# EFFECTS OF MULTIPLE CRIMPS AND CABLE LENGTH ON REFLECTION SIGNATURES FROM LONG CABLES

by

Charles E. Pierce,[1] Christophe Bilaine,[2] Fei-chiu Huang,[3] and Charles H. Dowding[4]

## ABSTRACT

The accuracy of time domain reflectometry (TDR) measurements of rock shearing with cable lengths greater than 60 m has not been adequately documented. This paper presents the results of controlled crimping and shearing of a 530 m long, 22.2 mm diameter coaxial cable for comparison with theory and the existing data from cables up to 60 m long. Effects of both single and multiple deformities along transmission lengths of 94, 268, and 530 m were investigated. The Northwestern University TDR Signature Analysis (NUTSA) program was employed to track and analyze reflection spikes in the waveforms produced by controlled deformation. The results show that pulse attenuation has a significant effect on signal reflections. Reflection amplitudes were reduced by 500% as cable length increased from 94 m to 268 m. Signal reflections produced by downstream deformations are slightly decreased (amplitude reduction < 1 m n single or multiple deformations are applied upstream on the cable. Deformation-reflection relationships can be characterized as bi-linear or exponential, and show that shear deformation can be effectively correlated with TDR reflection amplitude at distances up to 268 m.

## INTRODUCTION

This paper summarizes tests conducted at Northwestern University to relate deformation, distance and reflection coefficient amplitudes after propagation along coaxial cables as long as 530 m. Previous work for short cables *(7,8)*[5] has shown that the relationship between deformation and reflection coefficient could be approximated as linear for short cables (1 to 60 m). The purpose of this work is to clarify the relationships between deformation and reflection coefficient for both short and long cables up to 530 m. These relationships will allow a quantitative assessment of the usefulness of measuring shearing deformations with long cables. After a brief background section, the equipment and procedure are presented, and the influence of length on reflected voltage and related issues are discussed.

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[1]Research Assistant.

[2]Research Assistant.

[3]Post-Doctoral Fellow.

[4]Professor, Department of Civil Engineering, Northwestern University, Evanston, IL.

[5]Italic numbers in parentheses refer to items in the list of references.

## BACKGROUND

TDR has been employed by geotechnical and mining engineers to measure rock deformation since the early 1980's *(4)*. In this approach, coaxial cables are grouted into a rock mass that is expected to deform. Progressive, localized rock movement along joints deforms the cable, which produces a change in TDR pulse reflection signatures.

Research has focused upon correlation between field shear deformation and signature of the reflection coefficient. Double shear of very short cables (1 m) in the laboratory has lead to a proposed linear relationship between deformation and reflection *(8)*. Shearing of the cable produced the classical downward spike in horizontal signatures, and growth of the TDR reflection with increasing shear deformation is illustrated in *(4)*. Kim *(7)* sheared longer cables (up to 60 m) in the laboratory and verified this linear trend.

Results of this previous work are combined in figure 1 to show the degradation of the reflected pulse amplitude with increasing length of cable. For example, shearing a 12.7 mm diameter cable by 6 mm produces a reflection coefficient of approximately 70 m

Dowding *(3)* described the theoretical effects of attenuation and rise time (or dominant frequency) on long cables (greater than 152 m). These studies showed that initial pulse attenuation of 3.4% should be expected for a 152 m cable with 12 mm diameter. Rise time along the same cable increased by 20%. For a 1528 m cable, the signal attenuates 29% and rise time increases by 33%. There have been theories hypothesized for the effects of reflected pulse reduction, multiple reflections, or degradation of the rise time *(1)*. However, typical geotechnical applications are shallow

Figure 1.-Reflection coefficient versus shear deformation relationships for short coaxial

cables up to 60 m (after *(7)*).

and do not require cable lengths greater than 152 m, so it was previously thought that the degradation of a signal due to attenuation in cables less than 152 m would not be a significant factor.

