MEASUREMENT OF LOCALIZED FAILURE PLANES IN SOIL WITH TIME DOMAIN REFLECTOMETRY

by

Charles H. Dowding[1] and Charles E. Pierce[2]

ABSTRACT

This paper presents the development plan for a TDR-based metallic coaxial antenna cable system to locate failure planes in soil. The system depends upon affixing a compliant coaxial cable in a borehole to the surrounding soil mass with a compliant grout in a manner similar to that used for rock deformation systems. The problems in designing such a device are twofold: first, an extremely flexible cable with a low shear resistance needs to be designed and manufactured; second, the compliant grout and a grout placement scheme must be developed. After a brief introduction to previous techniques for field measurements of strain localization, this paper describes the expected soil-grout interaction and the details of the anticipated design of the cable and grout.

INTRODUCTION

Strain Localization and Traditional Measurement

Detection of strain localization in the field has in some ways been inhibited by the instruments employed for its measure, namely the inclinometer or slope indicator. The low resolution of the inclinometer almost precludes detection of thin shear zones in the field and leads to field measurements that are hypothesized to overestimate the thickness of the zones along which failure occurs *(12)*.[3]

Inclinometers measure deformation normal to the axis of a vertical casing via a 60-cm-long, gravity-sensing probe shown in the detailed sketch in figure 1*A (7)*. As the probe passes along the casing, an accelerometer measures the inclination of the casing. By successively adding the product of the inclination and the probe length as the probe is pulled up from an assumed fixed position, the casing profile can be determined as shown in figure 1*B*.

Figure 2*A* illustrates that the resolution of shear band detection with an inclinometer is equal to the probe wheelbase, L, which is typically 60 cm. In this example, it is assumed that the casing deforms conformally with a thin shear band, approximately 2 mm thick. As the probe is lowered down the casing and across the shear

---

[1] Professor.

[2] Research Assistant, Department of Civil Engineering, Northwestern University, Evanston, IL.

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

band, it will measure the same angle over a distance equal to its wheelbase (as indicated

A *B*

Figure 1.-*A,* Cross-sectional view of inclinometer and probe and *B,* schematic of inclination measurements taken with an inclinometer (after *(7)*).

by the two dotted positions of the probe). Resolution of band thickness is therefore limited to the length of the wheelbase even if readings are taken at intervals that are a fraction of the probe length. Furthermore, thin shear bands can be missed because of operator error, and for sufficiently localized shear it is not possible to move the probe through the kinked casing. Also, deformation at a shallow but distinct shear zone may prevent passage of the probe to deeper sections and restrict measurement altogether.

Figure 2*B* shows coaxial cable deformation across a shear band as thin as 2 mm. A 2-mm shear band is sufficient for detection with TDR measurements at typical transmission distances. However, for longer cables (*e.g.,* 600 meters), resolution can be reduced to 1000 mm.

Aside from the low resolution of shear band measurements resulting from probe geometry, several other disadvantages arise when using an inclinometer to detect thin shear bands. One concern is that the casing may be too stiff to conform to the soil deformation along thin, transverse shear bands in soft soils. Such soil-casing interaction will be a function of soil and casing stiffness.

Shear Band Measurement With TDR

TDR technology has been successfully adapted to measure rock mass deformation along thin joints *(5)*. Such measurement is accomplished by grouting a coaxial antenna cable in a borehole and measuring reflected voltage pulses which occur due to changes

A *B*

Figure 2.-Comparison of shear band resolution. A 2-mm shear band measured with *A*, an inclinometer and *B*, coaxial cable deformation.

in capacitance between the inner and outer conductors as the cable is pinched by shearing. Figure 3 shows the anticipated placement of a TDR cable system near an excavation in soil and its pinching at the location of the shear band. Figure 4 shows the waveforms collected during laboratory shearing of a coaxial antenna cable grouted into a precut pipe *(6)*. As the cable is sheared, the reflected signal exhibits a progressively larger downward spike in the waveform caused by the changing capacitance at the location of shear-induced pinching.

