

INNOVATIVE GROUNDWATER TABLE MONITORING USING TDR TECHNOLOGY

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ABSTRACT: This paper introduces an innovative and economically convenient measurement system that is based on a novelty method of installation, operation and remote control technology for ground watertable measurement. The technology is based on TDR (Time Domain Reflectometry) that employ a unique hollow coaxial cable. Installation is performed by CPT/DP penetration testing equipment, which in its nature, is relatively light, versatile, operative, and is not demanding of manpower or machinery. This method brings benefit to currently unreachable sites ex. steep slopes, places with little or no road access, option for setting up additional probes on existing structures etc., as the method doesn't require conventionally truck-mounted drilling rigs. Electronic origin of measurement offer the possibility of probe networking, remote sensing, automatic data acquisition and evaluation through developed software. Proposed measurement system has been laboratory tested, calibrated and installed on various sites over past 6 years in Slovak republic.

Keywords: TDR, Groundwater Level Measurement, Coaxial Cable, Penetration Testing

1. INTRODUCTION

Slope instability has been an issue worthy of concern in applied soil mechanics engineering for decades. It causes serious losses to both private and public sectors all over the globe and has been studied throughout history by many researchers, scholars, academics, and practitioners from different perspectives. Unfortunately, landslides with severe consequences regularly occur in potentially unstable areas, which are not covered by a soil monitoring system due to lack of funding or priority. There are several factors which initiate soil movement, but the principal trigger mechanism is the presence of water, generally formed in ground water level - phreatic or pressure combined with geological, geomorphological and climate conditions in certain time and locality. Over past 10 years, demand for automatic and remote sensing monitoring systems for collecting required geotechnical data, mostly soil deformation and water level, initiated competition between electric based techniques. TDR technology (Time Domain Reflectometry) is a technology that has been employed for a variety of uses in electrical engineering. Since the 1930's, TDR has been used for examining electrical properties of cables and transmission lines, and measuring electrical properties of organic liquids. Universality and further enhancement of the technology during the 1990 is led to monitoring of landslide slope movements, soil electrical conductivity or water content measurement in soil [3]. TDR uses principle of radar, where an electric voltage pulse is reflected from point where inconsistency of electrical

properties occurs, e.g. a damaged cable, change in dielectric constant of environment and is sent back. Signal travel time, hence time domain, and known propagation velocity determine localization of signal reflection. The development of a new type of TDR probe for measuring groundwater level was started in order to meet requirements for reliable, low cost, remote sensing capable and possibility of installation in vehicle inaccessible areas. Proposed groundwater level sensing is based on air-filled coaxial cable resembled to an open pipe piezometer. Measurements of water level are determined by travel time analysis of the reflected signal from air-water interface, hence TDR piezometer. Laboratory testing and calibration as well as field installation experiments and actual field data are presented.

2. LANDSLIDES MONITORING IN SLOVAKIA

The role of monitoring of negative factors of slope deformation is a highly demanded in Slovakia. Altogether, more than 5.25 % coverage of land is endangered by slope deformations, furthermore about 98 km of motorways and 67 km of railway lines pass through landslides. The most known landslides occurred in Handlova in 1953, Riecnica in 1961 and in Velka Causa, Kapusany, Nizna Mysla in 2010. The most often trigger factor of slope deformations in Slovakia is effect of underground water combined with geological, geomorphological and climate conditions. According to statistics of national geological institute of Dionyz Stur, localization of slope deformation is mostly in zones of Carpathian flysch

belt, then Neovolcanic, West Carpathians and Central Carpathian Paleogene zone.

The reason to implement TDR technology for deformation and groundwater monitoring in Slovakia was to find an attractive alternative to other water level measurement systems that would benefit in rapid and relatively easy installation, cost efficiency and suitability for remote sensing. Research and design of piezometer for phreatic water table based on TDR started in 2008 and later installed on three localities in Northern Slovakia – Dolna Tizina, Povazska Bystrica, and Brusno-Chrenovec. First two of them are presented in the article.

