Paper

Measuring Electromagnetic Emissions from Active Landslides

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Abstract—The paper describes the mechanism of electromagnetic emission generation in active landslides and measuring techniques. Special attention is given to electromagnetic emission fields. The author proposes an original system for measuring both continuous and pulsed magnetic emission of landslides. For such measurements boreholes must be drilled in the landslide. It is essential that the tubing constituting the borehole's lining be made of a material which does not attenuate magnetic fields. Besides its primary function, i.e. the registration of landslide magnetic field activity, the system can be used for the structural inhomogeneity of rock strata examination subjected to considerable stresses. The results of examinations of active and inactive landslide in Poland are presented. The post-extraction cave in the SMZ Jelsava Mine in Jelsava, Slovakia, is presented too.

Keywords*—*electromagnetic emission, landslide, sliding-down force, slip plane, slope stability.

1. Introduction

Landslides occur everywhere, cause similar damage in human infrastructure to earthquakes, volcano eruptions, floods, etc. [1]. The term "landslide" describes a wide variety of geological processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these [2]. The materials may move by falling, toppling, sliding, spreading, or flowing. A simple model describes landslide as a complex geologic body, consisting of a layers combination having contrasting physical properties.

It has been established that landslides when active become a source of electromagnetic radiation, which is due to the considerable mechanical stresses in the landslide's body and the friction resulting from the displacement of the landslide's moving layers, along slip surface direction, under sliding-down force F, as shown in Fig. 1. As a result, energy is released, which intensity depends on the landslide body composition (clay, gravel, rock, etc.) and landslide excitation degree. One of the forms of this energy is electromagnetic radiation, which often has an impulse character. This phenomenon usually appears a long time (even a few days) before landslide visible deformation or what worse abrupt disaster.

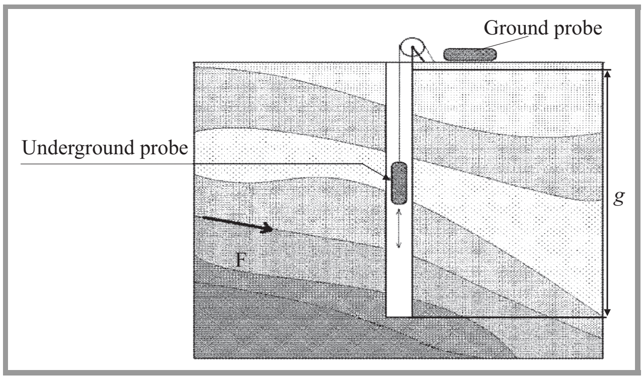

Fig. 1. Field measuring technique.

It has been found that landslide electromagnetic emission is within the low frequency range, practically it does not exceed 50 kHz. Depending on construction of measuring equipment, electric or magnetic component of emitted electromagnetic field can be measured. This is corroborated by the results of investigations carried out on the Stavlichar landslide, reported in [3]. Magnetic field emission with the maximum intensity at frequencies about 10 kHz was registered there. Also significant was the intensified electromagnetic emission observed in periods of the landslide's heightened activity, mainly after longer rainy periods [2]. Similar conclusions are drawn in [4] where the results of long-term research conducted on the Krasnaja Dubrava landslide are presented. The maximum intensity of emission occurred in 1–50 kHz range. Electromagnetic emission below 20 kHz was registered on the Karolinka landslide [5]. It is significant that the highest emission levels were appeared when large blocks of rock situated close to each other and other landslide layer inhomogeneities occurred in the landslide's body. Interesting results of the complex landslides in the Uzh Valley investigations are reported in [6]. The phenomenon often is called Pulsed Electromagnetic Emission (PEE) [5], [7], [8].