TDR technology has not yet been successfully applied to measure shear deformations in softer materials such as soil because of the lack of a suitable cable and grouting procedure *(12)*. Development of an appropriate cable-grout system should allow measurement of shear zones as thin as 2 mm and produce TDR reflections similar to those shown in figure 4.[4] Measurement of cable deformation by TDR allows for greater accuracy since very thin shear zones can be detected anywhere along the length of the cable in the ground. Test results displayed in figure 4 result from shearing of a 2-mm-wide saw cut in the outer pipe and grout. This detectable thickness is approximately 1/300 (2 mm/600 mm) that possible with an inclinometer, as illustrated in figure 2.

The resolution with which the shear zone can be located with TDR technology is

---

[4] A disclosure and patent application have been filed for this concept and cable.

a function of the cable length. TDR techniques can be used effectively to detect cable shear events separated by distances as small as 6 mm at cable lengths up to 30 m. Although a single shear event can be detected out to hundreds of meters, the ability to distinguish or resolve two adjacent shear incidences beyond 30 m is currently being studied at Northwestern University.

TDR has several other advantages over inclinometers for measuring shear bands in soil. The principal advantages are its automatic operation and uphole electronics, which lends itself to telemetric and multiplexing capabilities. Most importantly, monitoring can be undertaken without human interaction at the site. Unlike the inclinometer, which requires a human or mechanical means to raise and lower the probe, a TDR cable has no moving parts. Therefore, human interaction may be eliminated altogether. Secondly, location of the electronic pulser above ground allows easy access for repair and protects the pulser from damage due to underground deformation or ground water intrusion. Telemetric operation has been demonstrated with the remote measurement of rock deformation above an active longwall coal mine in southern Illinois *(4)*. Multiplexing capability further allows multiple cables to be monitored from the same uphole electronics.

Figure 3.-Example of field setup of cable and grout system to measure soil deformation along a shear band.

DEVELOPMENT PLAN

Soil-Grout Interaction

Failure modes of the soil surrounding the cable-grout system must be identified to assess local stress-deformation interaction at the soil-grout interface. Two types of failure, localized or non-localized, may occur at the interface of the soil and grout. A non-localized failure mode indicates significant soil movements occur in a relatively large radius of curvature. Such deformation may fracture the grout, but may not be sufficiently concentrated to locally shear the cable and thus preclude development of a detectable spike in the TDR waveform *(12)*.

Since current instruments cannot detect thin (less than 60 cm thick) bands, past observations of non-localized deformation could represent groups of thinner, localized shear bands. Use of TDR in soil should allow such a distinction between non-localized and localized failure.

When a shear band intersects the cable-grout column and fractures the envisioned weak and compliant grout, it will then deform the cable, which is also weak and compliant. However, yielding of the soil and subsequent flow around the grouted hole must be considered. Figure 5 illustrates that a typical cement grout is considerably stronger and stiffer than a medium stiff clay. In this case of a relatively strong and stiff grout, the soil movement would not fracture the grout or deform the cable sufficiently to cause a detectable TDR reflection. The objective is to design the strength and stiffness of the cable-grout system to equal the strength and stiffness of the in situ soil, so that the cable and grout will fracture and deform as the soil yields.

Figure 5.-Typical shear stress versus shear displacement results of a cement grout and medium stiff clay.

Design and Development of Cable

To accurately detect soil deformation along a localized shear surface, the cable must deform easily when subjected to localized soil shearing. Previous work *(4,6)* has shown that shearing of grouted coaxial antenna cable by rock joint deformation can be measured from TDR reflections with commercially available cables and pumpable grout mixtures. These coaxial cables have three principal components, as shown in the expanded view in figure 3. Two conductors, a solid, thin, metallic outer conductor (usually copper or aluminum) and a thin wire inner conductor, are separated by a dielectric material.

Most available cables are manufactured with solid polyethylene as the dielectric material. Polyethylene has a shear strength and stiffness (modulus of elasticity) of approximately 870 kPa and 3 GPa, respectively *(14)*. Such cables work well for detection of rock movement where the intact rock has shear strengths and stiffnesses (shear strength > 2 MPa, modulus > 1 GPa) greater than that of polyethylene, but would be too stiff for measuring localized deformation in weaker and more compliant soil (shear strength < 1 MPa, modulus < 100 MPa).

A dielectric material with lower shear strength and stiffness is necessary to produce a weak, deformable cable. A weaker and more compliant material, such as polystyrene foam, can replace polyethylene as the dielectric to produce a coaxial cable for TDR use in soil. Polystyrene foam has a shear strength and stiffness of 4 kPa and 280 kPa, respectively, considerably less than that of solid polyethylene.

