# COMPARING METHODS OF ESTIMATING CRACK VOLUME IN SHRINK-SWELL SOILS

A Senior Scholars Thesis

by

LEONARDO D. RIVERA

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2008

Major: Agricultural Systems Management

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Approved by:

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| Research Advisor: | Cristine Morgan |
| Associate Dean for Undergraduate Research: | Robert C. Webb |

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# ABSTRACT

Comparing Methods of Estimating Crack Volume in Shrink-Swell Soils (April 2008)

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Predicting soil crack formation and closure in high shrink-swell soils is crucial for modeling water movement and solute transport. However, soil cracking, as it occurs in natural conditions, is not well understood. The objectives of this research are to 1) compare shrinking and swelling of two Vertisols with different mineralogy and 2) compare three methods for estimating soil crack volume. The soils monitored include, Ships Clay (Very-fine, mixed, thermic Chromic Hapluderts), with mixed mineralogy and Burleson Clay (Fine, smectitic, thermic Udic Haplusterts), with smectitic mineralogy. During two drying events, vertical subsidence and cracking were measured on both soils. Vertical subsidence was measured at three locations in each soil with rods fixed at four depths. Rod movement was converted to soil crack volume by assuming equidimensional shrinkage. A second method for estimating crack volume used direct measurements of cracks in the field. A neutron moisture meter access tube was installed to measure soil moisture at each subsidence location. A total of 20 leveling and moisture measurements were completed and 10 hand measurements of cracking were made. At the completion of the study, full characterization of each measurement location was performed, including coefficient of linear extensibility (COLE) measurements.

These COLE measurements were used as a third method of estimating crack volume in relation to soil moisture.

The results showed the leveling-predicted crack volume was ten times that of the hand measured crack volume but followed the same temporal trend.  The leveling-predicted crack volume is the most accurate of the three methods.  COLE was also shown to be a good predictor a soils shrink-swell potential.

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# NOMENCLATURE

| | |
|---|---|
| COLE | Coefficient of Linear Extensibility |
| NMM | Neutron Moisture Meter |
| USDA | United States Department of Agriculture |
| NRCS | Natural Resources Conservation Services |
| $V_m$ | Volume of soil clod at 1/3 bar or field capacity |
| $V_d$ | Volume of soil clod oven dry |
| $L_m$ | Length of soil rod at 1/3 bar or field capacity |
| $L_d$ | Length of soil rod oven dry |
| $\Delta V$ | Change in soil volume |
| $\Delta Z$ | Change in soil layer height |
| Z | Original soil layer height |
| $V_{cr}$ | Soil crack volume |
| mm | Millimeter |
| cm | Centimeter |
| m | Meter |

| | |
|---|---|
| W | Crack width |
| D | Crack depth |
| L | Crack length |
| $\theta_t$ | Volumetric water content at time of measurement |
| $\theta_{fc}$ | Volumetric water content at field capacity or 1/3 bar |

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# CHAPTER I

# INTRODUCTION

Expansive soils cause more damage in the U.S. than earthquakes, tornados, hurricanes, and floods combined (Jones and Holtz, 1973). It is estimated that 20% of the soils in the United States can be subject to shrinking and swelling (Arnold *et al.*, 2005). Of the 12 soil orders recognized in soil taxonomy Vertisols are recognized for their shrink-swell properties (Soil Survey Staff, 1999). Vertisols cover 3,160,000 $km^2$ approximately 2.4% of the earth's surface. Under normal conditions these soils have very low infiltrations rates but when they dry, they begin to form cracks, creating voids in the soil where water can flow rapidly, increasing infiltration significantly. Because cracks create preferential flow paths, soil cracking can complicate modeling of soil hydrology. Successfully simulating water and solute transport across landscapes with shrink-swell soils is impossible without including soil cracking. Texas is well known for its soils with high shrink-swell potential, including areas of prime farmland and urban development such as the Texas Blackland prairie (Dallas-Fort Worth, Austin, San Antonio) and the Texas Coastal Plains (Houston). Because these soils are in high population and high management areas, it is ever more critical to understand the phenomena of crack formation to better understand the landscape hydrology and transport of nutrients, chemicals and particulates.

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This thesis follows the style of *Soil Science Society of America Journal.*

High shrink-swell soils are associated with high clay content and predominantly smectitic clays; soils reported with other minerals such as kaolinte have also been observed to have high shrink-swell potential. When these soils are subject to periods of wetting and drying, the formation of cracks in the soil leading up to the surface can drastically alter the landscape hydrology (Wilding and Puentes, 1988). These soils are believed to go through three shrinkage phases; structural shrinkage, normal shrinkage, and residual shrinkage (Stirk, 1954; Yule and Ritchie, 1980; Kirby *et al.,* 2003). During structural shrinkage, soil dries from saturation to field capacity; it is believed that there is little volume change. Normal shrinkage is where the most change in the soil volume will be observed and includes most natural field-moisture conditions. Residual shrinkage occurs in very dry soil moisture conditions (Kirbey *et al.,* 2003).