3. LABORATORY TESTING

In the period of 2008-2010 laboratory testing of new type piezometer for phreatic water table based on TDR principle was carried out. Sensing probe was formed by a waveguide – hollow coaxial cable where dielectric is an air. This construction format allow water freely penetrate the cable according to principle of communicating vessels where water balances out to the same level as it settles. Determination of water level is principally trivial while air is replaced by water that has different dielectric constant Eq. (1) which results in signal reflection at exact point.

$$\epsilon_w = K_w \cdot \epsilon_0 \quad (1)$$

Testing scheme plotted on Figure 1 consisted of a tube representing a borehole, measuring waveguide - hollow coaxial cable and TDR unit. Two types of sensing waveguides with 50 Ω impedance were tested Heliflex HCA 58-50 with 5/8'' and HCA 12-50 with 1/2'' diameter. Water level was increased and decreased in many cycles while taking measurement by TDR and controlled and compared with measuring tape.

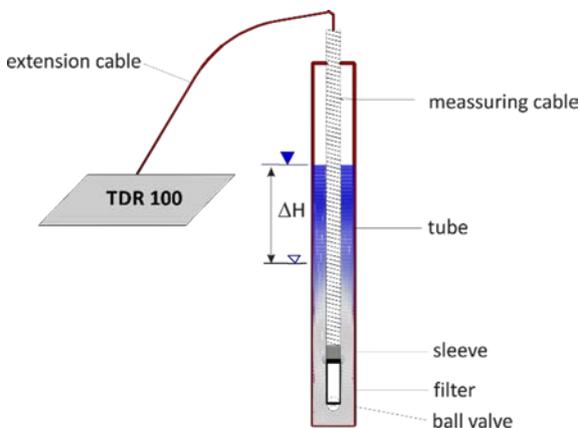


Fig. 1 Laboratory testing scheme

Acquired data were sorted, compared and analyzed. As in radar, TDR utilizes the roundtrip travel time in the air section to determine the water level, proper data reduction method of travel time determination and calibration of pulse propagation velocity was needed. The precise time of reflection that corresponded the position of the interface-required calibration, due to different velocity of propagation in lead and sensing cable. Waveguide with 5/8'' diameter was feasible due to larger inner space where water can freely intrude.

4. FIELD INSTALLATION AND TESTING

In 2010 and 2011 TDR piezometer probes were installed on three test sites in northern and western Slovakia, situated on slopes that are inaccessible to trucks. These sites were selected intentionally to confirm feasibility of installation using penetration test equipment.

4.1 Installation method

Installation of TDR piezometers were to small diameter holes of ø 35 - 40 mm carried out by static CPT or dynamic penetration equipment. Detail of special adaptor needed for installation to certain depth is shown on Fig. 2.

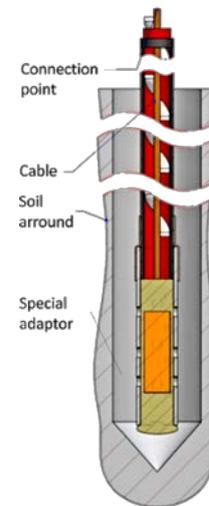


Fig. 2 Detail of installation using penetration equipment

Principally, determination of TDR ground water level is similar to standpipe piezometer which is based upon equilibration of standpipe water pressure with that at the measurement point and pore pressure is calculated Eq.(2):

$$\Delta u = \Delta h \cdot \gamma_w \quad (2)$$

4.2 Test site Povazska Bystrica

Test site is located near town Povazska Bystrica in Northern Slovakia, where new bypass road was built in cut off of the hill in difficult geological conditions that was affected by landslides. Area belongs to the territory of hill called St. Helena, which ranks to orographic northwestern nesses of Strazovske Mountains. The relief in the studied area reflected the obvious connection between the resistance of rocks against weathering processes and morphology of the terrain. Orlovske layers make the top of the area of interest and are represented predominantly by sandstone containing thin marls or marlits inserts. Soft shape of lower part of the area is made up with spherosiderit layers with low resistance against weathering processes resulting in eluvial-deluvial deposits of clayey sediments that are susceptible to sliding.

Geotechnical monitoring of slope deformations was performed on the site mainly by inclinometers, and 3D inclinometers. Water pressure in layers important for stability calculations was measured

by open pipe piezometers in certain depth level. There were two or more significant water level horizons. In badly accessible places (I8, I8-P) TDR inclinometer and TDR piezometer were installed.

