Quantification of cable deformation using TDR-experiments

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ABSTRACT. *Time Domain Reflectometry (TDR) is gaining widespread attention as a cost-effective method to monitor ground movements in both soil and rock. It has been used successfully for a number of years to monitor deep-seated failures in soil deposits and for monitoring many different kinds of movements in rock masses. A chief benefit of using this technology is that it can be a cost-effective means of remotely monitoring the effectiveness of slope hazard remediation measures. TDR cannot determine the actual amount of movement. In this paper, laboratory results of an experiment using opencast mine model and press machine with RG-6 coaxial cable were conducted. The results indicated a relationship between the reflection coefficient and the shear displacement. Increase in the deformation was proportional to the reflection coefficient. Reflection coefficients were 0.093 to 0.415 for RG-6 coaxial cable, for the displacement of 0mm to 7 mm in the model and 0.135 to 0.91 for 0mm to 4.4mm deformation from load 0Kg to 1200Kg. This investigation is a part of Science and Technology Project sponsored by Ministry of mines, Government of India (GOI).*

RÉSUMÉ. *La réflectométrie temporelle (TDR) attire de plus en plus l'attention en tant que méthode rentable de surveillance des mouvements de la terre dans les sols et les roches. Au fil des années, il a été utilisé avec succès pour surveiller les dommages profonds dans les sédiments du sol et pour surveiller de nombreux types de mouvements dans les masses rocheuses. L'un des avantages principaux de l'utilisation de cette technologie est qu'elle peut constituer un moyen rentable de surveiller à distance l'efficacité des solutions apportées aux risques de pente. Le TDR ne peut pas déterminer la quantité réelle de mouvement. Dans cet article, des tests de laboratoire ont été réalisés avec un modèle à ciel ouvert et une presse à câble coaxial RG-6. Les résultats ont indiqué une relation entre le coefficient de réflexion et le déplacement en cisaillement. L'augmentation de la déformation était proportionnelle au coefficient de réflexion. Les coefficients de réflexion étaient de 0,093 à 0,415 pour le câble coaxial RG-6, avec un déplacement de 0 mm à 7 mm dans ce modèle et de 0,135 à 0,91 pour une déformation de 0 mm à 4,4 mm d'une charge comprise entre 0 kg et 1 200 kg. Cette enquête fait partie d'un projet scientifique et technologique financé par le Ministère des Mines du gouvernement indien (GOI).*

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KEYWORDS: *time domain reflectometry (TDR), coaxial cable, reflection coefficient, opencast model.*

MOTS-CLÉS: *réflectométrie temporelle (TDR), câble coaxial, coefficient de réflexion, modèle à ciel ouvert.*

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1. Introduction

Cable is perhaps the most commonly used transmission line type for RF and microwave measurements and applications. Apart from the communication application coaxial cable is working as a sensor in TDR for pre-detecting ground deformations in underground and surface mines. There are different types of coaxial cables available with different characteristic impedances (Anderson *et al*., 1996; Anderson and Welch, 2003). The basic principle of TDR is similar to that of radar. In TDR, a cable tester sends a pulse voltage waveform down a cable grouted in a borehole. If the pulse experiences a change in the characteristic impedance of the cable, it is reflected (Figure 1). This can be caused by a crimp, a kink, the presence of water, or a break in the cable. The cable tester compares the returned pulse with the emitted pulse and determines the reflection coefficient of the cable at that point. Electrical energy travels at the speed of light in a vacuum but travels somewhat slower in a cable. The TDR generates a very short rise time electromagnetic pulse that is applied to a coaxial system which includes a TDR probe for rock mass deformation and samples and digitizes the resulting reflection waveform for analysis or storage. The elapsed travel time and pulse reflection amplitude contain information used by the on board processor to determine quickly and accurately rock mass deformation for slope stability measurement or user-specific, time-domain measurement. A 250-point waveform should be collected and analysed in approximately two seconds. Each waveform should have approximate up to 2,048 data points for monitoring long cable lengths used in rock mass deformation or slope stability. TDR for determining ground movement requires reading the cable signature at regular time intervals. Ground movement, such as slip along a failure zone, will deform the cable and result in a change in cable impedance and a reflection of energy. This change can be used to determine the location of shear movement.