The most common unit is pulses per second (PPS), but this is entirely conventional. PEE fields are registered by a probe lowered in a measurement borehole having depth g. Depending on realization, probe reacts to the electric or the magnetic component of the electromagnetic field. An additional receiver may be placed on the ground surface in the immediate vicinity of the borehole to register the overground electromagnetic fields affecting the measurements. For rapid landslides with high velocity rate of slope movement, only surface receiver can be used [3]. In this case the magnetic aerial was placed on the ground and shielded against interferences only by the metal case. Signal from aerial fed an impulse counter with sensitivity var-

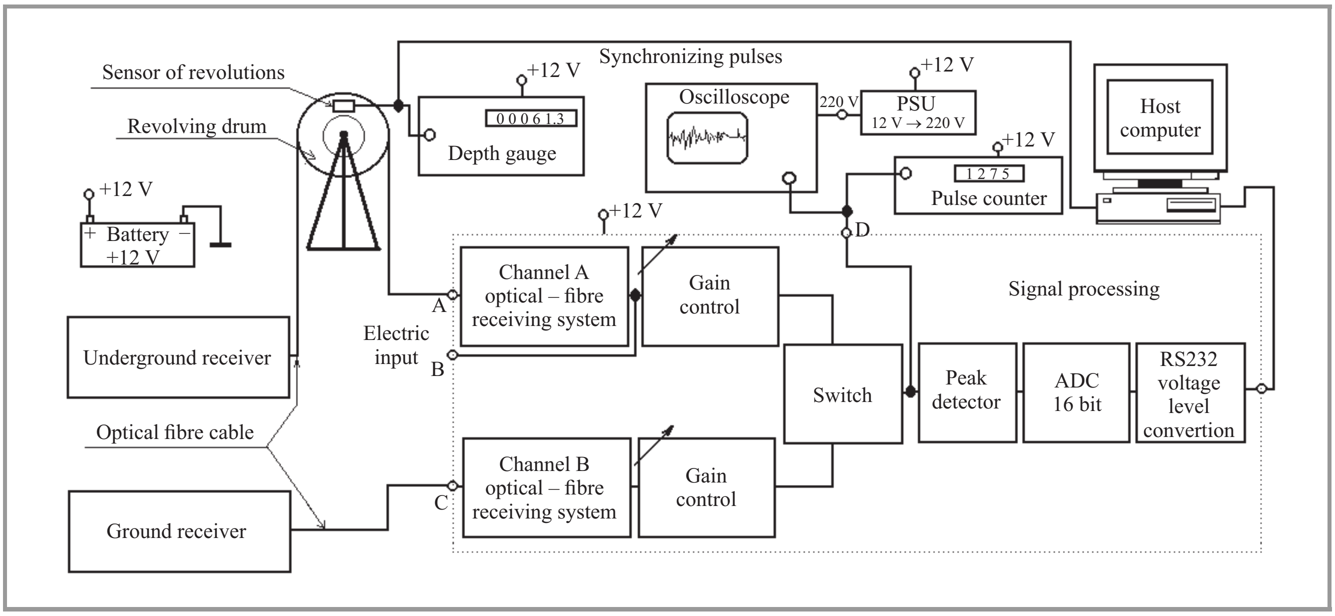

Fig. 2. Block diagram of system for measuring electromagnetic activity of landslides.

ied in the range 20–50 μV. Number of pulses indicated intensity of landslide movement processes. Other interesting measurement equipment is a portable device called the Cerescope [9]. This magnetic field receiver, reveals maximum sensitivity at 12.8 kHz, counts number of pulses in the 100 ms period. Measurements results can be stored in a build-in RAM memory and then easily transferred to the host computer.

The main sources of electromagnetic radiation from active landslides are piezoelectric effect, cracks formation process and streaming potential. The piezoelectric effect is dominant in landslides rich in sand, gravel and rock inclusion, situated mainly in the layers adjacent to the slip surface. In this case electromagnetic emission is observed in the frequency range of 10^2–10^6 Hz [10], [11]. Under mechanical stress micro and macro-cracks are formed inside landslide body. This process is often accompanied by electromagnetic emission with a wide frequency spectrum, even up to 10 MHz [12]–[16]. Streaming potential originates when an electrolyte is driven by a pressure gradient through a porous medium, forms Electrical Double Layer (EDL) [17], [18]. Fluid flow in the landslide mass is treated as an electrolyte. High pressure regions in the landslide body cause disturbance in fluid flow and its mechanical oscillation in capillaries, what provokes electromagnetic emission [3], [19]–[21]. This mechanism is dominant in the landslides consist of clay, without bigger inclusions of rock [22], [23]. In real landslides electromagnetic emission phenomenon is caused by all of the mentioned above sources in different proportion.