**Coefficient of linear extensibility**

Soil cracking behavior, as it occurs in its natural conditions, is not well understood. One difficulty that is associated with understanding soil cracking is determining the best method of measuring crack volume in the field. There are a few different methods for quantifying soil cracking in the field and in the lab. One method is through the use of published lab measurements that describe the shrink-swell potential of a soil, the Coefficient of Linear Extensibility (COLE) (Morgan, 2003). A second form of measurement is conducted by measuring the height change of the soil as it shrinks, assuming equidimensional shrinking and calculating the shrinkage in the soil (Arnold *et al*., 1973; Bronswijk *et al*., 1991). A more direct form of measurement is by directly measuring cracks in the field (Kishne et al., 2008). This method is time consuming and the accuracy is unknown. These methods, and the assumptions associated with them have never been tested or compared to each other.

The Coefficient of Linear Extensibility (COLE) is a lab-based value that quantifies the swelling and shrinkage potential of a soil layer (Grossman *et al.,* 1968). COLE is calculated by using the difference in volume of a soil ped when moist and dry;

$$COLE = \sqrt[3]{\frac{V_m}{V_d}} - 1 \qquad [1]$$

where $V_m$ is the soil volume at field capacity $m^3$ $m^{-3}$ and $V_d$ is the soil volume oven dry $m^3$ $m^{-3}$. Another method of measuring COLE is $COLE_{rod}$, which is conducted with the use of a saturated soil paste that is molded into rods that may be trimmed to various lengths and then dried and the length measured. It is calculated as $COLE_{rod}$ = (Lm – Ld)/Ld, where Lm is the length and 33 kPa tension and Ld is the length when dry (Vaught *et al.,* 2006; Jong *et al.,* 1992). Both Methods of obtaining COLE and $COLE_{rod}$ have been shown to be highly correlated (Vaught *et al.,* 2006; Jong *et al.,* 1992). The easiest way of obtaining a COLE value for a particular soil is by locating it in the USDA-NRCS Soil Survey. The COLE recorded in USDA-NRCS Soil Survey data, however, is likely to be less accurate than direct measurement at a specific location because it is a number to be applied to the range of soils that fit a particular classification. This easy access to COLE for a soil is an advantage for using COLE to estimate crack volume.

There are several reasons COLE may not be the best parameter to use in predicting changes in crack volume from changes in soil water content. COLE measurement using natural soil clods assumes equidimensional shrinkage, which may not be true for in situ conditions. Knowledge of the degree of vertical shrinkage compared to horizontal shrinkage is important in estimating changes in crack volume on soil shrinkage or swelling. Another disadvantage for using COLE to predict crack formation is that COLE is variable in the field and has a fairly high coefficient of variation of measurement in the lab (Anderson *et al.,* 1973). Values of COLE has been shown to be highly correlated with clay content, fine clay content, and specific surface area (Anderson *et al.,* 1973; Jong *et al.,* 1992), all of which can express considerable spatial variability across a landscape.

**Height change measurements**

Another means of estimating soil crack volume in shrink-swell soils is by measuring the change in vertical thickness of the soil and assuming a relationship between vertical and horizontal shrinkage, usually assumed to be equidimensional. This method is less time consuming than the method of actual geometrical measurements of cracks. This could possibly be a better proxy for estimating soil crack volume than COLE. By assuming equidimensional shrinkage we can use an equation to estimate crack volume from Bronswijk *et al.* (1991) and Bauer *et al.* (1993). The changes in layer thickness are used to estimate crack volume per unit area ($V_{cr}$):

$$\Delta V = (1 - (1 - \Delta Z/Z)^3)Z, \text{ and} \qquad [2]$$

$$V_{cr} = \Delta V - \Delta Z, \quad [3]$$

where Z is the layer thickness (mm), ΔZ is change in layer thickness (mm) and ΔV is change in crack volume per unit area (mm).

Estimating crack volume per unit area from measurements of vertical thickness of soil has been used in research reported in the literature, but the method has not been validated. Kirby *et al.* (2003) measured soil height change by fixing rods at depth intervals throughout the soil profile and measuring height changes of rods in relation to a fixed point. Their research site was conducted on foothills of the Liverpool Ranges on a soil classified as a giant Endocalcareous, Self-mulching, Black Vertisol (Isbell, 1996). They found a correlation between moisture content change and height change of the soil at different depths, but did not investigate actual cracking. Arnold *et al.* (2005) used the same method of height measurements on a site near Riesel, TX where the dominant soil is Houston Black (fine, montmorillonitic, thermic, udic Haplustert). Crack volume was estimated using measured height changes and modeled soil moisture to drive a crack flow model.