TDR piezometer I8-P was installed in the bore made by DP equipment. Sensing waveguide had length 7.9 m capturing the first water level horizon. Before embedding the waveguide, calibration measurement had to be performed with no water. Figure 3 shows two measurements of ground water level, the first one as of April 2010 and the most recent from June 2014. It is obvious that sensing waveguide is still in good condition and doesn't suffer any damage or deterioration of key parameters. As seen on the figure, apparent waveguide length is 8.6 m and has to be adjusted by signal velocity propagation $v_p = 0.92$. This is due to different propagation velocity in lead coaxial cable and sensing waveguide. Therefore, while taking measurements, the parameter v_p is set to 1.0. Last taken data say that groundwater was in 3.68 m depth. It must be noted that 0.6 m section of waveguide sticking out above the ground level should be subtracted.

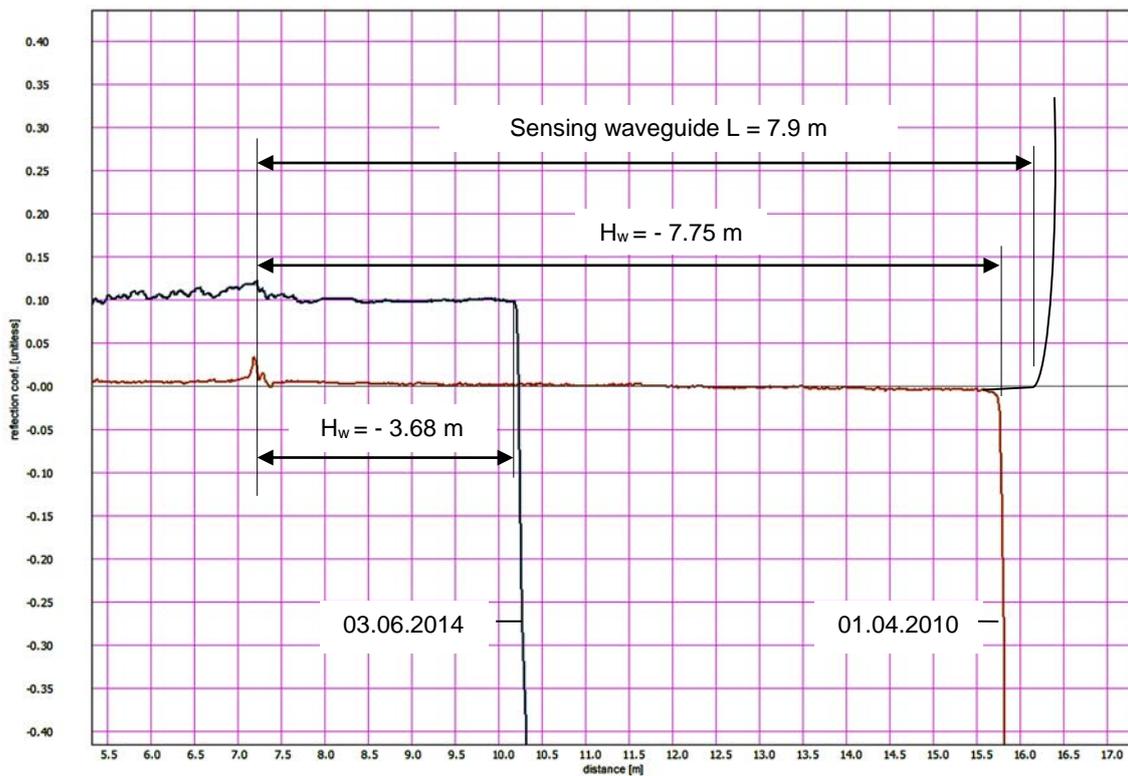


Fig. 3 Measurement of GW level in piezometer I8-P at Povazska Bystrica

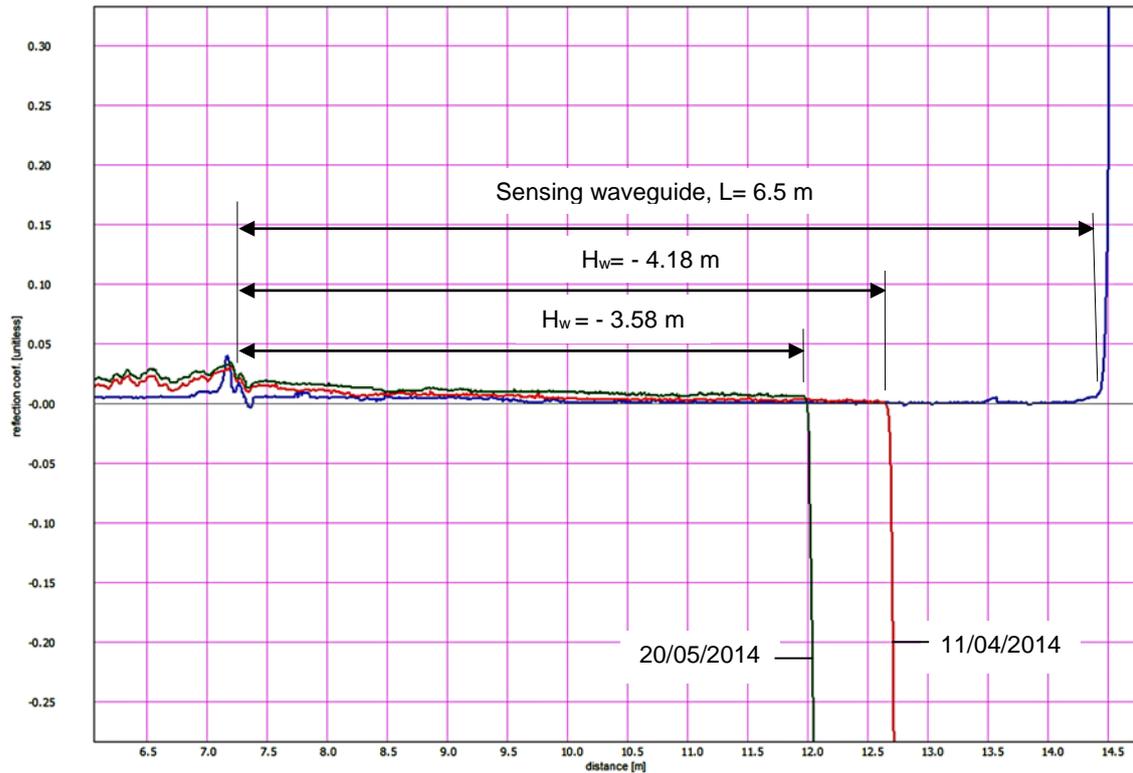


Fig. 4 Measurement of GW level at locality Dolna Tizina

4.3 Test site Dolna Tizina

Locality of Dolna Tizina is situated in Central Carpathian paleogene. According to the geomorphological division of the territory of the Slovak Republic, considered territory belongs to Fatra-Tatra region of Zilina basin subunit Varinske Podolie. Based on the documented visible external signs, whole area of slope deformation is a part of morphologically significant landslide activity, which has length of about 250 m and width of 130 meters. Within this relatively extensive active area two smaller partial landslides were identified in transportation and accumulation part. The primary cause in the development of landslide activity was erosion of local stream in the bottom part of area of interest.

Buoyancy effects of water and the presence of disturbed shear zones were the main trigger factors of the slope deformation. Ground water level at the time before remediation works reached the accumulation zone level 2 m below the ground surface, while two distinct horizons of GW level were found. Effectiveness of drainage wells, in particular, showed a significant decrease of buoyancy effects in the transportation and accumulation zone of the landslide.