2. Landslide Activity Measuring System

There are not any commercial magnetic field strength meters available on the market, which can be adopted to examine magnetic activity of landslides. In this situation the proper measurement system was designed and built by the author. It is able to register both the pulsed and continuous magnetic field component along the measurement borehole down to depth g (Fig. 1), and its detailed description with the investigative method presentation, is included in patent application [24]. Measurements can be performed using two probes, referred to as measuring receivers. One of the probes, called an underground probe, is lowered in the measurement borehole at a prescribed measuring step Δg through the predicted slip plane (see Fig. 1). In the model system the measuring step is 5 cm. The other probe constantly registers the magnetic field near the borehole. From the measurement point of view, the field represents an interfering signal. It has been found that many active landslide areas are characterized by a narrow range of intensified magnetic field emission frequency. Hence the measuring probe should have the properties of a band magnetic field receiver with mid-band frequency f_o corresponding to a frequency for which the landslide magnetic activity is most intense. After laboratory tests [25], for the model system f_o = 14.5 kHz was adopted, but can be varied (even during the tests). The receiver's sensitivity is $4 \cdot 10^{-6}$ A/m, at f_o = 14.5 kHz. A block diagram of the measuring system is shown in Fig. 2 and general view of system is presented in Fig. 3. The signal from the measuring receivers is transmitted by 120 m long armored fibre-optic lines whereby the system's sensitivity to electromagnetic interference is greatly reduced. In this situation the underground receiver can be treated like a spot-receiver, receives only magnetic field strength at depth g. Sockets A and C are the inputs for the optical receivers for respectively the underground probe and the surface probe. The optical signal is converted into an analogue domain and amplified in the range 1–10 V/V. In addition, an electrical input (socket B) is provided for the signal from the underground probe. A signal switch with a unit amplification constitutes another block. Next, the output signal is fed into a peak detector and can be observed on oscilloscope (output D). As an option an pulse counter is provided which directly indicates the activity of the landslide at depth g. It is connected also to point D. The constant voltage corresponding to the trace's instantaneous peak value is converted by an A/D converter which at its output provides digital information in the RS232 interface. The obtained momentary constant voltage value informs us about the intensity of the landslide processes. The measuring signal (output E) is fed into a computer and stored on its disk. In field conditions the measuring system is supplied with a voltage of 12 V from a car battery. The measuring receivers have their own battery power supply.

Fig. 3. General view of measuring system: 1 – revolving drum with optical fibre, 2 – underground receiver, 3 – processing block, 4 – ground receiver, 5 – computer.

Described above measuring system is innovative compared with solutions presented in other papers [3], [5], [7], [9]. Connection of the underground receiver with the processing block by means of an optical fibre and equipped this probe with the independent non-disruptive battery supply (without a DC/DC isolated power converter or similar device), significantly reduces influence of electromagnetic disturbances. It allows increase receiver's sensitivity to $4 \cdot 10^{-6}$ A/m, at $f_o = 14.5$ kHz. Similar, even sophisticated devices [5], [7], without an optical connection between receivers and other units, reveal the maximum sensitivity no better than 10^{-5} A/m. In contrast to other measurement devices, presented measurement system can register the continuous and pulsed magnetic field component. The measurement device is equipped with many useful features, like the portable revolving drum with the optical fibre leading system, the full two-channel signal processor and the depth counter, which automatically triggers the computer's signal input. To increase functionality, combination the measurement device with a battery powered low power consumption embedded computer is possible.