Resolution is dictated primarily by the rise time of a voltage pulse arriving at discontinuities. A substantial increase in rise time occurs along cable lengths of 152 m or greater. Degradation (increase) of rise time of any pulse results in larger reflection widths and depends upon both the TDR pulser and the transmission cable. For instance, previous work *(4)* has shown that two crimps 15 mm apart could be detected at a distance of 0.6 m using a 30 µs square pulse source with an initial rise time of 3 ps. At a distance of 60 m, it was not possible to distinguish crimps any closer together than 75 mm using the same TDR pulser.

## EXPERIMENTAL WORK

### Cable Testing Equipment

Cable selected for this project is a 22.2 mm diameter solid aluminum coaxial cable, commercially available from Comm/Scope[6] as product number P-3 75-875CA, without its plastic sheath. This cable has been used in the field to monitor rock mass deformation with TDR *(2)*. The solid aluminum outer conductor is separated from a copper-clad aluminum inner conductor by an expanded polyethylene dielectric. Propagation velocity for this cable is listed as 87% of the speed of light, which was confirmed in the laboratory.

A 530 m spool of cable was unrolled around the perimeter of the outdoor track at Northwestern University (figure 2*A*) and extended approximately one and a half times around the track. Part of the challenge in deploying the cable was to find a secure location that protected the unusually long cable from being displaced, damaged, or stolen during the three weeks of testing. A Tektronix 1502B cable tester and a laptop computer were used to acquire the TDR waveforms. The computer controls the cable tester via the SP232 Host Application program provided by Tektronix. The metallic coaxial cable is linked to the cable tester through a 1 m precision coaxial cable. Experimentation with each successively shorter length of cable was begun by cleanly cutting the end with a hacksaw. Shear and crimp deformations were then consistently applied along successively shorter cable lengths of 530, 268, and 94 m.

Crimps were produced by squeezing the cable with a set of adjustable vise grips. The depth of the crimp is set by adjusting the separation of the grips. An optimally crimped cable diameter was found to be 15 mm, corresponding to a 30% diameter reduction. The length of the crimp is controlled by the grip head width of 12 mm. Total crimp length is controlled by placing contiguous crimps in succession along the cable. Crimp lengths varied from 12 mm (1 grip width) for the shortest cable, as shown by the right cable in figure 2*B*, to 48 mm (4 grip widths) for the longest cable. Reference TDR

[6]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

reflection amplitudes were at least 5 m

Shearing produces a much different change of cable geometry, as shown in the left cable of figure 2*B*. This single shear deformation was generated with a shearing box specially constructed at Northwestern University for this purpose. Two photographs of this device are shown in figures 3*A* and 3*B*. The box is constructed in two halves with a screw penetrating the center of the top half to drive the shear block inside the box. This inner block, shown between the two halves in figure 3*A*, secures the cable and moves vertically as the screw is rotated by the aluminum knob on the left. The screw is manufactured with 20 threads per inch, or approximately 0.8 threads per mm. Since each thread represents one revolution, each complete rotation displaces the shear block by (1/0.8) = 1.25 mm. This device differs from that which produced the double shear deformations in previous work (figure 1), where two distinct shears developed along the cable and created two adjacent spikes or a single, wider spike at the shear location, depending on the transmission distance.

Top and bottom semi-circular channels of both the inner block and the outer box are grooved to a radius slightly greater than 11 mm, as shown in figure 3*A*. A narrow circular passage for the 22 mm diameter cable is created when the shear box is fully assembled. The cable is tightly bound within this passage to minimize slippage during shear. The top semi-circular channel on the side of the shear box shown in figure 3*B* also has a radius slightly greater than 11 mm, but the bottom groove is 29 mm deep to allow the deforming cable to displace freely. This unconstrained dispacement results in a single shear where the cable passes into the inner block.

## Cable Testing Procedure

A common set of tests were performed on the successively shorter lengths of cable to address issues of attenuation, resolution, and sensitivity. Attenuation measurements were determined from both TDR reflection slope and amplitude at the open end of the cable. Resolution of cable discontinuities was found by crimping the cable at an increasingly greater separation distance until two signal reflections were completely distinguishable. Sensitivity in this study is defined as the minimum shear deformation required to create a 1 m

A consistent testing procedure for crimp and shear deformation was employed near the end of each length of cable. The four step procedure consisted of first placing a crimp within 3.3 m of the cable end, then shearing the cable in front (upstream) of the crimp, then shearing the cable again in front of the first shear, and finally placing a second crimp in front of the second shear. This routine yields a series of crimp, shear, shear, crimp, and open end discontinuities in that order progressing toward the cable end, and is referred to as the basic testing procedure throughout this paper. In addition, other crimps and/or shears were made along each cable after those consistently applied in the basic procedure. The results from some of those deformations are discussed in this paper and are described where appropriate.