The activity of slope failure started in 1997 due to excessive torrential rainfall when local road and fencing were damaged. In 2001, the landslide was

re-activated when creeping slide mass at accumulation zone endangered adjacent properties. In 2003, re-initiated movements were threat again. Later in 2006, slope failures extended to sides with decrease of terrain in the active zone from 2 to 2.5 m. Soil movement caused structural damages of house no. 358 that remained uninhabitable.

Owing the soil instability, a TDR piezometer was installed in 2010 employing dynamic penetration technique to create a bore. Waveguide calibration preceded its soil embedment. The same process with measured data described in previous section should apply. Figure 4 shows data of ground water dynamics in last 1.5-month span. Relatively rainy end of April 2014 and beginning of May 2014 resulted in rise of groundwater level of 0.55 m.

5. AUTO DATA EVALUATION USING MEDIAN FILTER

In the next section, principles of automatic ground water level determination are proposed. Since the measurement system consists of cables that are not perfectly homogenous, noise can have notable influence on its performance. While TDR signature is a non-linear signal, the powerful method has to be employed for waveform examination with respect to recognition of lead cable that can be several hundred meters long and sensing cable, which length is particularly up to 30

m. For automatic data evaluation, perhaps, the most fundamental form of signal manipulation is that of filtering, which describes a rule or procedure for processing a signal with the goal of separating or attenuating a desired component of an observed signal from either noise, interference, or simply from other components of the same signal. It is obvious from the TDR signal, that water level is in the point where sharp transition represented by waveform drop occurs. Localization of this point by numerical methods is a way to automatic water level detection. Therefore, use of running median filter - a nonlinear signal processing method in this application aiming at exploiting the system's nonlinearities or the statistical characteristics of the underlying signals. The running median was first suggested as a nonlinear smoother for time-series data [1].