3. Field Measurements

Preliminary field measurements by means of the landslide activity measuring system were carried out on the Falkowa landslide in Nowy Sącz, Poland (see Fig. 4) in August 2005.

Fig. 4. Measurement sites location: Jaroszów, Nowy Sącz and Jelsava.

During that period the landslide exhibited any activity, which was objectively confirmed by measurements concurrently performed by means of an inclinometer. The cause of the landslide low activity was a prolonged long dry period, which occurred before the measurements. The landslide is composed of solely a mass of clay flowing in its entire volume without any distinct slip planes. The probe was introduced into the measurement boreholes drilled for the inclinometric measurements. The boreholes were lined with a plastic tube, which does not damp electromagnetic fields. The registered traces of magnetic field along the profiles of the boreholes named O1 and O2 are shown in Figs. 5a and 5b.

Then measurements were carried out on the active landslide Jaroszów, situated near Wrocław, Poland (see Fig. 4), during long time periods, between August 2005 and September 2006. The landslide body is composed of clay mixed with gravel with inclusion of small pieces of sandstone and dolomite blocks. The multiple slip surfaces are situated in the landslide lower part, at depths between 10–17 m. Results of landslide activity, e.g. cracks, faults, are visible on the surface of landslide too, see Fig. 6. Investigations in the Jaroszów landslide were carried out using the existing boreholes B1 and B2 made for inclinometric measurements. The boreholes' lining has the form of a plastic tube. The registered curves of magnetic field component along the boreholes and auxiliary information about the monthly rainfall level [25] are presented in Figs. 7a and 7b.