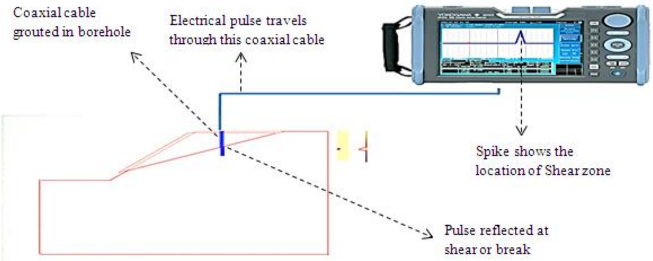

Figure 1. Basic Principle of TDR

2. Reflection theory

A signal traveling along an electrical transmission line will be partly, or wholly, reflected back in the opposite direction when the traveling signal encounters a discontinuity in the transmission line, or when a transmission line is terminated with other than its characteristic impedance. Reflection coefficient describes the ratio of reflected wave to incident wave at the point of reflection, where circuit parameter has a sudden change. This value varies from -1 (for short load) to +1 (for open load), and becomes 0 for matched impedance load. The coaxial cable used in a TDR system provides a one-dimensional path for propagation of an electromagnetic wave which is generated by a voltage pulse from the TDR. The cable consists of outer and inner conductors separated by a material with a known dielectric constant. Propagation of the voltage wave along the coaxial cable is controlled by four fundamental properties of the cable: inductance *(L*), resistance (*R*), capacitance (*C*), and conductance (*G*). For relatively short cables (< 100 m), resistance and conductance can be assumed to be constant. The PC-TDR Software presents the graphically as a plot of the reflection coefficient, versus Length of cable. The distance between the TDR and deformity (X) can be precisely determined by the round-trip travel-time (T_R) and propagation velocity (Vp) of the cable.

$$X = Vp\ T_R/2 \tag{1}$$

3. Structure of cable

Coaxial cable has a core wire, surrounded by an insulation jacket which is a PVC material (Figure 2). Normally the shield is kept at ground potential. Then it is surrounded by a copper mesh which is often constituted by braided wires. The inner dielectric separates the core and the shielding apart. The central wire carries the RF signal, and the outer shield is considered to prevent the RF signal from radiating to the atmosphere and to keep outside signals from interfering with the signal carried by the core. The electrical signal always travels along the outer layer of the central conductor, and as a result, the larger the central conductor, the better signal will flow. Coaxial cable is a good choice for carrying weak signals that cannot tolerate interference from the environment or for higher electrical signals that must not be allowed to radiate or couple into adjacent structures or circuits (Anderson and Welch, 2003). Coaxial cable is typically designed as 50 ohms, 75 ohms, and 93 ohms depending upon the application.

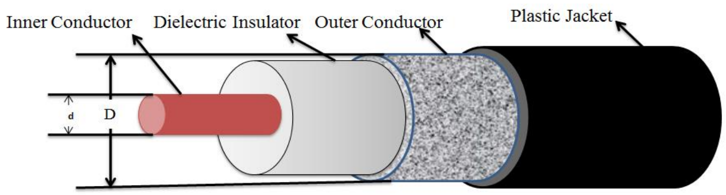

Figure 2. Structure of cable

4. Laboratory experiment

A laboratory test was carried out on the TDR system to check the response of the TDR with the applied deformation. RG-6 type of co-axial cable is selected, and the reading is taken in the PC-TDR software. Laboratory set-up used to test the response of the TDR to applied deformation is shown in Figure 5. The response of TDR is then to be determined with deformation applied precisely mm by mm using the open cast model. RG-6 is used for the test with the specifications:

RG-6 is used for the test with the specifications:

(I) Velocity of propagation (V_P) = 66% = 0.75

(II) Maximum Operating Frequency = 1 GHz

(III) Diameter(mm) = 6.5 mm

(IV) Operating temperature(C) = -40^0 to $+80^0$

(V) Characteristic Impedance(Ω) = 75

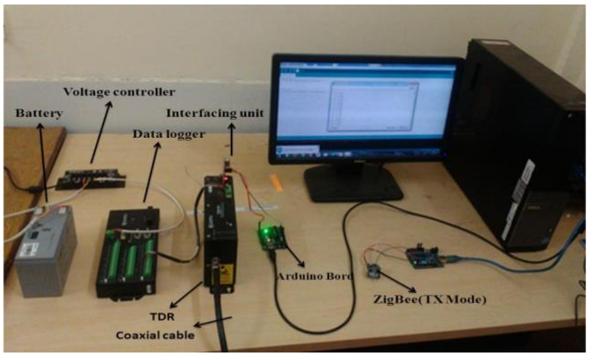

Figure 3. Electronic instruments used for a laboratory experiment

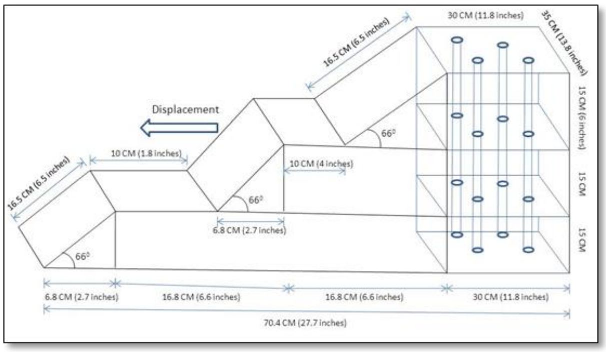

Figure 4. Opencast Block Model for laboratory test

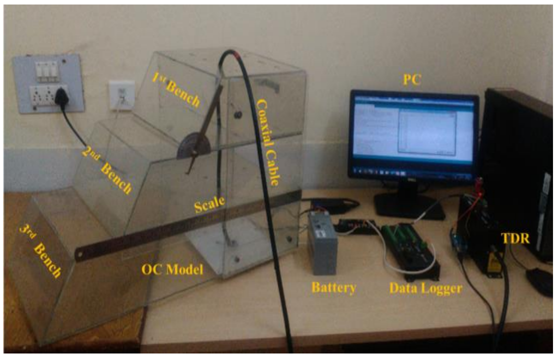

Figure 5. Set up used for the laboratory test

In the first test, RG-6 type of co-axial cable was deformed by model, and the TDR response was checked. This Open Cast (OC) mine model was designed using a Plexiglas and represents the open cast mine with three numbers of benches. The arrangement is done so that middle bench can move forward representing the bench movement. The model was having the arrangement of scale so that displacement can be measured. The Opencast Block Model for the laboratory test is shown in Figure 4. Table 1. Shows the reading of the reflection coefficients taken by TDR system when deformation applied by model. Same results are represented in graphical form in Figure 6.

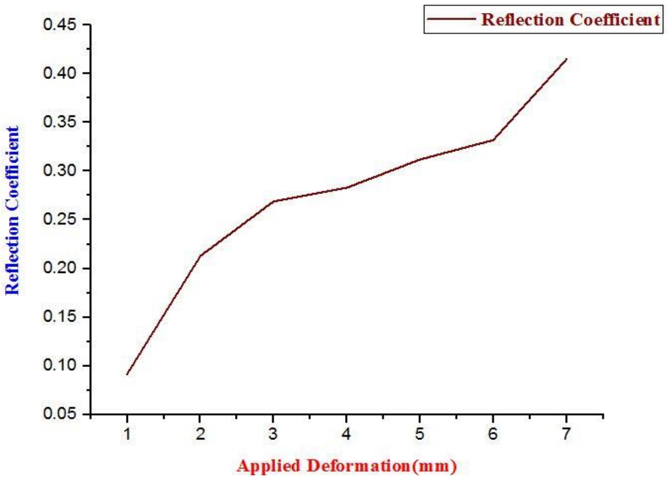

Figure 6. Reflection Coefficient Vs. Applied Deformation

Table 1. Response observed from the TDR with applied deformation

Applied Deformation(mm)	Reflection Coefficient
1	0.0916
2	0.213
3	0.269
4	0.283
5	0.312
6	0.332
7	0.415

The reflection coefficient is a parameter that describes how much of an electromagnetic wave is reflected by an impedance discontinuity in the transmission medium. It is equal to the ratio of the amplitude of the reflected wave to the incident wave (Dowding *et al*., 1988; Kane *et al*., 2001; Lin, 2009). The impedance of the coaxial cables changes with the applied deformation, so a higher value of the reflection coefficient at the length where deformation is applied compared with other points of the cable. It can be concluded from the results of the above test that TDR senses the deformation occurring along the coaxial cable sensitively. It can be used successfully for the slope stability monitoring of the open cast mines. Changes in reflection coefficient caused by deformation of the cable are best modeled regarding changes in impedance and expressed as follows:

$$\text{Reflection Coefficient } (\rho) = (Z1 - Z0)/(Z1 + Z0) \tag{2}$$

Here, $Z1$ = characteristic impedance of the deformed section of cable and $Z0$ = characteristic impedance of the unreformed cable. Changes in ρ caused by deformation in the cable. The characteristic impedance increases due to the applied deformation so that reflection coefficient also increases.