**Hand measurements**

The third method of estimating crack volume in shrink-swell soils is through the use of hand measurement of geometrical dimensions in the field. Directly measuring soil crack geometry in the field is time consuming and wrought with uncertainty of how crack width changes with depth. To add to the uncertainty, short, high-intensity rains cause the upper part of the soil to swell and close cracks on soil surface, while subsoil cracks are not evident from surface observation. To measure a 1$m^2$ area when conditions are favorable it takes as much as two hours, depending on the extent of the soil cracking that has occurred (Kishne, 2007). To accurately quantify crack volume per unit area, about 4 $m^2$ is required, not including replication (Kishne *et al.*, 2008). Because of these difficulties, direct measurement of crack geometry is not widely used as a method of estimating soil crack volume.

**Project objectives**

The overall objective of this research is to improve the efficiency of direct in-field crack measurements and understand the difference three methods of estimating soil cracking. The three methods for estimating soil crack volume will be compared. These methods are 1) using USDA-NRCS COLE values and measurements of soil moisture, 2) measuring height changes of rods and assuming equidimensional shrinkage, and 3) actual crack measurements.

# CHAPTER II

# METHODS

**Site descriptions**

The Burleson Site is located near Snook, TX, coordinates 30°29’17.60”N, 96°27’27.08”W. The soil series is a Burleson Clay (Fine, smectitic, thermic Udic Haplusterts) with 0 to 1 percent slopes. The site was chosen for its high shrink-swell potential and smectitic clay mineralogy. During the measurements, the site was in native grasses managed for grazing, but was historically was under a cotton-corn rotation. It had been untilled for four years prior to site installation.

The Ships is located approximately 2.63 km NW of the Burleson location, 30°30'26.22"N 96°28'25.91"W. The soil series is a Ships Clay (Very-fine, mixed, thermic Chromic Hapluderts), which is in a floodplain with 0 to 1 percent slopes. During the measurements the site was managed for grazing without improved grasses. The Site was plowed prior to installation and was then grazed, flooded, and plowed intermittently. During the wetter parts of the year livestock were not kept in this area due to risk of flooding. The site was chosen because of it high shrink-swell potential and mixed mineralogy

**Site set-up**

In August 2006, at each of the two sites, three replicates of the instrumentation were installed. This instrumentation included a set of soil-anchored rods to measure shrinkage and swelling and a neutron probe access tube. Additionally, one reference monument per site was also installed. At each site and replication, iron rods were anchored at different depths of 20, 40, 80, and 120 cm (Fig. 1). A Giddings Probe (Giddings Machine Company, Windsor, CO) was used to install the rods. First, a 5-cm diameter hole was augured to the desired depth then quick-drying cement was used to anchor the appropriate length rod to the bottom of the hole. A 5-cm diameter aluminum sleeve was then inserted to line the hole around the rod to prevent contact friction with the soil and allow the rod to move unrestricted by the soil above the depth of the anchor. The monument was installed similarly using a piece of rod iron that was anchored to a depth of 3 m. It was assumed that there would be minimal vertical movement of the soil at the 3-m depth. A 5-cm diameter neutron moisture meter access tube was then installed to allow soil water content measurements to be taken at different depths. The site set up is shown in Fig. 1. The four rods and access tube were distanced about 50 cm apart in a straight line (Fig. 1). Each of the replicate locations were spaced about 10 meters from each other. Fence panels were installed around each replicate location within a site to prevent animals or humans from stepping on the surface rods and tube –the area where the hand-measured estimates of crack volume would be made.

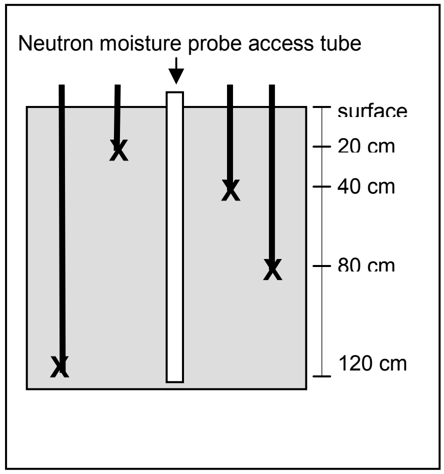


**Fig. 1.** Schematic of rod and access tube set-up for each replicate measurement station. There were three replicates per site.

**Measurements**

Measurements were made at both sites starting in August 2006 and ending in December 2007. The measurements of changes of elevation of the rods were made fortnightly, while the hand crack geometry measurements were taken whenever cracks were visible at the surface. Moisture measurements were made, at the same time the leveling measurements were conducted, using a neutron moisture meter (Model 501 DR, Campbell Pacific Nuclear, Concord, CA). In August 2007 a new Model 503 DR was purchased and used in place of the 501 DR. Rainfall was measured using tipping bucket HOBOware Rain Gauges at each site.

