MEASUREMENT OF TAILINGS CONSOLIDATION USING TDR TECHNOLOGY

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TDR is based on the principle of cable radar and is used with a variety of probes and coaxial cables to measure volumetric water content. In the case of saturated tailings, changes in the volumetric fluid content occur as the tailings solids displace pore fluids and recent studies with segmented probes at two mines have shown that TDR may provide a reliable means for monitoring tailings consolidation and the impact on operating storage capacity and long term closure. Laboratory tests have been performed using a Georgia kaolin slurry. The propagation velocity profile was measured using a MoisturePoint segmented probe during the test. Although the qualitative trend is promising, it will be necessary to do a more fundamental analysis of changes in the TDR waveform rather than simply using the default algorithm in order to improve the sensitivity.

1 MEASUREMENT OF VOLUMETRIC WATER CONTENT

Time Domain Reflectometry (TDR) was developed by the power and telecommunications industries to locate faults in cables. A cable tester launches a voltage pulse into a coaxial cable, parallel pair wire or twisted pair wire. If a probe consisting of two or more parallel rods is embedded in a porous medium and a voltage pulse is launched along this probe, a reflection is created at the top of the probe and a second reflection is created at the end of the probe so the travel time can be measured. The particular probe shown in Figures 1 and 2 is segmented such that reflections are created at the top and bottom of each segment (ESI, 1997). Since the segment lengths \( L_p \) are fixed, the pulse velocity along each segment can be computed as twice its length divided by the time \( t \) required for a pulse to travel along the segment and back. Typically, this velocity is normalized with respect to the speed of light, \( c \ (= 3 \times 10^8 \text{ m/s}) \), and expressed as a dimensionless propagation velocity,

\[ V_p = \frac{2L_p}{ct} \]  

This ratio of velocities is approximately equivalent to the dielectric constant of the medium in which the probe is embedded. Since the dielectric constant of water is about 81 while that of mineral soil grains is 3-5, the measured dielectric constant is
predominately a function of volumetric water content,

$$\theta_v = \frac{V_w}{V_t}$$  \hspace{1cm} (2)$$

where $V_w$ is the volume of water and $V_t$ is the total volume. The relationship between volumetric water content and propagation velocity is linear (Herkelrath et al. 1991),

$$\theta_v = b \left( \frac{1}{V_p} \right) - a$$  \hspace{1cm} (3)$$
as shown in Figure 3 for clay loam and nickel mine tailings. The slope, $b$, and offset, $a$, are functions of the particular porous material, and they are determined by conducting laboratory calibrations (Topp et al., 1994; Zegelin and White, 1994).

2 CURRENT DEVELOPMENTS - DIRECT MEASUREMENT OF CONSOLIDATION

As tailings consolidate, there is an increase in the volume and weight of solids,

$$\Delta W_s = \gamma_w G_s \Delta V_s$$  \hspace{1cm} (4)$$

where $G_s$ is the specific gravity of the solids. If the tailings are saturated, and there is no change in the total volume, an increase in the solids volume is equal to a decrease in the volume of displaced water,$\Delta V_s = - \Delta V_w$, so

$$\Delta W_s = -\gamma_w G_s \Delta V_w .$$  \hspace{1cm} (5)$$

Combining with eqtn [2],

$$\Delta W_s = -\gamma_w G_s V_t \Delta \theta_v$$  \hspace{1cm} (6)$$

which states that as the tailings consolidate and solids displace water there is a decrease in the volumetric water content. This is measured using TDR technology as discussed earlier.

2.1 Preliminary field trials

Field trials have been performed in the beach area of a gold mine tailings impoundment in California and a phosphatic clay tailings impoundment in Florida using the segmented probe shown in Figures 1 and 2. This probe was simply pushed into the tailings and measurements made using the push-button TDR unit. For these initial trials, only near-surface profiles in the beach area along the embankment were obtained. Direct samples were also collected for laboratory determination of water content. The profiles in Figure 2 show that the TDR measurements reflect changes in moisture content with depth as did the oven-dried samples.