Waveforms were collected at a number of intervals during crimping and shearing of the cable. For example, shear was typically carried out to a deformation of 10.2 mm, which corresponds to 8 full rotations of the shear box handle. TDR signatures were collected for each rotation and saved as a separate output file. The Northwestern University TDR Signal Analysis (NUTSA) program *(6)* was employed to analyze and evaluate the signals stored in these files. Altogether some 250 files were collected from three lengths of cable and evaluated with NUTSA. This data acquisition, retrieval and comparison system allowed rapid quantitative analysis and comparison of such a large number of files. Other applications of NUTSA are discussed in *(5)*.

## DISCUSSION OF RESULTS

Results from this project are presented in three main sections: (1) influence of distance, (2) influence of multiple deformations, and (3) findings from crimp optimization and resolution. A summary of the data collected during this study is presented in table 1 under the categories listed as undeformed cable, crimped cable, and sheared cable. The actual length of each cable was determined as the distance from the pulse source to the cable end, marked by a near vertical upward reflection at a horizontal scale of 1 ft/div. The amplitude of this reflection is taken as the difference between its plateau and the base line reflection coefficient.

The crimp lengths chosen for each cable and their corresponding reflection amplitudes are listed in table 1. It should be noted that the results for 410 m were taken from crimps and shears placed at that distance along the 530 m cable. Resolution measurements were determined using two crimps separated by progressively shorter distances. Sensitivity results, and reflection amplitudes for a shear deformation of 7.6 mm, are displayed in the sheared cable column.

### Influence of Distance on a Single Shear Reflection

Distance has a dramatic effect on the signature produced by a single shear, as illustrated in figure 4. This figure compares the signal reflections produced by shear deformation of 7.6 mm near the end of 530, 268, and 94 m cables. Amplitudes of these three reflections, as well as that at 410 m, are listed in the last column of table 1. Signal reflections correspond to the first shear applied during the basic procedure, where the shear is 1.6 m in front of the crimp. The apparent separation distance between the crimp and open end increases from 0.6 to 3.3 m as the cable length increases. In this comparison, crimp lengths vary for each length of cable, so the crimp reflections cannot be compared in the same manner as the shear reflections.

The shear on the 94 m cable produces a typical spike with a 12.5 m
reflection. At 268 and 530 m the shear reflections are more trough-like, with smaller amplitudes (2.5 and 1.2 m
However, the voltage reflection at 268 m is more easily distinguished than the one at 530 m, and can be identified as shear deformation. This suggests that small shear displacements can be detected at distances up to 530 m using TDR, but the signal reflections may not be sufficient to quantify rock or soil movement. This insufficiency arises from the low sensitivity (very small amplitudes) and the low resolution (very wide reflections) of cable deformations at this distance. Thus the correlation between reflection coefficient and shear deformation is more likely limited to cables up to 268 m in length.

Figure 5 compares the reflected amplitudes of 12.7, 10.2, 7.6, and 5.1 mm shear deformation at distances ranging from 3 to 530 m. A family of curves for this range of shear deformation is obtained from the multiple measurements. Degradation occurs rapidly and minimum shear deformation necessary to detect a 1 m

Table 1.-Summary of results for undeformed, crimped, and sheared cables.

| UNDEFORMED CABLE | | CRIMPED CABLE | | | SHEARED CABLE | |
|---|---|---|---|---|---|---|
| Cable Length (m) | Open End Reflection (m | Crimp Length (mm) | Reflection Amplitude (m | Resolution (cm) | Sensitivity (mm) | Reflection Amplitude (m 7.6 mm Shear Deformation |
| 94 | 797 | 12 | 22 | 20 | 1.3 | 12.5 |
| 268 | --- | 24 | 5 | 46 | 3.8 | 2.5 |
| 410 | --- | 48 | 9 | --- | 5.1 | 1.9 |
| 530 | 747 | 48 | 5 | 152 | 7.6 | 1.2 |

waveform increases with propagation distance from source to location of the shear. Therefore the longer the distance, the smaller the observed reflection amplitude for the same shear deformation. This reduction in amplitude results from attenuation of the signal with distance along the cable, as well as the degradation in rise time.