Other cable components will include an inner conductor of solid copper wire and a braided exterior copper conductor, which has relatively little stiffness and strength in shear. It is hypothesized that the loosely braided exterior conductor will be completely flexible and not affect deformation of the dielectric material. Beyond such mechanical considerations are the electrical properties of braided copper cables with noise levels so great as to preclude their use for TDR monitoring.

Design and Development of Grout

A cementitious grout mixture is required to stabilize the borehole and integrate the cable with the soil mass. This grout must be stiff enough to maintain hole stability, but also compliant and weak enough to fracture in the localized shear zone without affecting the soil mass movement. In other words, it is important that the soil, cable, and grout components deform as a single unit in the localized zone shown in figure 6. Flowable fill, also known as a controlled low strength material (CLSM) *(1)*, has physical properties similar to soil and thus could be employed as the weak grout. CLSMs typically consist of cement, fly ash, fine aggregate, and water, and have moduli in the range of 70 MPa to 7 GPa. By varying the fractions and types of the components, a stable yet compliant and weak material can be designed and produced.

According to the American Concrete Institute *(1)*, flowable fills have unconfined compressive strengths in the range of 350 kPa to 2 MPa. Research at Northwestern University, sponsored by the American Flyash Association (AFA) *(15)*, has shown that flowable fills with a small to zero percentage of cement and higher amounts of flyash produce CLSMs with unconfined compressive strengths as low as 70 to 140 kPa and moduli on the order of 70 MPa.

Figure 6.-Shearing of cable-grout-soil system in a direct shear device.

To ensure that the grout does not interfere with the transfer of soil deformation to cable deformation, the shear strength and stiffness of the CLSM should match, within a reasonable range, the strength and stiffness of the in situ soil. Theory of plasticity *(11)* has shown that two-dimensional stresses perpendicular to the cable, or cable-grout contact pressure, cannot exceed nine times the shear strength of clay without general failure and flow around the cable-grout system. Field tests show that this coefficient may be closer to 14 for undrained conditions *(10)*. The appropriate range for CLSM shear strength can be determined from the shear strength of the soil to be monitored. The target grout stiffness can also be estimated from laboratory stress-strain data.

The CLSM grout selected for this application must also have a sufficiently low viscosity to be pumped easily down the hole. Grout pumpability will be investigated in the laboratory. Plasticisers and/or expansive agents will be added to the CLSM grout to improve performance, if necessary.

Example of Composite System

The following example demonstrates that an appropriate cable-grout system can be developed for field implementation. It has been hypothesized that a weak and compliant cable can be designed with a shear strength and stiffness of 4 kPa and 280 kPa, respectively. According to Trimble *(15)*, a CLSM can be produced with an unconfined compressive strength, q_u, of 100 kPa and stiffness of 300 MPa, which are both appreciably greater than corresponding properties of the cable. Thus the grout controls the consideration of soil compatibility with the cable-grout system.

Localization of deformation has been observed to occur in medium to stiff overconsolidated clays *(2)*. A medium stiff clay, for example, may have a shear strength, c, of 100 kPa and stiffness of 100 MPa. Shear strength of the CLSM described above is equal to half of its unconfined compressive strength, or $c = ½\, q_u$, which in this case is 50 kPa. Grout shear strength is less than the shear strength of the medium clay, and the grout stiffness is only slightly greater than the clay stiffness. Hence the cable-grout system suggested here would be easily expected to capture localized shear deformation in a medium stiff clay with similar properties.

Finno *(8,9)* observed failure of a soft clay along a localized shear band during construction of a braced excavation. Chung *(3)* measured the undrained shear strength and stiffness of the soft Blodgett till adjacent to an excavation and found that the Blodgett till has an average shear strength of 24 kPa and stiffness of 12 MPa. To ensure that the cable and grout system fails first, general plastic bearing failure of the soft clay around the cable and grout cannot occur. Thus, cable-grout contact pressures should not exceed one-third of the clay bearing capacity, 9c. The value 9c is conservatively reduced by a factor of 3 to ensure behavior within the elastic range. Therefore, if the grout shear strength is less than c), or 3c of the soil, the grout will fail first. In this example, 3c of the Blodgett till is approximately 72 kPa and the grout shear strength is 50 kPa. It appears that even the soft clay will fracture the grout before it flows in general plastic failure around the grout.