*Rod Elevation Measurements*

Measurements of the change in elevation of the rods fixed at different depths in relation to the monument were made with field survey leveling equipment. The measurements from August 2006 to July 2007 were made using a Pentax AL-320 optical level; the measurements after July 2007 were made using a Sokkia SDL 50 laser level. The equation used to estimate crack volume using soil height measurements was from Bronswijk (1991) and Bauer *et al.* (1993). The changes in layer thickness were used to estimate crack volume per unit area ($V_{cr}$).

*Measurements of crack dimensions*

Hand measurements of the geometrical dimensions of cracks were made at the same time as the leveling measurements whenever cracks were visible at the surface. To be considered a crack worth measuring, a crack had to be at least 2 cm deep or 1 cm wide - if it did not meet this criteria it was considered surface crusting and was not measured. Measurements were made with the use of a “Crackometer”. A Crackometer consisted of a set of 6.35-cm wide by 0.79-cm thick steel strap cut to various lengths. The Crackometer was used to measure the vertical depth of a crack relative to the surface by placing it into the crack until it touched the bottom. The length and the width of a crack was measured with a flexible retracting tape measure. A measurement of the length, width, and depth of a crack were taken approximately every 10 cm unless there was a significant change. Each measurement was called a node and used to extrapolate a model of the crack volume (Fig. 2). The crack volume was calculated assuming that a crack has triangular geometry. The formula used to calculate crack volume is:

$$V_{hcr} = \left(\frac{1}{3}\right) * L * \left(\left(\frac{1}{2}W_1 * D_1\right) + \left(\frac{1}{2}W_2 * D_2\right) + \sqrt{\left(\frac{1}{2}W_1 * D_1\right) + \left(\frac{1}{2}W_2 * D_2\right)}\right) \qquad [4]$$

where $V_{hcr}$ is the estimating crack volume, L is the length between each node, W is the width of crack at the node, and D is the depth of the crack at the node. The measurements are conducted in a 1 m x 1 m PVC frame typically at four different areas within each site.

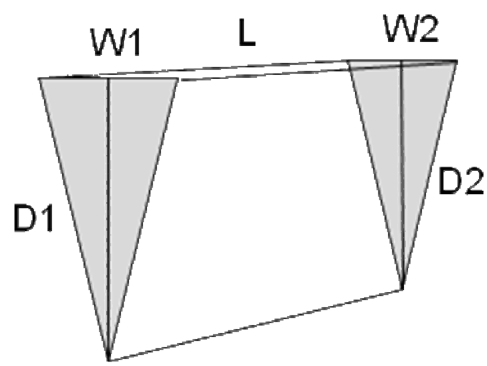


**Fig. 2**. Schematic of crack geometry and measurement points.

*Shrinkage-Swelling from COLE and moisture measurements*

The soil water content measurements that were taken at the time of the rod-elevation measurements were used along with the COLE values that were determined from the lab analysis to estimate change in layer thickness. The neutron moisture meter was used to measure volumetric soil water content at 5 different depth zones (10 to 30, 30 to 50, 50 to 70, 70 to 90, 90 to 110, and 110 to 120 cm). Average COLE values for each depth zone were calculated using the measured COLE values made using soil clods removed from different depths. . The formula used to determine the change in layer thickness from COLE and volumetric soil water content was:

$$\Delta Z = COLE_{ave} (\theta_t - \theta_{fc}) \times Z \qquad [5]$$

Where $\Delta Z$ is your change in layer thickness, $COLE_{ave}$ is the average COLE value for the layer, $\Theta_t$ is your volumetric moisture content at time of measurement, $\Theta_{fc}$ is the volumetric water content of the soil at field capacity, and Z is the original thickness of the soil layer. The $\Delta Z$ values were then used in conjunction with the Bronswijk (1991) and Bauer *et al.* (1993) equation to calculate total crack volume per unit area.

**Site soil cores for COLE and soil characterization**

The rods, neutron access tubes, and fencing at the Burleson Site were removed on December 4$^{th}$, 2007, and on December 5$^{th}$, 2007, at the Ships Site. As the sites were cleared, a Giddings Probe was used to take three cores to an average depth of 200 cm at each of the three measurement-locations within a site. These cores were used to obtain samples from which to characterize the soil at each location. The first of the three cores was used to collect clods for COLE measurements. In each soil horizon, three clods were removed and coated in saran. With the remaining cores, bulk samples were collect for analysis of particle size, salinity, organic carbon, and total carbon. The lab analysis methods are based from the Soil Survey Laboratory Methods Manual Version 3.0, January 1996.