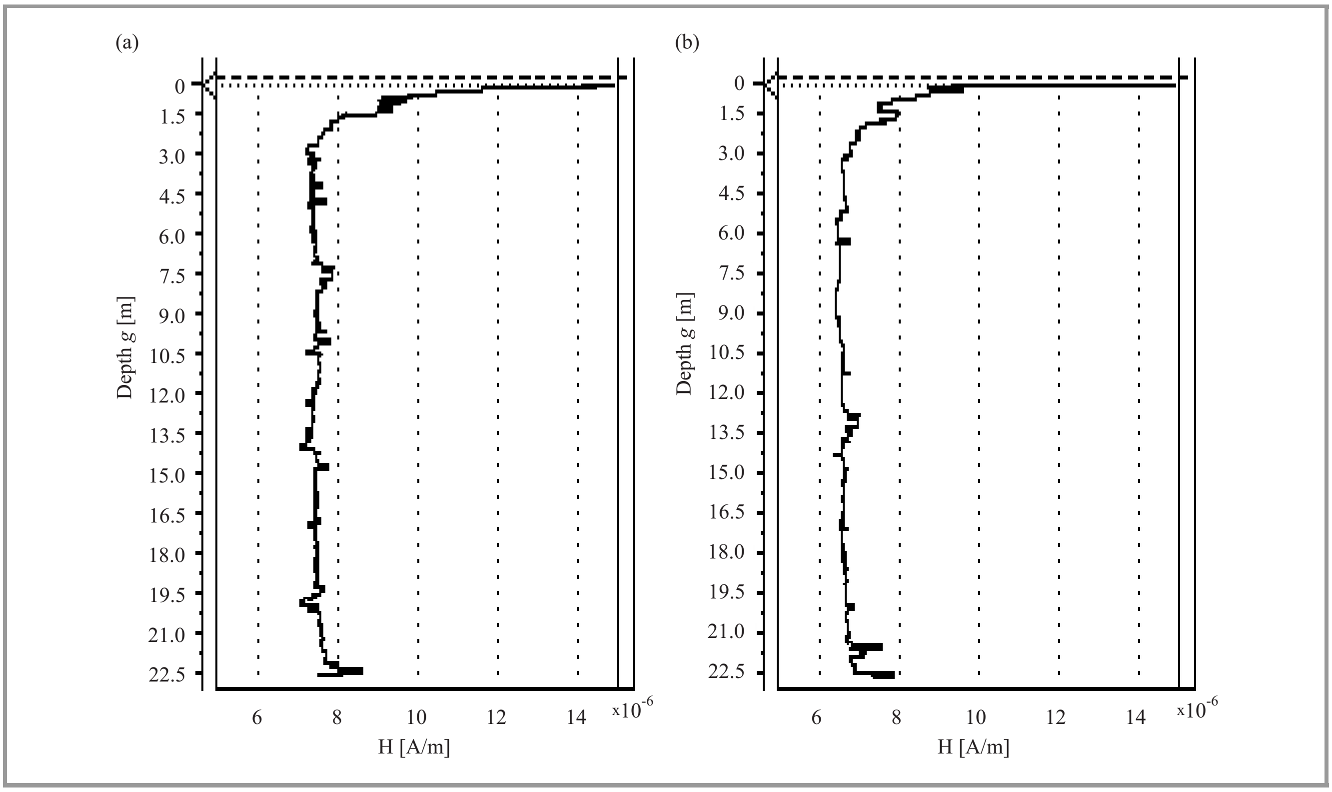

Fig. 5. Variation of magnetic field strength versus depth along: (a) O1 and (b) O2 boreholes on the Falkowa landslide, at $f_o = 14.5$ kHz.

The next measurements were carried out in September 2005 in the SMZ Jelsava Magnesite Mine in Jelsava, Slovakia, see Fig. 4. The measurements were performed in boreholes drilled in the roof of a cave created when the magnesite deposit was worked out. The roof is composed of mainly grey dolomite with inclusions in the form of small magnesite blocks or agglomerations of magnesite blocks. The results of the magnetic emission measurements presented in Figs. 8a–8d are supplemented with cross sections of the rock mantle surrounding the cave, made available courtesy of the SMZ Jelsava Mine.

Fig. 6. Surface and local road degradation on the Jaroszów landslide.

In all cases boreholes were located far from human settlements, roads, electric traction or other objects which might be a significant source of electromagnetic interferences.

4. Measurements Discussion

All the presented results of magnetic field strength measurement were carried out with the system equipped with both the underground and on ground receiver. The magnetic field traces registered on the Falkowa and Jaroszów landslide and in the SMZ Jelsava Mine area show initial rapid increase in magnetic field strength, in the form of a rapidly falling impulse which already at a depth of 1–3 m decays and the registered magnetic field returns to the current background level, as evidenced by the traces for all boreholes: O1, O2, B1, B2 J43, J129, J133 and J135. The above phenomenon is a disturbance, which occurs in each measurement. It is due to the strong penetration of various overground electromagnetic fields into the ground. In this case, such interference is not eliminated to a substantial degree by the auxiliary overground receiver (see the measuring system description).

The measurements carried out on the Falkowa landslide revealed only near-surface interfering signals. The fact that no magnetic field emission was registered in the boreholes at the depths at which slip planes occur was due to two factors:

- during that period the landslide exhibited any activity,
- there are no rock blocks in its body – the stresses generated in rock strata or blocks are the source of the most intensive magnetic field emission.