From the reflection theory, the applied deformation changes the shape of the cable results in the variation of impedance in the cable at a particular location (Kane, 1996; Kane *et al.*, 2004). So some of the energy is reflected back from the shear zone, and after capturing the reflected wave, TDR analyses both signals and gives the output in the form reflection coefficient values. Hence by increasing the deformation manually concerning scale fixed to the model, the shape is changing as shown in Figure 7.

The change in capacitance and characteristic impedance at the location of cable deformation gives the change in the reflection coefficient also. A linear relationship between reflection coefficient and deformation was observed (Dowding *et al*., 1989; Dowding and Kevin, 2000). This result was considered encouraging because it suggests that, for a given type of cable, there is a direct, linear, and measurable relationship between the cable signal and shear deformation.

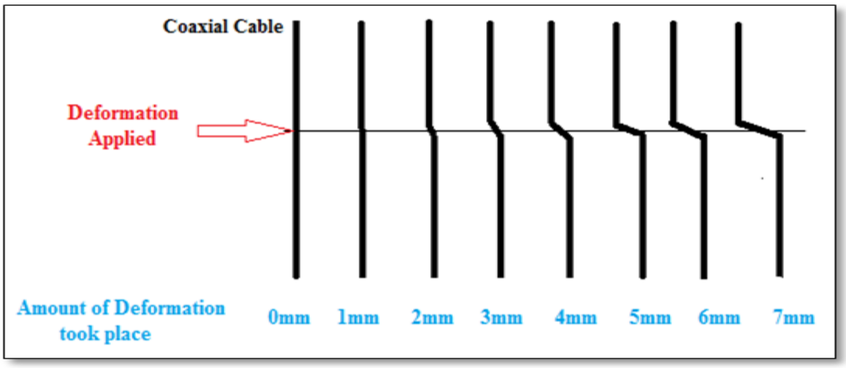

Figure 7. Changes in the coaxial cable shape with applied deformation

5. Test through hydraulic press machine

Automatic hydraulic laboratory press of 30-ton clamp capacity was used for the test. Waveforms were collected at some intervals during the test; TDR signatures were collected for each load and saved as a separate output file. A summary of the data collected during this test is presented in Table.2 under the categories listed as undeformed cable and sheared cable. Figure 8 shows Laboratory setup for testing of coaxial cables using Press Machine. Coaxial cable can be considered as a distributed series inductance with a distributed capacitance between the inner and outer conductors conductor with an insulating spacer between the two. The common electrical property referred to in coaxial cable is the characteristic impedance (Dowding *et al*., 2003; Karthik and Jayanthu, 2015). Impedance is the total resistance to the flow of electrical energy within the cable. It is a complex value defined by the cable’s resistance, capacitance, inductance, and conductance, and is the equivalent value of these items combined. It is the most important characteristic to discuss since it is derived from all the other electrical properties in the cable. Characteristic Impedance is commonly measured using a TDR.

The impedance of the RF coax cable is chiefly governed by the diameters of the inner and outer conductors.

$$\text{Characteristic Impedance}(Z_0)=(138\log(D/d))/\text{sqrt}(\mathcal{E}) \tag{3}$$

$$\text{Capacitance}(C) = (24.1*\mathcal{E}r)/(\log(D/d)) \tag{4}$$

$$\text{Inductance } (L) =0.459\log (D/d) \tag{5}$$

$\mathcal{E}r$=Relative permeability of the dielectric D = Inner diameter of the outer conductor d = Diameter of the inner conductor.

Table 2. Responses observed from the TDR during press test

Load (Kg)	RC	Change in the diameter/ Deformation (mm)
0	0.135	0
300	0.2365	0.12
400	0.290	3.87
500	0.363	3.9
600	0.364	3.97
700	0.501	4.1
800	0.64	4.16
900	0.74	4.1
1000	0.84	4.1
1100	0.9	4.22
1200	Cable damaged	Cable damaged