Attenuation has a significant effect on reflection coefficient, as can be seen in both figures 4 and 5. However, attenuation heretofore has not been studied this intensively because of the difficulty of working with a 530 m long cable. This study shows that for cables shorter than 90 m, attenuation plays a fairly significant role in detection of signal change. In other words, the attenuation-distance relationship must be known.

For long cables, noise is an important consideration, which can be deduced from figure 5. For example, the noise level was typically 1 to 2 m
m cable. Since a 10 mm shear produces a 4 to 5 m flection amplitude at this distance, TDR is limited in quantification of deformation to larger shearing events with long cables. However, as shown in figure 5, quantitative measurement of small shear displacements is still possible for cables as long as 268 m. Connecting a pulser to the monitoring section of a cable with a low-loss cable may allow quantitative measurement at distances greater than 268 m.

The curves shown in figure 5 have been developed as a correlation chart for geotechnical engineering purposes. A quick estimate of deformation can be obtained from this plot by first locating the point defined by the distance from the source to the detected spike and the corresponding reflection coefficient. Interpolation between the two nearest curves yields an approximate value of the cable deformation. This graphic procedure allows visual determination of the cable deformation directly from the reflection amplitude. It is important to realize that this chart is only valid for the 22.2 mm diameter cable studied here. Other calibration charts should be developed for other types of cables with variable diameters and lengths to create a workbook of correlation plots.

More data points are needed to accurately define the trend of reflection resulting from a single shear with distance, especially for distances ranging from 10 to 100 m. Additional data will allow validation of an empirical relationship from the graphs and a comparison to theoretical analysis of attenuation (currently in progress at Northwestern University).

## Effects of Multiple Cable Deformities on Signal Reflection

### Degradation of Voltage Reflection Due to Crimps

The top and middle graphs produced by NUTSA (figures 6*A* and 6*B*) show the waveforms collected at the end of the 94 m cable before and after a second crimp was placed in front of two shears, one crimp and the open end. The first crimp is located 0.6 m up the cable from the open end and 1.6 m down the cable from the first shear, which is also spaced 1.6 m from the second shear, as shown in figure 6*A*. A second crimp is then placed 1.6 m up the cable from the second shear, and the resulting waveform is shown in figure 6*B*.

The waveform in figure 6*C* illustrates the amplitude difference between the top and middle signals displayed with NUTSA. This difference waveform represents the effect of the second crimp on the signal reflections produced by the following shears, crimp, and open end. A positive (upward) difference indicates a reduction of the signal reflection from the top waveform to the middle waveform and an increase in reflection amplitude is shown as a negative (downward) difference. These differences were calculated for many TDR signatures collected during testing to evaluate the effects of a single discontinuity on the TDR reflection of downstream cable discontinuities.

*A*

*B*

*C*

Figure 6.-TDR waveforms displayed with NUTSA showing signal reflections *A*, before application of upstream crimp; *B*, after crimp application; and *C*, as the arithmetic difference between the two waveforms.

The effect of the upstream crimp on the existing shear and crimp reflections was minimal. The difference waveform shows no difference of 1 m
or second shear. The difference for the crimp is also indistinguishable from random noise. This general trend of minor degradation (less than 1 m of prior signal reflections due to a second crimp was noted for all lengths of cable investigated. The reflection at the open end appeared to have increased about 2 m increase was considered negligible since the original amplitude at the open end was about 750 m

Additions to the basic procedure (crimp-shear-shear-crimp) were also examined to further define signal degradation. For the 410 and 530 m distances, a third crimp was placed at a greater distance up the cable from the second crimp. This third crimp also had virtually no effect on the existing signal reflections (*i.e.*, difference < 1 m

## Effect of Shearing to Failure

To investigate the impact of large shear deformations on signal reflections, a third shear was placed a short distance upstream of the second crimp and taken to failure, thereby producing a new open end at the shear location. This shear also produced minimal change in the magnitude of reflections made by previously existing crimps and shears.