The compilation in Figure 3 illustrates that the relationship between water content and TDR travel time is materials-specific which is consistent with the experience of all users (Topp et al., 1994; Zegelin and White, 1994; Hook and Livingston, 1996).
This is a limitation of all techniques used for in situ measurement of water content in clays and organic soils. Among the factors identified by researchers have been the influence of high specific surface, bound water, and the frequency content of the voltage pulse as it travels along the probe (O’Connor and Dowding, 1999).

Use of TDR in loam, sand, and gravel can produce accuracies of ±0.03 m³/m³ and this can be improved with material-specific calibration. The field trials have highlighted the need for establishing a rigorous calibration protocol for various tailings to assure that the collected data is reliable. As current studies continue, it will be possible to determine the accuracy required for monitoring consolidation.

2.2 Use with existing consolidation model

A reliable testing technique to evaluate the highly nonlinear constitutive relations of soft, cohesive soils has been developed (Znidarcic et al, 1992; Abu-Hejleh et al, 1995). The technique is an enhanced seepage induced consolidation test which eliminates most of the limitations of the previously existing methods and the theory has been implemented in the CONDES finite element program (Yao and Znidarcic, 1997). However, topographic surveys and indirect measurements are still required for field validation, and one of the main shortcomings of this approach to tailings impoundment modeling is the reliance on laboratory testing of slurry samples to obtain consolidation characteristics for the analysis. While the developed laboratory testing methods are reliable they can never address the issue of material variability within a single impoundment. The amount of testing required to properly characterize a typical impoundment would be prohibitively expensive and time consuming. It is also important to note that prior to impoundment filling, there is no way of obtaining representative samples for the tailings. Material segregation is omnipresent during the filling operation and consolidation characteristics change dramatically as the slurry is sorted by grain sizes. The only way of overcoming this major obstacle is to monitor and determine consolidation characteristics as tailings are being deposited in the field. TDR technology in combination with CONDES has the potential to effectively address this need.

3 EXPERIMENTAL SETUP

3.1 Sample preparation

Georgia kaolin with the initial void ratio of $e_{00} = 4.7$ and the initial height of $H_0 = 85.4$ cm was poured into a transparent acrylic cylinder. The TDR probe manufactured by ESI Environmental Sensors (Figure 4), was placed vertically in the cylinder and fixed into position before the clay was poured in. The probe stayed in this fixed position throughout the test in order to ensure that the TDR test sections stayed in their positions as well as to provide good contact between the probe and the surrounding soil. TDR readings were taken for segments 3, 4 and 5. Since segment 2 was fully submerged into the clay slurry only during the first few days of the consolidation process, readings for this segment were discarded.
3.2 Boundary conditions

A consolidation test was conducted in three phases as shown in Figures 4 and 5. The effective stress at the top of the sample was equal to zero during Phase I and Phase II. Phase III commenced with the lowering of the water level below the top surface. This produced negative pore water pressures in the upper layers of the clay column which resulted in the corresponding increase of the effective stress at the top of the soil. The bottom boundary of the sample was subjected to a pressure head of 40 cm during Phase I while a negative pressure of 65 cm of water was imposed at the bottom boundary during Phase II and Phase III.

4 CONSTITUTIVE MODELS

Constitutive models used in the CONDES program are the relationship between effective stress and void ratio

\[ e = A(\sigma' + Z)^B \], \hspace{1cm} (7)

and the relationship between hydraulic conductivity and void ratio

\[ k = Ce^D \]. \hspace{1cm} (8)

Parameters A, B and Z in equation [7] were obtained by fitting the experimental values of the effective stresses and corresponding void ratios. The void ratio at zero effective stress (i.e., the void ratio of the slurry poured into the container) was found to be 4.7. The void ratio of 2.36 measured at the end of Phase III at the bottom of the soil column corresponded with an effective stress of about 14.3 kPa. Parameters C and D in equation [8] were found by matching the predicted settlement curve with the measured curve as shown in Figure 5.

5 EXPERIMENTAL RESULTS

Final void ratio profiles obtained by sampling the soil column for gravimetric measurement of moisture content are compared with the final void ratio profile calculated by CONDES in Figure 6. The final volumetric water content profile is plotted in Figure 7. The numerical model is consistent with the gravimetric measurements in the lower portion of the slurry column.