Regarding definition of the running median filter, a discrete time sequence $x(n)$ of N samples in time instants $n = 0, 1, 2, \dots, N$ must be defined. The running median passes a sliding window of length M samples over the time sequence $x(n)$ that selects, at each instant n , an odd number of M consecutive samples to comprise the observation vector $\mathbf{x}(n)$ as Eq.(3):

$$\mathbf{x}(n) = [x(n-M+i)], \quad i=1, 2, \dots, M \quad (3)$$

The median smoother operating on the input sequence $x(n)$ produces the output sequence $y(n)$, defined at time instant n as Eq.(4):

$$y(n) = Median\{\mathbf{x}(n)\} \quad (4)$$

Setting the symmetric observation window, operator $Median\{.\}$ is then defined as follows Eq.(5):

$$y(n) = Median\{\mathbf{x}(n)\} = \tilde{x}((M+1)/2) \quad (5)$$

, where $\tilde{x}((M+1)/2)$ is the $((M+1)/2)$ -th element of the vector $\tilde{\mathbf{x}}(n)$. Vector $\tilde{\mathbf{x}}(n)$ contains the same elements as the vector $\mathbf{x}(n)$ but the elements in vector $\tilde{\mathbf{x}}(n)$ are in ascend order of their values.

The reason of applying a running median filter consists in smoothing neighboring extreme values of the signal with no effect on subsequent evaluation.

After the waveform is smoothen using median filter as shown on Fig. 5, signal is processed in decision block and threshold procedure is performed finding discrete time index m , where signal exceeds pre-set level. It means, that index m is smallest positive integer that satisfies condition

$y(m) > threshold$ or $y(m) < threshold$, meaning the former no water presence in cable, the latter water presence in cable.

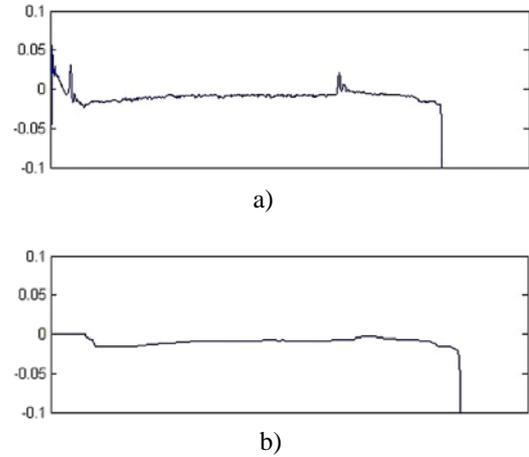


Fig. 5 TDR waveform a) as measured b) after median filtering

Adjusted index m value corresponds to signal travel time from transmitter to water level and back. Since propagation velocity is known, distance from reference point to water level can be obtained from Eq.6:

$$L_m = \frac{1}{2}(t_2 - t_1)v_L \quad (6)$$

, where L_m is the length of sensing waveguide, t_1 is reflected signal travel time in lead cable, t_2 is reflected signal travel time in measuring waveguide. Hence, value of L_m is measured water level. Issue of system calibration is not discussed while quality and manufacturing precision of sensing waveguide guaranties its material characteristics.

6. CONCLUSION

Despite the fact that air-dielectric TDR piezometer was first proposed by [3] in 1990's, its wide spread hadn't been yet very successful. A new type of TDR probe for groundwater level determination proposed in the paper, comprising of waveguide Heliflex HCA58-50 and Campbell Scientific hardware. We developed software for taking measurements and data processing. First field application was set 4 years back in 2010, when TDR piezometers were installed into a small diameter bore of 30-40 mm, created with equipment for dynamic or static penetration. This technique was proved feasible and viable on condition that skilled and experienced manpower. Recent data from two probes are presented showing that sensing waveguide as a key element, is in good condition and still work.