# CHAPTER III

# RESULTS

## Soil characterization and lab analysis

After the measurements were completed at the Ships and Burleson Sites, the measurement locations were characterized and samples were sent in to the lab for full analysis (Table 1). The lab analysis of the COLE values showed that the Ships Site had higher COLE values than the Burleson Site. Average COLE values for other Ships Clay soils series were 0.096 m $m^{-1}$, the average COLE value for the Ships Clay at the Ships Site was 0.16 m $m^{-1}$. Average COLE values for Burleson Clay soil series are 0.11 m $m^{-1}$, the average COLE value for the Burleson clay at the Burleson Site was 0.13 m $m^{-1}$. The field characterization showed that these locations had typical classification of their respective soil series. The Ships Site had a buried A horizon and secondary calcium carbonate forming in deeper portions of the soil profile. The Burleson Site had secondary calcium carbonates forming at 80 cm and deeper in all three locations with the Site and a lithologic discontinuity starting at 180 cm.

## Weather data

During the duration of our measurements the Burleson location received 1496.4 mm of precipitation while the ships location received 1673.2 mm of precipitation (Table 2). During the cracking event in 2006 the ships and Burleson location received approximately the same amount of rainfall. During the cracking even in 2007 the Ships

**Table 1.** Results from field characterization of horizon nomenclature and lab analysis of COLE in relation with depth of horizons.

| Burleson | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Location A | | | Location B | | | Location C | |
| **Depth** | **Nomen-clature** | **†COLE (cm/cm)** | **Depth** | **Nomen-clature** | **COLE (cm/cm)** | **Depth** | **Nomen-clature** | **COLE (cm/cm)** |
| 0-12 | Ap1 | 0.138 | 0-18 | Ap | 0.128 | 0-18 | Ap | 0.123 |
| 12-21 | Ap2 | 0.125 | 18-37 | A | 0.138 | 18-48 | Bw | 0.122 |
| 21-55 | Bw | 0.137 | 37-91 | Bss | 0.149 | 48-80 | Bss | 0.125 |
| 55-90 | Bss | 0.131 | 91-126 | Bssk1 | 0.140 | 80-119 | Bssk1 | 0.124 |
| 90-133 | Bssk1 | 0.146 | 126-179 | Bssk2 | 0.142 | 119-180 | Bssk2 | 0.142 |
| 133-188 | Bssk2 | 0.154 | 179-217 | B'ss | 0.128 | 180-230 | B'ss | 0.134 |
| 188-230 | B'ss | 0.129 | | | | | | |

| Ships | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Location A | | | Location B | | | Location C | |
| **Depth** | **Nomen-clature** | **COLE (cm/cm)** | **Depth** | **Nomen-clature** | **COLE (cm/cm)** | **Depth** | **Nomen-clature** | **COLE (cm/cm)** |
| 0-19 | Ap | 0.157 | 0-20 | Ap | 0.129 | 0-20 | Ap | 0.115 |
| 19-40 | Bss1 | 0.154 | 20-57 | Bw | 0.143 | 20-60 | Bw | 0.146 |
| 40-79 | Bss2 | 0.148 | 57-91 | Bss | 0.138 | 60-100 | Bss | 0.142 |
| 79-125 | Assb1 | 0.188 | 91-113 | Assb1 | 0.159 | 100-137 | Assb | 0.168 |
| 125-166 | Assb2 | 0.193 | 113-142 | Assb2 | 0.158 | 137-167 | Asskb | 0.167 |
| 166-198 | Bsskb1 | 0.187 | 142-171 | Bssb | 0.162 | 167-205 | Bsskb | 0.195 |
| 198-225 | Bsskb2 | 0.187 | 171-200 | Bsskb | 0.150 | | | |

†Coefficient of Linear Extensibility (COLE)

**Table 2.** Precipitation data collected over period of measurements.

| Month | Burleson (mm) | Ships (mm) |
|---|---|---|
| August 2006 | 31 | 67 |
| September 2006 | 95.6 | 84.8 |
| October 2006 | 359 | *359 |
| November 2006 - March 2007 | 446 | 262 |
| April 2007 | 80.8 | 83.2 |
| May 2007 | 80.8 | 124.6 |
| June 2007 | 146.6 | 57 |
| July 2007 | 123 | 186.8 |
| August 2007 | 34.4 | 104.8 |
| September 2007 | 19.8 | 108 |
| October 2007 | 79.4 | 106 |
| November 2007 | 0 | 130 |
| December 2007 | 0 | 0 |

* Data used from Burleson Location due to suspicious readings

location received approximately 40% more rainfall than the Burleson location over a longer duration of time which cause little cracking to occur in the Ships location.