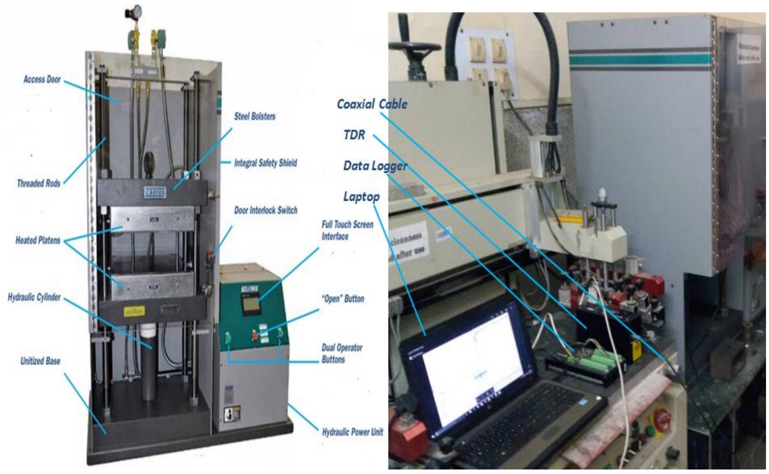

Figure 8. Laboratory setup for testing of coaxial cables using Hydraulic Press Machine

From the Eq. (3), (4) and (5) it is clear that characteristic impedance of the coaxial cable is dependent on the inner and outer diameter of the cable. For example in RG6 Cable, When the load is zero, the diameter of the cable is 6.5 mm when loading increases gradually up to 1100Kg the cable gets suppressed, and diameter was reduced to 2.28mm. Testing of coaxial cable with TDR and press machine indicated the RC of 0.135 – 0.9 vis-à-vis change in the diameter of the cable 0mm-

4.4mm. The change in the diameter of the cable due to load was considered as deformation. The diameter of the cable was changed with applied load, and corresponding changes also observed in RC values (Qian and Shan, 2015; Xu and Pierce, 2013). Pictorial representation of changes in cable signature and cable diameter with respect to applied Load of RG6 coaxial cable is shown in Figure 10. Table 2 shows the Variation of RC and Diameter of RG-6 Coaxial Cable with respect to. Load. The plot against RC and Diameter of RG-6 Coaxial Cable with respect to Load is shown in Figure 9. Figure 8 shows the laboratory setup for testing of coaxial cables using Hydraulic Press Machine.

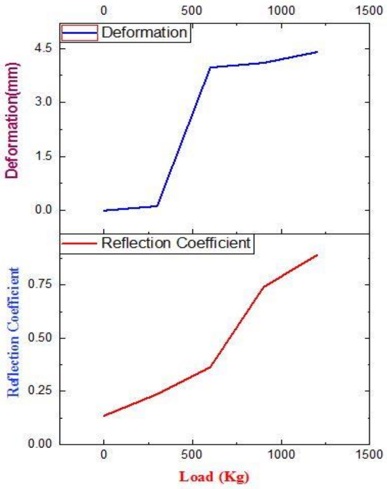

Figure 9. Load vs reflection coefficient and deformation

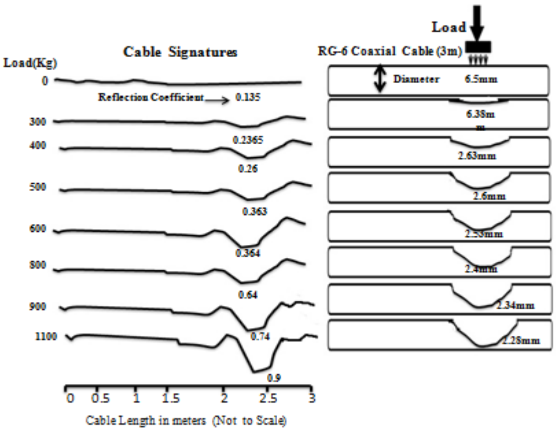

Figure 10. Representation of changes in cable signature and cable diameter w.r.t applied

6. Conclusions

The results of TDR behavior with the RG-6 coaxial cable under different test conditions strongly suggest that TDR can be used to determine the rate of ground movement of the slope failure along the TDR cable locations, provided calibration curves are obtained for each location.Testing of the coaxial cable with TDR and OC model indicated the reflection coefficient of 0.0916 - 0.415 vis-à-vis increase in the deformation from 0mm-7mm. Testing of coaxial cable with TDR and press machine indicated the reflection coefficient of 0.135 – 0.89 vis-à-vis change in the diameter of the cable 0mm-4.4mm. These encouraging results were considered for implementing the above TDR system of slope monitoring in the opencast mines in India as a part of Ministry of Mines, Government of India (GOI) sponsored the project. This result suggests that small shear Displacements and loads the TDR can be detected the signal reflections may be sufficient to quantify rock or soil movement. This graphic procedure allows visual determination of the cable deformation directly from the reflection amplitude. Rock/soil shear deformation can be effectively quantified when TDR reflections are sufficient amplitude to allow reliable quantification. Recommendations are given for continuing implementation by TDR for slope monitoring.

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