Shear growth was tracked to failure and the results of reflection coefficient versus shear deformation are shown in figure 7 for the 94 m cable. Positive amplitudes represent downward reflections and negative amplitudes represent upward reflections. This plot shows that amplitude increases with deformation until a short circuit was created between

Figure 7.-Reflection coefficient versus shear deformation for a 94 m cable sheared to failure.

17.8 mm and 19.1 mm shear deformation. Subsequently an open end occurred at 27.5 mm shear deformation, which is larger than the initial diameter of the cable. This response indicates that deformation can be correlated with the reflection coefficient to 78% reduction of the original diameter, exceeding previous estimates of a 50% reduction limit. However, the amplitude-deformation relationship becomes highly non-linear at such large deformations, as shown in figure 7. This test was reproduced in the laboratory for a short cable and the results were verified.

## Voltage Reflections from Multiple Shears Only

A second scheme involving only shear deformation was developed to monitor signal reflections along an 88 m long cable, which was previously 94 m in length. Shears were applied consecutively in four locations near the open end of the cable. Minor degradation of the TDR reflections at existing shear deformation locations was noted during the process of subsequent shearing.

Figure 8 shows the results of reflection coefficient versus deformation for a series of single shears recorded separately between 82.6 m and 86.3 m. Three of four data sets follow the same trend, while the fourth one (shear at 85.6 m) is offset by a constant 2.5 mm on the deformation axis. If the curve is shifted 2.5 mm to the left along this axis, the trend would coincide with the others. This offset may have resulted from miscommunicating the initial number of shear rotations, as 2.5 mm is equal to 2 revolutions of the drive screw. For the completeness of the record, these results are presented here but will not be included in the following figures and analysis. Only those data which follow the most populated trend will be analyzed.

A small change in cable deformation produces a dramatic change in reflected voltage amplitude, as figure 8 demonstrates. However, a larger increase in reflection coefficient occurs when a critical value of deformation is reached, leading to a bi-linear or exponential representation of reflection versus deformation. For the data shown in figure 8, the break in the curve appears to be at 7.5 mm deformation. Beyond this threshold deformation, an exponential rise characterizes the trend of reflected amplitude versus deformation.

The reflected voltage-deformation relation for the 88 m cable can be compared with the results presented in figure 1. In figure 8, the approximation of a straight line for small deformations is acceptable as long as a second, steeper slope for larger deformations follows the initial slope. This bi-linear approach is necessary to match the measured exponential rise in amplitude. More importantly, the reflected voltages at constant deformation continue to decline with cable transmission length. This declination with an 88 m long cable is not large enough to impair monitoring potential, but attenuation should be taken into account to accurately model the behavior of reflected voltage amplitude for

TDR measurements.

## Optimum Crimp Geometry and Placement

Table 1 (columns 3 and 4) lists the crimp length and respective amplitude for crimps produced on 94, 268, 410, and 530 m cables. At 94 m, which is a typical cable length in present field applications, a single crimp, 12 mm wide and 15 mm deep, yields

Figure 8.-Reflection-deformation data for four consecutive shears placed near the end of 88 m cable.

a 22 m *A*, is easily detectable with TDR and serves as an excellent location marker. Even at 530 m, a 48 mm crimp (with no upstream deformation) produces a partial spike with an amplitude of 5 m discernible and useful for marking location along the cable. Therefore cable lengths up to 530 m can be accurately marked with relatively little deformation.

As the cable length increases, the crimps must necessarily be longer for identification, and a combination of these two factors produces signal reflections that

correspondingly become wider. Thus it is important to minimize the crimp dimensions, especially at greater lengths, to produce a small, yet discernible voltage reflection. Current field practices produce multiple reference crimps yielding 20 m
reflection. These results (table 1) indicate that crimps with 5 m
sufficient for marking cables, thereby reducing the required crimp length.

