on the non–tidal tilt rate. The present estimation of the rate for the warning state that was once improved during tilt measurements has been valid since 1989. The tilt change warning rates are set at 1 μrad per day and 15 μrad per month in arbitrary direction for T2 in a deep crystalline–based setting and at 5 μrad/day and 50 μrad/month for T1 in the moving block [Košťák 1990].

3.2. Non–tidal tilts, local microtremors and long–period noise

A detailed course of non–tidal tilts is monitored by the vector course of instant relative tilts at 0:00 UTC every day. An example is shown in Fig. 2 for the first quarter of 1994 when more frequent local microtremors were recorded since the last quarter of 1993. The midnight is marked by a shorter line and the date is marked at longer lines. The dimension of tilts is the second of arc ($1'' \simeq 5\,\mu$rad). The time of occurrence of a local seismic event is marked by an arrow and $'x'$ is added before the arrow when more events were detected during one day.

Nearly monotonous tilt of about $1.15''$ to the south was derived at T2 in this interval, the same as in the previous long–term observations. The course of tilt at T1 was more complicated with short changes of tilt direction and some tilt loops. The frequency of local seismic events first recorded in 1991 (1 or 2 per quarter of a year) increased at the end of 1993 when a change of tilt direction occurred. Since then up to the middle of 1995 the maximum frequency of these events was 15 per quarter of a year. Simultaneous observations of tilts and seismic events confirm the decreased state of slope stability.

Another interesting case of the detected local ground motion is illustrated in Fig. 3. Seismogram (A) of the intermediate horizontal seismometer at S3 shows a nearly quiet trace without a visible response to the common meteorological microseisms in the lower part. Due to the tilt of the instrument base zero position of pendulum shifted up to the limiting screw and the seismograph was out of regular