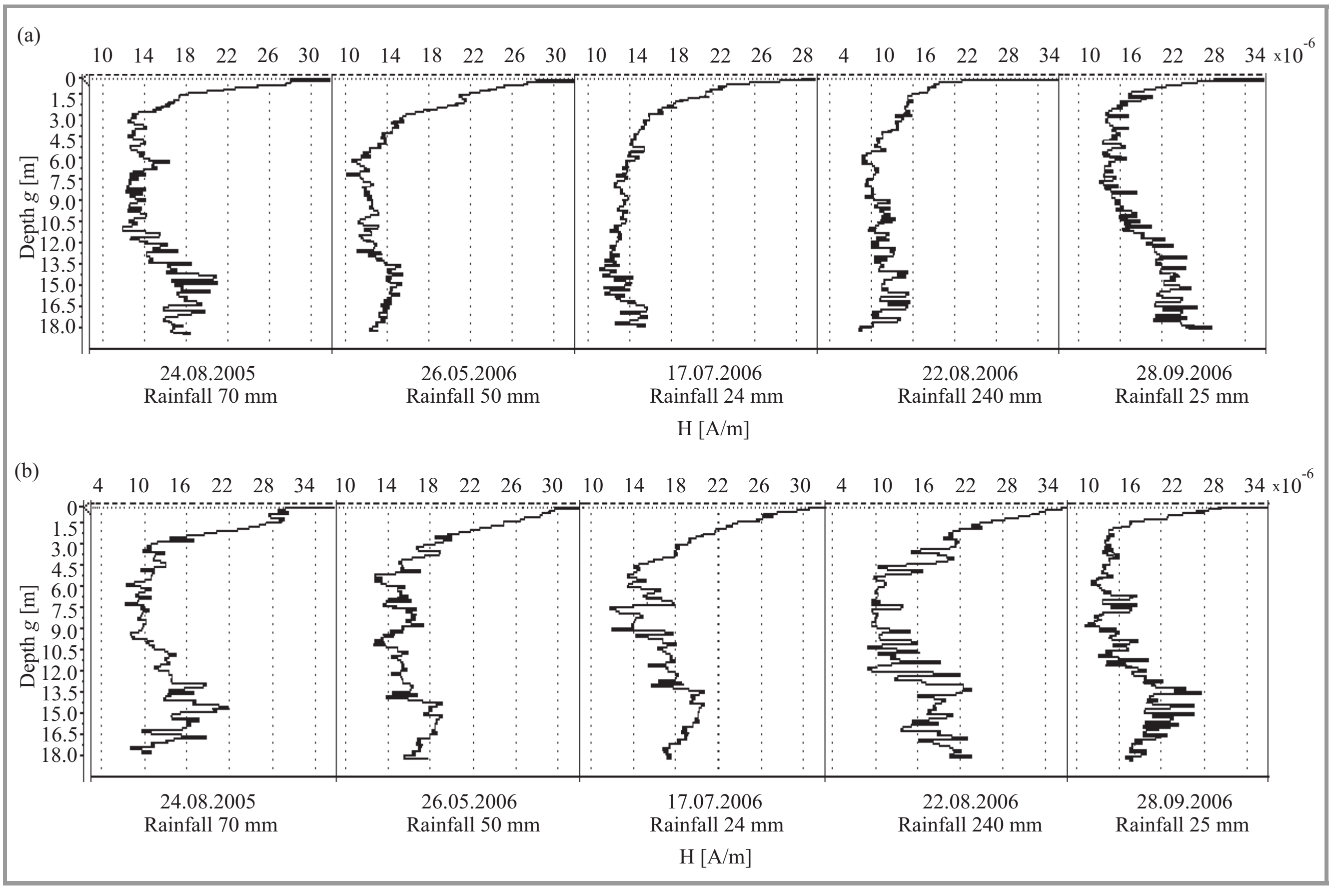

Fig. 7. Variation of magnetic field strength versus depth along: (a) B1 and (b) B2 borehole on the Jaroszów landslide, at f_o = 14.5 kHz and monthly rainfall levels.

This is corroborated by the measurements carried out in the magnesite mine in Jelsava, where distinct magnetic emission of the rock strata in which stresses occurred was observed. Also the rate and continuity of flow of the landslide is important. The Falkowa landslide periodically (after rainy periods) exhibits increased activity. The inclinometric measurements show that the flow rate of the landslide is rather low – maximum 70 mm per annum. For the last three years the annual average flow rate of the landslide strata has been about 25 mm. This means that it is too slow for the method to be effective. According to [3], the minimum flow rate of a landslide composed of only clayey materials needed to generate a magnetic field emission measurable by equipment with a sensitivity similar to that one used in the measurements should be about 4 mm per 24 h.

The Jaroszów active landslide exhibits continued slip movement at depths 1–17 m, what was proved by various geological examinations and inclinometric measurements during period of electromagnetic measurements. Internal tension of landslide body causers visible deformation on its surface, what is shown in Fig. 6. Mainly after prolonged rainy periods the Jaroszów landslide increased its activity. This fact is clearly seen in Figs. 7a and 7b, revealed a sharp increase in magnetic field emission strength in August 2005 and August – September 2006 period at depths corresponded to slip surfaces presence.