The time history in Figure 8 shows that as the solids consolidated, there was a decrease in the travel time, \( t \). Therefore, the velocity \( V_p \) was increasing which is consistent with the relationship in equation [6].

In Figure 9, numerically-determined and gravimetrically-determined volumetric water contents are plotted versus TDR measurements of travel time expressed as \( 1/V_p \). As the slurry consolidated, the water content decreased and the travel time decreased which is consistent with the relationship in equation [6]. As the volumetric water content decreased from an initial value of 0.825 to a final value of 0.72, \( 1/V_p \) deceased from 5.2 to 4.8.
6 DISCUSSION

In Fig 6 and Fig 7, it is apparent that the most consistent numerical results were obtained at the bottom of the soil column. This portion of the column corresponded with the TDR probe segment 4 and segment 5. The results higher in the column diverge from the numerical model, and the TDR measurements in Figure 8 show that within segment 3 the behavior of the slurry must be different. Since the TDR measurements are based on dielectric properties which are highly dependent on free water, it appears that there must be a change in this property for slurry above a height of 40 cm in the column.

This difference is also apparent by comparing Figure 9 and Figure 3. The summary in Figure 3 reiterates the well-known fact that the relationship between volumetric water content and travel time is very dependent on the material dielectric properties. Obviously, there are concerns about the free water content but these studies may help to provide insight into the effect of bulk density on TDR measurements (O’Connor and Dowding, 1999).

The time history in Figure 8 is consistent with the settlement time history in Figure 5 and represents promise for this technique for insitu monitoring of consolidation of saturated materials. The results in Figure 9, on the other hand, make it apparent that it may not be useful for obtaining measurements that can be used in the CONDES numerical model.

It is important to remember that we are most interested in the CHANGE in volumetric water content versus time. The absolute values plotted in Figure 9 are within the range of +/- 0.03 m$^3$/m$^3$ which is consistent with other published results. Perhaps the accuracy in CHANGE in volumetric water content may be +/- 0.003 m$^3$/m$^3$.

It should also be noted that ESI has updated the firmware algorithm for determining the travel time along each segment of the probe. This algorithm has not been tested in this application.

7 SUMMARY

Laboratory tests have been performed using a Georgia kaolin slurry with an initial void ratio of 4.7 that was consolidated under self-weight to a final void ratio of 2.35. This corresponds to a decrease in volumetric water content from 0.825 to 0.72. The propagation velocity profile was measured using a MoisturePoint segmented probe during the test and, using the default firmware algorithm for determining travel time along each segment, the measured $1/V_p$ decreased from 5.2 to 4.8. Considering such a small change in $1/V_p$ over a very large change in void ratio, the sensitivity of TDR is much less than that which is possible from gravimetric measurements of water content. Although the qualitative trend is promising, it will be necessary to do a more fundamental analysis of changes in the TDR waveform.

8 REFERENCES


Figure 1. Measuring water content of tailings using segmented TDR probe
Figure 2. Schematic of segmented probe and depth profile of volumetric water content obtained in phosphatic clay tailings.

Figure 3. Relationship between volumetric water content and propagation velocity for a variety of materials; phosphatic clay and gold mine tailings from present studies; clay loam and nonclay soils (Hook and Livingston, 1996); nickel tailings (Sun, 1996).
Figure 4. Segmented probe in acrylic cylinder for laboratory test of kaolin clay slurry consolidation. The initial solids height $H_0$ was 85.4 cm and the final solids height $H_f$ was 55 cm. Note the change in pore pressure at the bottom of the cylinder for Phases II and III.

Figure 5. Time history of settlement of the top of the solids within the acrylic cylinder.
Figure 6. Profile of gravimetrically measured void ratio versus depth after completion of Phase III. Note that three (3) gravimetric samples were taken within the depth interval of each TDR probe segment.

Figure 7. Profile of gravimetrically determined volumetric water content versus depth after completion of Phase III.
Figure 8. Time history of TDR pulse travel time, $t$, for segments 3, 4, and 5. Each data point is an average of three (3) TDR measurements.

Figure 9. Correlation between travel time, $1/V_p$, measured with TDR, and volumetric water content as (a) calculated by CONDES, and (b) measured gravimetrically at the beginning of Phase I and at the completion of Phase III.