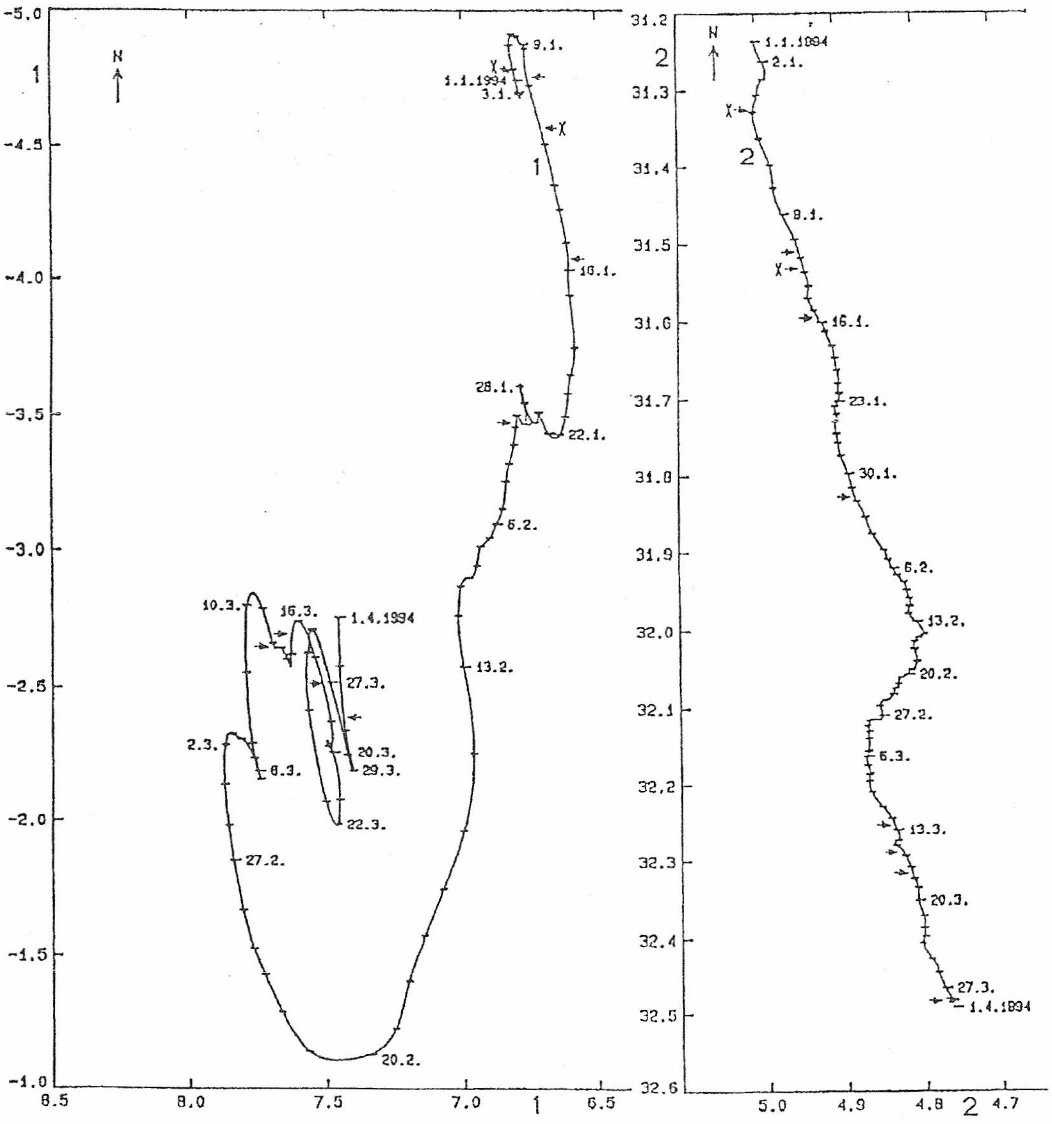

FIG. 2. Vector diagram of non–tidal tilt changes at T1 (1) and T2 (2) and time of local microtremors recorded at S1 and S2 in the first quarter of 1994.

operation. At 11 hours 38 minutes UTC a standard blast from the local mine was recorded and since that time irregular noise with periods of about 10 seconds was recorded till the next day early morning. Then again only regular meteorological microseisms were recorded. The tiltmeters at T1 (Fig. 3, B) detected similar course of non–tidal tilts as that shown in Fig. 2. It means that they made a loop or nearly loop with the direction of tilts from SE to NW, then to the E and then back to SE. This way two independent instruments detected the same effect of ground motion [Tobyáš 1995].

It means that the pendulum position has changed due to the tilt of the instrument