An analysis of appropriate series of measurements carried out in Jelsava reveals that each borehole is characterized by a peculiar trace of magnetic field intensity versus depth, what is shown in Figs. 8a–d. Within the measurement series for each borehole one can notice recurring anomalies which are the basis for the further interpretation of the results. An analysis for borehole J135 (Fig. 8d) shows a sharp increase in magnetic field emission activity at depths 30–40 m and 55–75 m. The geological section shows that magnesite blocks occur in the dolomite at the above mentioned depths. According to intensity of the registered emission one can conclude about the size of the inhomogeneities in the rock mantle. An analysis of the magnetic field emission in borehole J129 (Fig. 8b) also shows that at a 35–55th meter of its depth there is a distinct anomaly attributable to the occurrence of four magnesite blocks situated close to each other. Whereas comparing the measured magnetic emission profiles with the geological section of borehole J43 (Fig. 8a) one can see that the boundaries between the magnetic field emissions originating from magnesite layer situated close to each other become blurred. This may be also caused by substantial levels of magnetic field emissions originating from rock blocks lying close to each other.

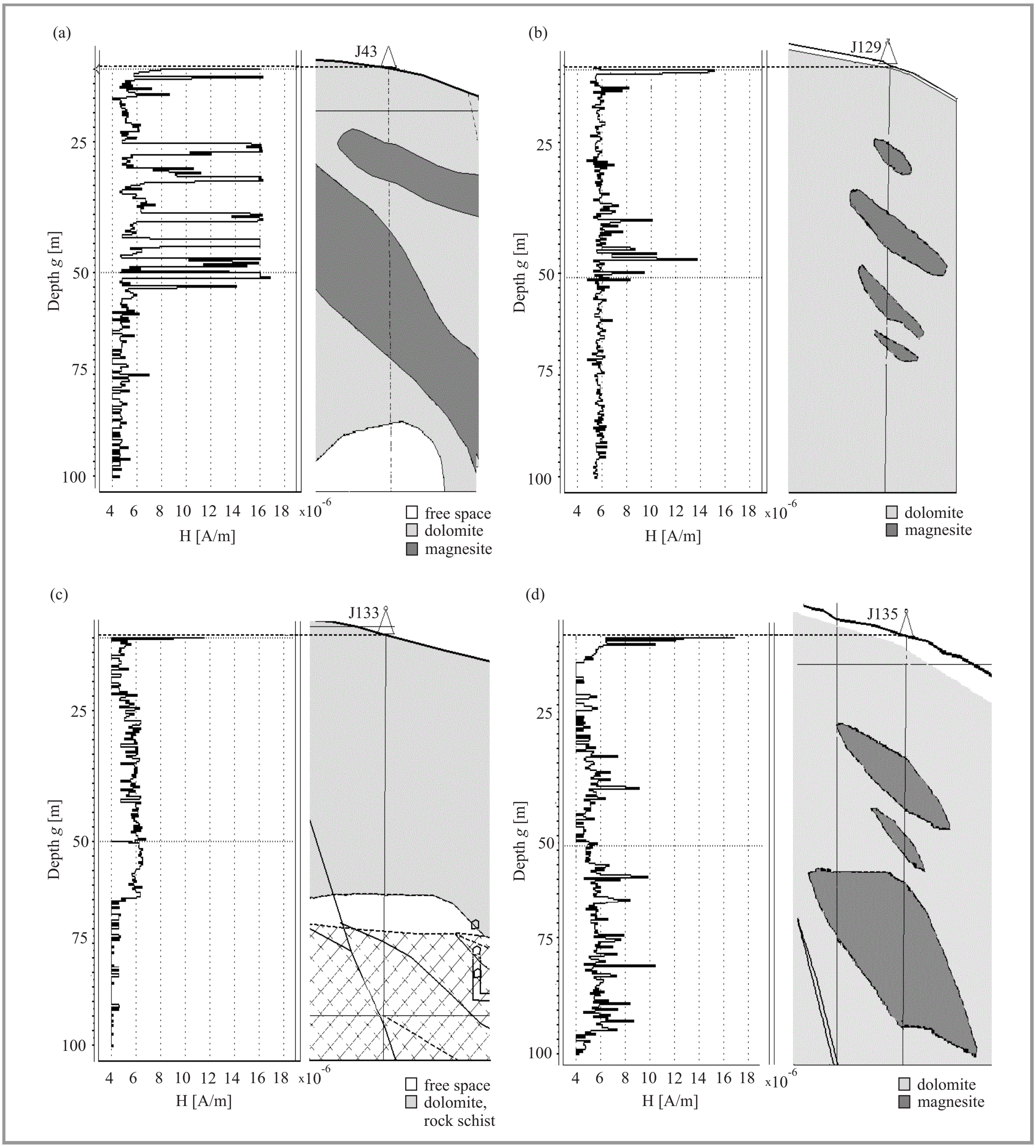

Fig. 8. Variation of magnetic field strength versus depth along: (a) J43, (b) J129, (c) J133 and (d) J135 boreholes drilled in the roof of a cave in Jelsava, at f_O = 14.5 kHz.

The emission for borehole J133 (Fig. 8c) is clearly divided into two zones. One zone, extending from the surface of the ground down to about the 55th meter, exhibits magnetic emission corresponding in the geological structure mainly to dolomite with small inclusions of other rock materials. No magnesite blocks occur here. The other zone is practically devoid of emission, which is due to the presence of a large post-extraction recess originating at the borehole J133 55th meter. Generally, all the measurements show the absence of magnetic emission in empty post-extraction spaces. This seems to be natural for the considerable, at such low magnetic field intensities, distances from the emission sources, i.e. the rock strata. The cause of the magnetic emission may be the mutual pressure