**Crack volume measurements**

The three methods of estimating crack volume provided a wide range of values for predicted crack volume. The leveling measurements were taken on twenty-one different dates. The Burleson Site locations had the same cracking trends but different volumes for the three locations (Fig. 3). Location A had the lowest crack volume occur during the first cracking event in 2006 and the second highest amount of crack volume occur during the second cracking event in 2007 even though it had the highest average COLE values. Location C had the highest crack volume occur during both cracking events. More crack volume was measured in during the 2007 cracking then in 2006 even though more heavy amounts of rainfall occurred that summer. The Ships Site locations showed the same cracking trend but different volumes for the three locations as well (Fig. 4). Location A for the ships location had the lowest amount of crack volume occur during the first cracking event in 2006 even though it had the highest average COLE values. The first cracking event for the Ships location had a significant amount of crack volume occur; however, during 2007 minimal cracking occurred because of the heavy rainfall it received and the locations position in a floodplain.

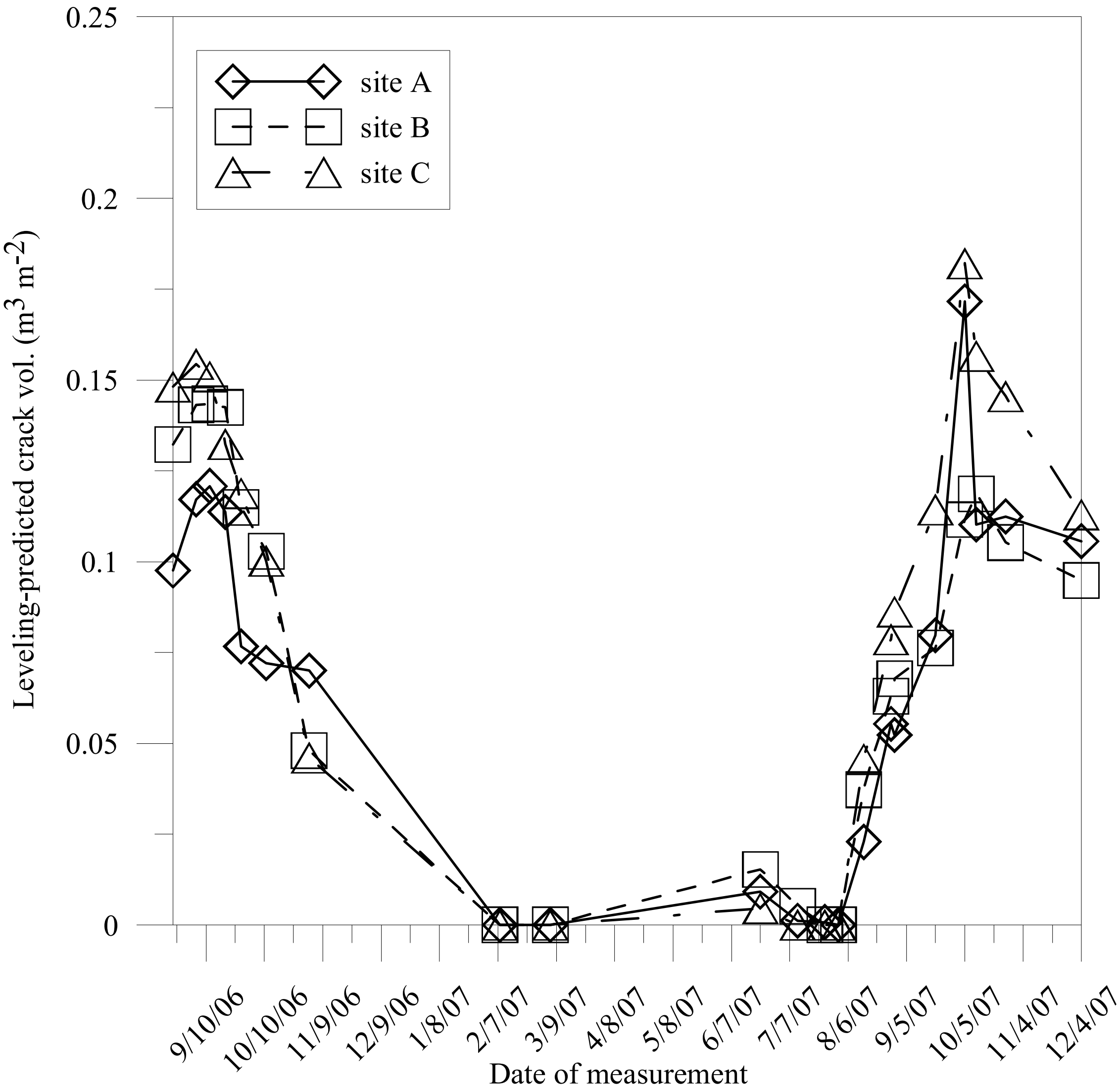


**Fig. 3.** Results of leveling-predicted crack volume for the Burleson location in m$^3$ of crack volume per m$^2$ of soil surface.