Compatibility of the proposed grout with soft clays should be estimated with CLSM properties measured under saturated conditions. Properties reported by AFA were not measured under saturated conditions and are hypothesized to be stronger and less compliant in that dry state. This hypothesis will be examined during the development of the cable and grout by testing these CLSMs under saturated conditions.

SUMMARY

The concept, and steps in the development, of a cable-grout system to measure thin shear bands in soil with TDR techniques have been presented. With this system, movement along a single, 2-mm-thin shear band can be detected. Multiple shear bands as close as 6 mm can be resolved with TDR, whereas the inclinometer can only distinguish shear events separated by at least 60 cm. Such a high-resolution instrument will provide accurate detection of localized shear deformation and thus provide a measurement technique to distinguish between general bulging and localized failure.

A TDR-based system also allows remote, automated operation of a field instrument and assumes the same approach as that employed for shearing of rock joints. However, development of this device will require a new type of cable that is much more compliant than those used to measure rock deformation. This cable is necessary but not singly sufficient because an equally compliant and weak CLSM grout is needed to integrate the cable with the soil mass.

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.

REFERENCES

1. American Concrete Institute. State-of-the-Art on Controlled Low Strength Materials (CLSM). ACI Publication, Committee 229, 1989.
2. Burland, J.B., T.I. Longworth, and J.F.A. Moore. A Study of Ground Movement and Progressive Failure Caused by a Deep Excavation in Oxford Clay. Geotechnique, v. 27, No. 4, 1977, pp. 557-591.
3. Chung, C.K. Stress-Strain-Strength Behavior of Compressible Chicago Glacial Tills. Ph.D. Dissertation, Northwestern University, Evanston, IL, 1991, 153 p.
4. Dowding, C.H. and F.C. Huang. Early Detection of Rock Movement with Time Domain Reflectometry. Accepted for publication, Journal of Geotechnical Engineering, ASCE, v. 120, No. 8, 1994, 28 p.
5. Dowding, C.H., M.B. Su, and K. O'Connor. Principles of Time Domain Reflectometry Applied to Measurement of Rock Mass Deformation. International Journal of Rock Mechanics and Mining Science, v. 25, No. 5, 1989, pp. 287-297.
6. _____. Measurement of Rock Mass Deformation with Grouted Coaxial Antenna Cables. Rock Mechanics and Rock Engineering, v. 22, 1989, pp. 1-23.
7. Dunicliff, J. Geotechnical Instrumentation for Monitoring Field Performance. John Wiley, 1989, 577 p.
8. Finno, R.J., D.K. Atmatzidis, and S.B. Perkins. Observed Performance of a Deep Excavation in Clay. Journal of Geotechnical Engineering, ASCE, v. 115, No. 8, 1989, pp. 1045-1064.
9. Finno, R.J. and S.M. Nerby. Saturated Clay Response During Braced Cut Construction. Journal of Geotechnical Engineering, ASCE, v. 115, No. 8, 1989, pp. 1065-1084.
10. Mackenzie, T.R. Strength of Deadman Anchors in Clay. M.S. Thesis, Princeton University, Princeton, NJ, 1955.
11. Meyerhof, G.G. The Ultimate Bearing Capacity of Foundations. Geotechnique, v. 2, 1951.
12. Peterson, D. Evaluation of Coaxial Cable/MTDR Method for Quantifying Highwall Movement. Syncrude Canada Ltd, Research Report 93-4, Edmonton, April, 1993, 411 p.
13. Rhee, Y. Experimental Evaluation of Strain-Softening Behavior of Normally Consolidated Chicago Clays in Plane Strain Compression. Ph.D. Dissertation, Northwestern University, Evanston, IL, 1991, 236 p.
14. Society of Plastics Industry. Plastics Engineering Handbook. Reinhold Publishing, New York, 3d ed., 1960.

15. Trimble, K. Flowable Fill with Nonstandard Aggregates. NSF-REU Research with American Flyash Association, Internal Report, Department of Civil Engineering, Northwestern University, 1993, 37 p.

Figure 4.-TDR signatures for shearing of a coaxial cable in a direct shear device (after *(6)*).