exerted by different types rock blocks, e.g., a magnesite block compressed by dolomite strata. The registered increased magnetic emission of compressed magnesite blocks confirms the observations made during laboratory tests [25] in which magnesite specimens being crushed exhibited higher emission levels than those exhibited by dolomite specimens subjected to crushing. The knowledge of stresses distribution in the rock strata along the profiles of the investigated boreholes would be very helpful. Then one could determine the relationship between the stresses in the magnesite strata and in the dolomite strata and the intensity of the magnetic field emitted by them. It should be noted that the presence in the ground of magnetic field components originating from other sources (not directly connected with the activity of the investigated rock strata) cannot be excluded. The presence of such fields should be treated as an additional source of interference. This problem is considered in [26], [27].

5. Summary

Electromagnetic emission measurement from active landslides and other geophysical complex structures is a new useful method of slope stability assessment. Classical geological methods (e.g., inclinometric, GIS and piezometer analysis, etc.), do not provide continuous monitoring of landslide condition. Measurements are carried out only, e.g., once per week, month – not continuously, what is their main disadvantage. With the developed measurement system, it is possible to create an early warning system, which will be able to warn, when electromagnetic emission strength, provokes by landslip process, exceed the critical level. To this end proper magnetic field sensors, continuously register electromagnetic emission, should be placed in the boreholes, protected by non-conductive pipe, at depths where the slide process is expected. For broad landslide areas, with many measuring points, it is also possible create a battery powered sensors mesh network. Similar miniaturized measurement systems can be used in coal mines to warn against rockburst. It has been established [12], [13] that rock before mechanical destruction reveals decreased level of electromagnetic emission.

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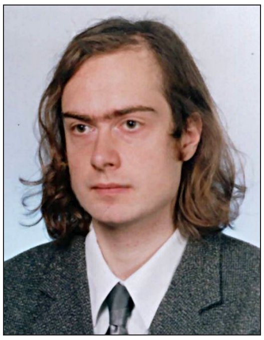

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