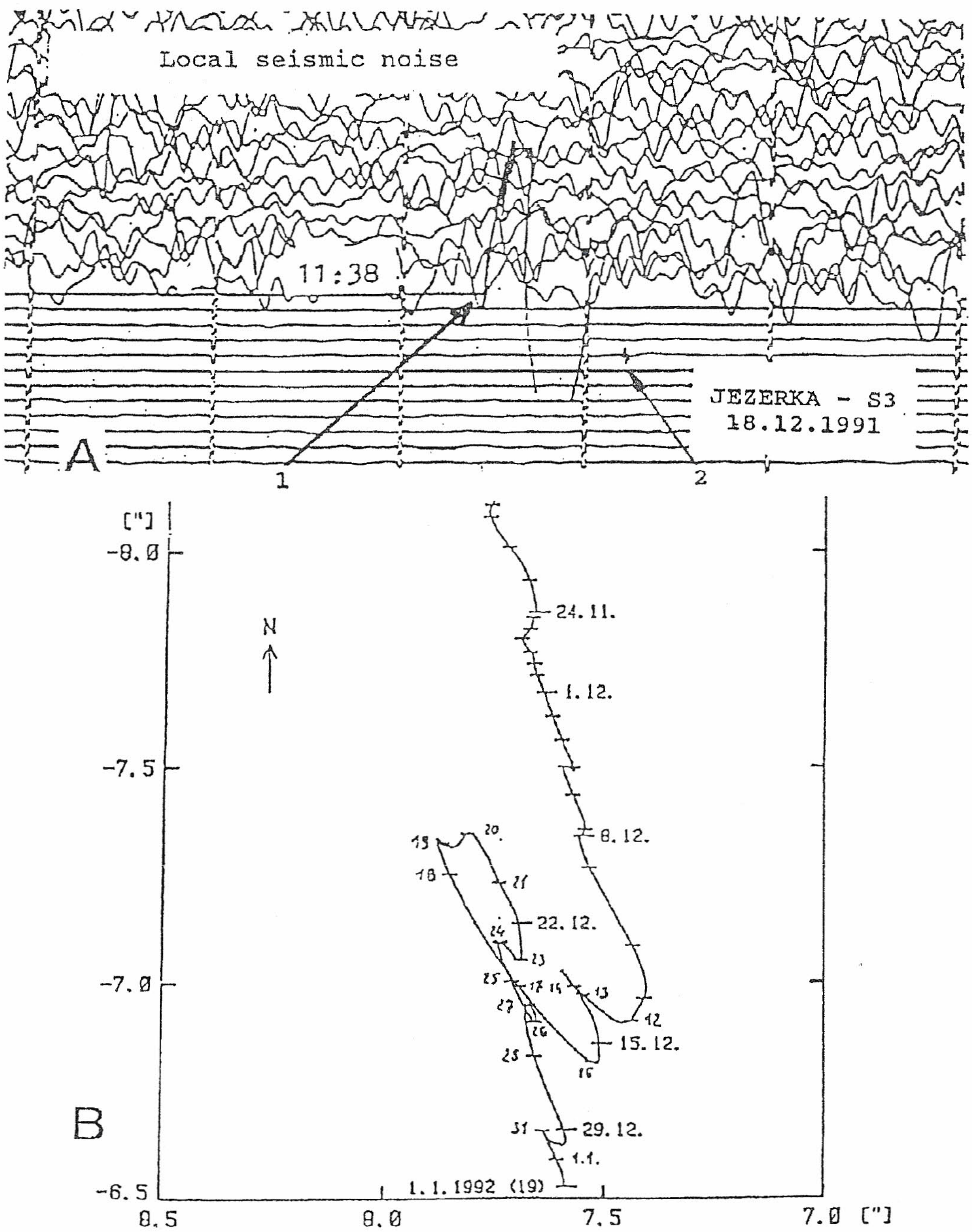

FIG. 3. A part of the seismogram recorded at S3 on Dec. 18, 1991 (A) and the tilt changes course at T1 from Nov. 20, 1991 to Jan. 1, 1992 (B). 1, 2: quarry blasts in the CSA and the Libouš mines.

base and started to operate quite "automatically". According to the records of seismographs at the nearest station at Vysoká Pec we suppose that the seismic efficiency of the blast was quite normal and that the motion in the gallery was excited due to the lower stability of blocks A and B at that time.

4. CONCLUSIONS

Continuous monitoring of non–tidal tilt changes and occurrence of local seismic microtremors allowed to detect fine motions in the free blocks of the Jezerka Hill slope and to differentiate spontaneous influence of gravity on the slope with a weakened stability or the combined influence of gravity and seismic loading. Because of the safety pillar that had been left in the open pit the observed effects did not display a distinct progressive tilt rate and tremor frequency. Since September 1993 automatic digital record was put in operation with transmission of collected data through a modem to the computer centre of the gravimetric department at Příbram once a day. It helps to increase the accuracy, reliability and fast evaluation of tilt changes. Analog records in the central laboratory at the foot of the slope allow the guard to check the situation without any interruption and to carry out additional discrete measurements on the slope without any delay. To improve the reliability of seismic event discrimination by the laboratory staff another microbarograph was installed near the S2 station in 1995.

The long–term monitoring of tilt changes and seismic tremors in connection with slope sliding is useful for the acquisition of data about failure of rocks in natural conditions with dimensions between laboratory model tests and volume of weak earthquake sources. Much attention should be devoted to both the following of the measurements up to the potential total destruction of the slope and to the assembly of factors that accelerate the preparatory phase and the course of slope sliding itself. With further progress of mining in the CSA open pit mine next "hazardous" slope with worse geological conditions by Jezeří will be reached in the near future and the recent experience with the monitoring of tilts and seismic phenomena can be applied also there in the local exploration gallery.

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