In addition, the current practice of producing a large number of crimps can and should be changed to reduce the amount of energy loss that occurs as the pulse passes through these multiple deformations. A number of options are available. If the location of interest is known, a single crimp may be placed near this location. Until the cable is completely severed from shearing, the end of the cable serves as its own distance marker. Perhaps two crimps might be employed if the location of deformation is dispersed or unknown. Since use of a large number of crimps is more of an historical artifact unless very accurate locations of cable defects are necessary, a small number of crimps is recommended. Measurements presented herein show that one and two crimps will not affect the shear deformation-voltage reflection relationships.

## Resolution

Resolution clearly decreases in a non-linear manner as distance from the source to the crimps increases, as indicated by the data in table 1 (column 5). An inverse relationship between resolution and distance should be expected as the rise time increases with cable length and subsequently increases the width of signal reflections. This trend is demonstrated in figure 4, where the apparent width of crimp reflections increases from 0.6 to almost 2 m as the cable distance increases. However, it should be noted that the physical crimp lengths are not the same for each cable. The crimp reflection widths are also larger than the corresponding shear reflection widths in each case, which indicates that resolution is governed by the crimps. This means that two adjacent shears can be resolved at distances smaller than those listed in the table; so these values are considered to be conservative.

## CONCLUSIONS AND RECOMMENDATIONS

This paper has evaluated the distance-deformation-reflection relationships for both crimp and shear deformation along metallic, coaxial, 22.2 mm diameter cables of 94, 268, and 530 m lengths. These relationships have been established in previous studies for cable lengths up to 60 m. To verify findings obtained with the shorter cables, consistent crimp and shear deformations were produced on each of the three longer cable lengths and analysed with time domain reflectometry measurements. From these measurements, the issues of: (1) signal degradation for single and multiple deformations, (2) crimp optimization and (3) resolution of TDR reflections have been investigated for cable distances up to 530 m.

From the results presented herein, the following conclusions are advanced:

1. Pulse attenuation and rise time degradation with distance dramatically affect the shape and amplitude of the reflection signature of a single shear. Reflection amplitude is reduced by approximately 500% from 94 m to 268 m, and reflection width is increased,

as cable lengths increase.

2. Rock/soil shear deformation can be effectively quantified with TDR measurements at distances up to 268 m from the pulse source. Crimp and shear deformations can still be detected at 530 m, but TDR reflections are not of sufficient amplitude to allow reliable quantification.

3. Degradation of deformation-induced voltage reflections resulting from upstream single and multiple crimps and shears is generally minimal (less than 1 m
cable lengths up to 530 m.

4. Resolution decreases non-linearly as cable length increases, thereby making accurate TDR measurements for long distances such as 530 m difficult.

5. Crimping cables to establish reference TDR reflections can and should be minimized to produce reflection amplitudes of approximately 5 m
number and size of crimps will reduce the risk of interference with shear deformation. In addition, the cable end reflection serves as a distance marker.

During this project, a number of further avenues of investigation were uncovered and include:

1. Other cable diameters and lengths should be investigated to measure their response to crimps and shears as a function of distance. Development of charts for typical cables will provide a standard method for translating reflection to deformation in geotechnical engineering settings.

2. The response of a dual transmission-monitoring cable system should be investigated for potential reduction of attenuation effects on a single shear. Preparation for this research is currently underway at Northwestern University.

## ACKNOWLEDGMENTS

This research was funded by the Bureau of Mines of the U.S. Department of the Interior, contract number PO212469, under the direction of Dr. Kevin M. O'Connor, Civil Engineer in the Twin Cities Research Center.

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*A*

*B*

Figure 2.-*A*, Layout of coaxial cable around track; *B*, comparison of sheared cable (left)

and crimped cable (right).

*A*

*B*

Figure 3.-Shearing box designed and constructed at Northwestern University showing *A*, box components and *B*, fully assembled device.

*A*

*B*

*C*

Figure 4.-TDR reflections for a crimp and 7.6 mm shear deformation on *A*, 94 m cable; *B*, 268 m cable; and *C*, 530 m cable.

Figure 5.-Reflection coefficient versus transmission distance relationships for four different magnitudes of shear deformation.