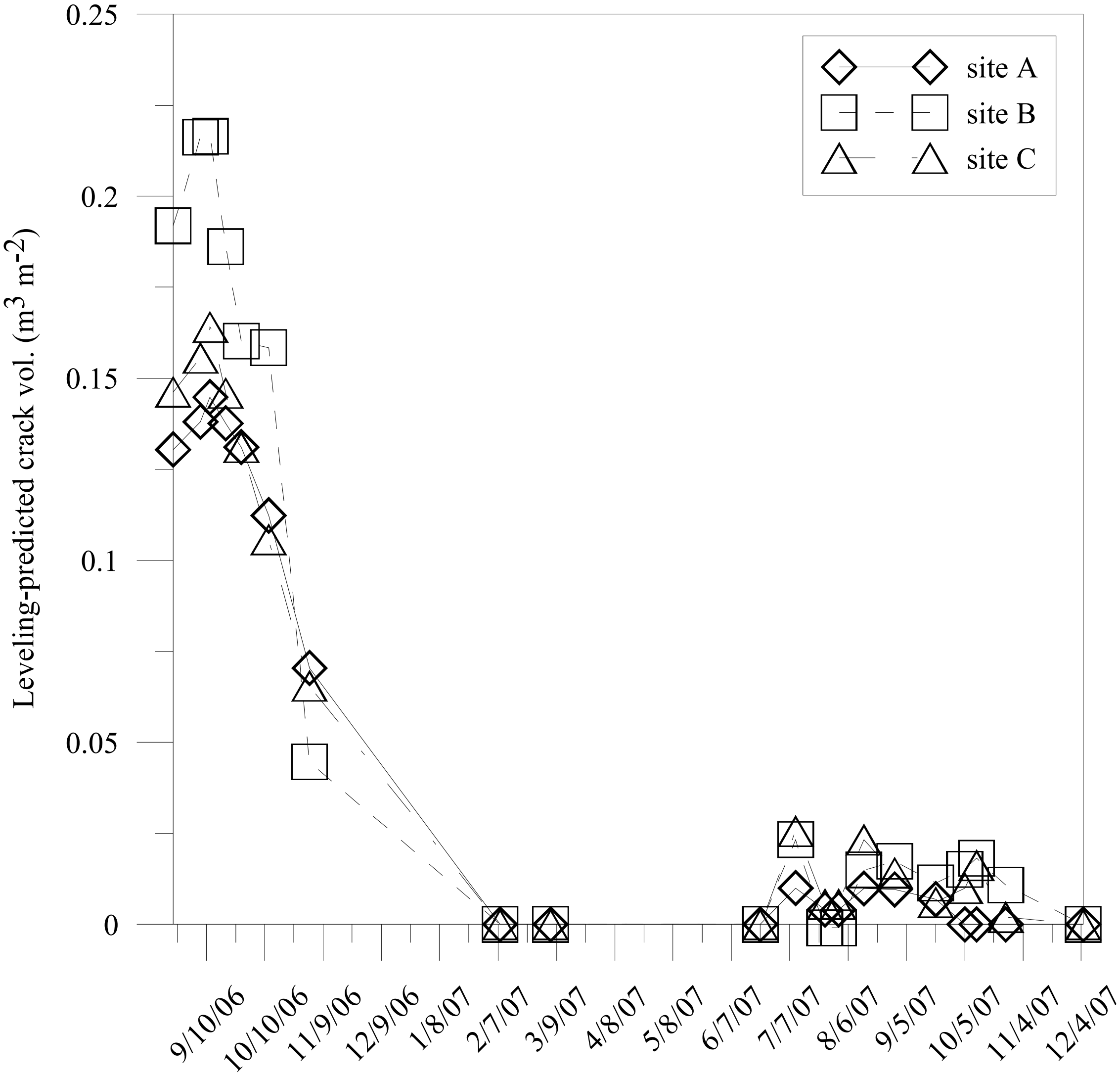


**Fig. 4.** Results of leveling-predicted crack volume for the Ships location in $m^3$ of crack volume per $m^2$ of soil surface.