Assumption of clogging the inner space by fine particles of clay surrounding soil was not confirmed due to special sand filter at the bottom. Even if the clogging was the case, a probe replacement could be possible both physically and economically. The large pulse reflection at the air-water interface allows measurement at considerable distances, therefore when multiplexed one TDR point can cover area of hundreds meters benefitting in hardware cost reduction. New areas can be monitored with no or reduced access roads that suffer from potential of geohazard risk, e.g. steep slopes, dense forests, active landslides.

Electric nature of the technology is perfect not only for remote sensing but for automatic data processing and evaluation. Running median filter is used for smoothen TDR signature reducing noise, interference or reflection in the cable and for revealing water level at exact point where threshold value is exceeded.

Couplings and connectors are probably the weak link in the chain as they are exposed to humid and corrosive environment when installed unprotected.

Next research will head to building remote sensing measuring system with automatic groundwater level detection and improving reliability of the technology.

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8. REFERENCES

- [1] Arce R.A., Nonlinear Signal Processing. Hoboken, New Jersey: John Wiley & Sons, 2005
- [2] Chung C. et al., New TDR waveguides and data reduction method for monitoring of stream and drainage stage.
- [3] Connor K.M., Dowding C.H., Geomeasurements by Pulsing TDR Cables and Probes, Boca Raton: CRC Press, 1999
- [4] Decky M., Drusa M., Pepucha L., Zgutova K. Earth structures of transport constructions, Harlow, Essex: Pearson, 2013. 180 p., ISBN 978-1-78399-925-5
- [5] Dowding, C. H., O'Connor, K. M., Geomeasurements by Pulsing TDR Cables and Probes, Boca Raton: CRC Press, 1999. ISBN 08-493-0586-1
- [6] Drusa M., Cheben V. 2012. Implementation of TDR Technology for Monitoring of Negative Factors of Slope Deformations, Proceedings of SGEM 2012 Vol. II. ISSN 1314-2704 p.143-150, DOI: 10.5593/sgem2012
- [7] Drusa M., Cheben V., Prohovniková P., 2013. Functionality of TDR Piezometers and Inclinometers for Monitoring of Slope Deformations In: Sgem 2013: 13th international multidisciplinary scientific geoconference: conference proceedings. Vol. II. - Sofia: STEF92 Technology, 2013. - ISBN 978-954-91818-8-3. pp. 157-164.
- [8] Drusa, M., Cheben, V., Stolarik, L., Prohovnikova, P.: Laboratory calibration of TDR measurements of underground slope deformations. In: Theoretical foundation of civil engineering: XXII Slovak - Polish - Russian Seminar: Žilina, Slovak Republic, 09.09.2013 - 13.09.2013. Moskva : Izdatelstvo ASV, 2013. ISBN 978-5-93093-986-6. - S. 437-442.
- [9] Drusa, M., Cheben, V. Bulko, R. 2014. New Technologies Implemented In Geotechnical Monitoring on Transport Constructions, In SGEM 2014 Proceedings, Book 1 Vol.2 pp. 651-656, ISBN 978-619-7105-08-7, DOI: 10.5593/sgem2014B12
- [10] Marschalko, M., Yilmaz, I., Kristkova, V., Fuka, M., Kubecka, K., Bouchal, T.: An indicative method for determination of the most hazardous changes in slopes of the subsidence basins in underground coal mining area in Ostrava (Czech Republic). Environmental Monitoring and Assessment 02/2012; DOI:10.1007/s10661-012-2571-7
- [11] Muzik, J.: Analysis of Geotechnical Structures Using Meshless Local Petrov-Galerkin Radial Point Interpolation Method, In SGEM 2014 Proceedings, Book 1 Vol.2 pp. 651-656, pp. 41-48, ISBN 978-619-7105-08-7, DOI: 10.5593/sgem2014B12
- [12] Segalini, A, Carini, C.: Underground Landslide Displacement Monitoring: A New MMES Based Device, Landslide Science and Practice, vol. 2, 2013, Early Warning, Instrumentation and Monitoring - Margottini, Canuti & Sassa Eds. - Springer London pp. 87-93 - DOI: 10.1007/978-3-642-31445-2
- [13] Yilmaz, I., Marschalko, M., Yildirim, M., Dereli, E, Bednarik, M., (2012) Preparation of the GIS based kinematic slope instability and slope mass rating (SMR) maps: an application to a railway route in Sivas (Turkey). Bulletin of Engineering Geology and the Environment. DOI: 10.1007/s10064-011-0384-5

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