The hand crack measurements were not conducted as many different times as the leveling measurements due to the amount of time required for completing these measurements. The hand-measurements were taken on ten different dates. The hand-measured crack volume provided varying results for the Ships and Burleson location. The hand-measured crack volume for the Burleson location provided similar values throughout the three Site locations (Fig. 5). The cracking events in 2006 and 2007 provided varying results. In 2007 approximately two to three times more crack volume was measured by hand than in 2006. Location B had the highest amount of crack volume measured in 2007. The hand measured crack volume measured at the Ships location provided similar values throughout the three locations (Fig. 6). The cracking events in 2006 and 2007 provided the same values unlike the Burleson location. The three different methods of estimating crack volume followed the same trend but provided significantly different values for predicted crack volume. The Burleson location had the highest measured crack volume come from the leveling-predicted crack volume (Fig. 7). The hand-measured crack volume was ten times less than the leveling-predicted. The COLE-predicted crack volume followed the same trend as the leveling-predicted but predicted approximately half the amount of crack volume than the leveling-predicted. The Ships location also had the highest measured crack volume come from the leveling-predicted crack volume (Fig. 8). The COLE-predicted crack volume also followed the same trend as the leveling-predicted crack volume but predicted half the amount of crack volume, accept during the 2007 cracking event; COLE predicted more crack volume during the 2007 cracking event.

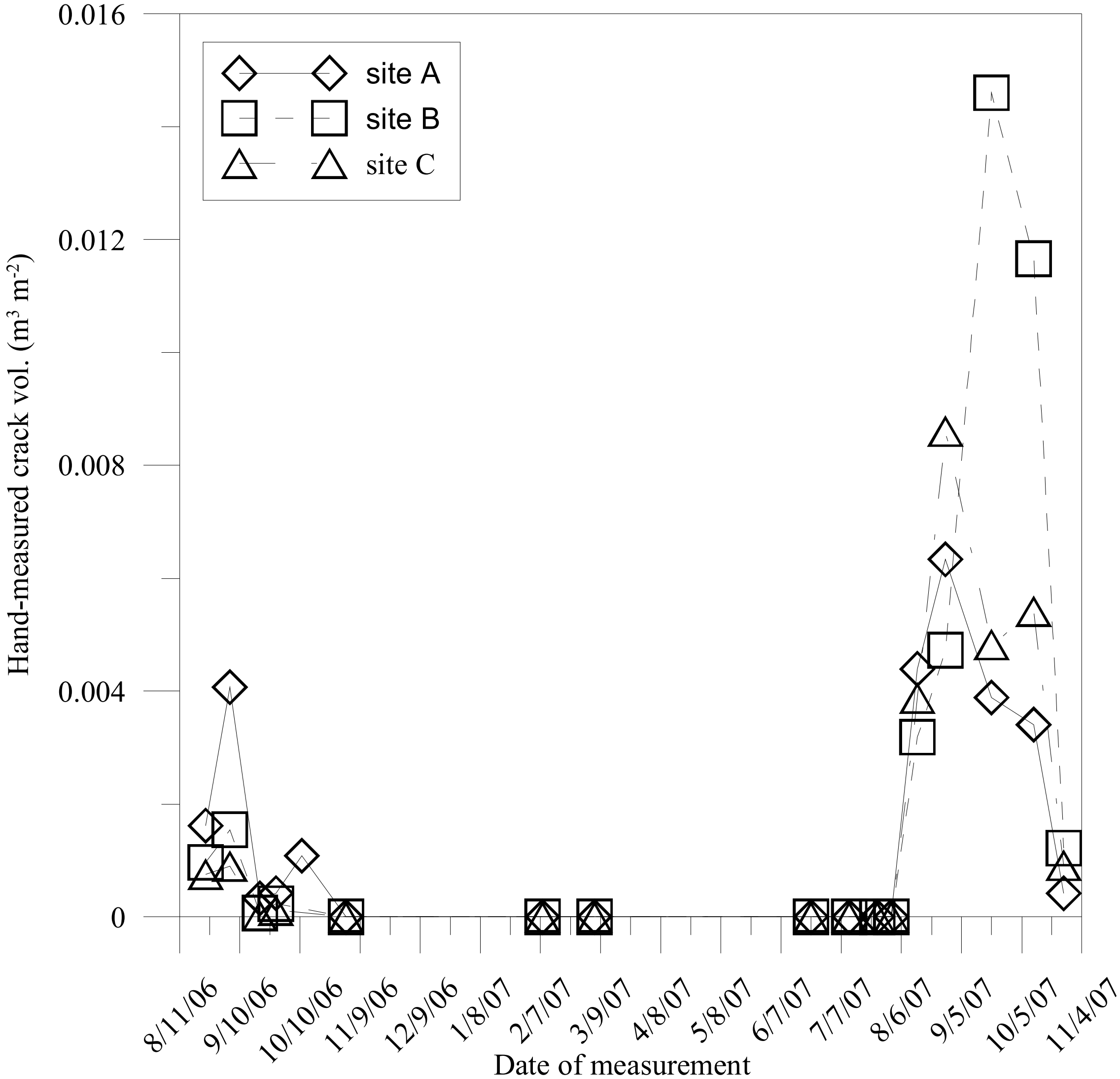


**Fig. 5.** Results of hand-measured crack volume for the Burleson location in $m^3$ of crack volume per $m^2$ of soil surface.

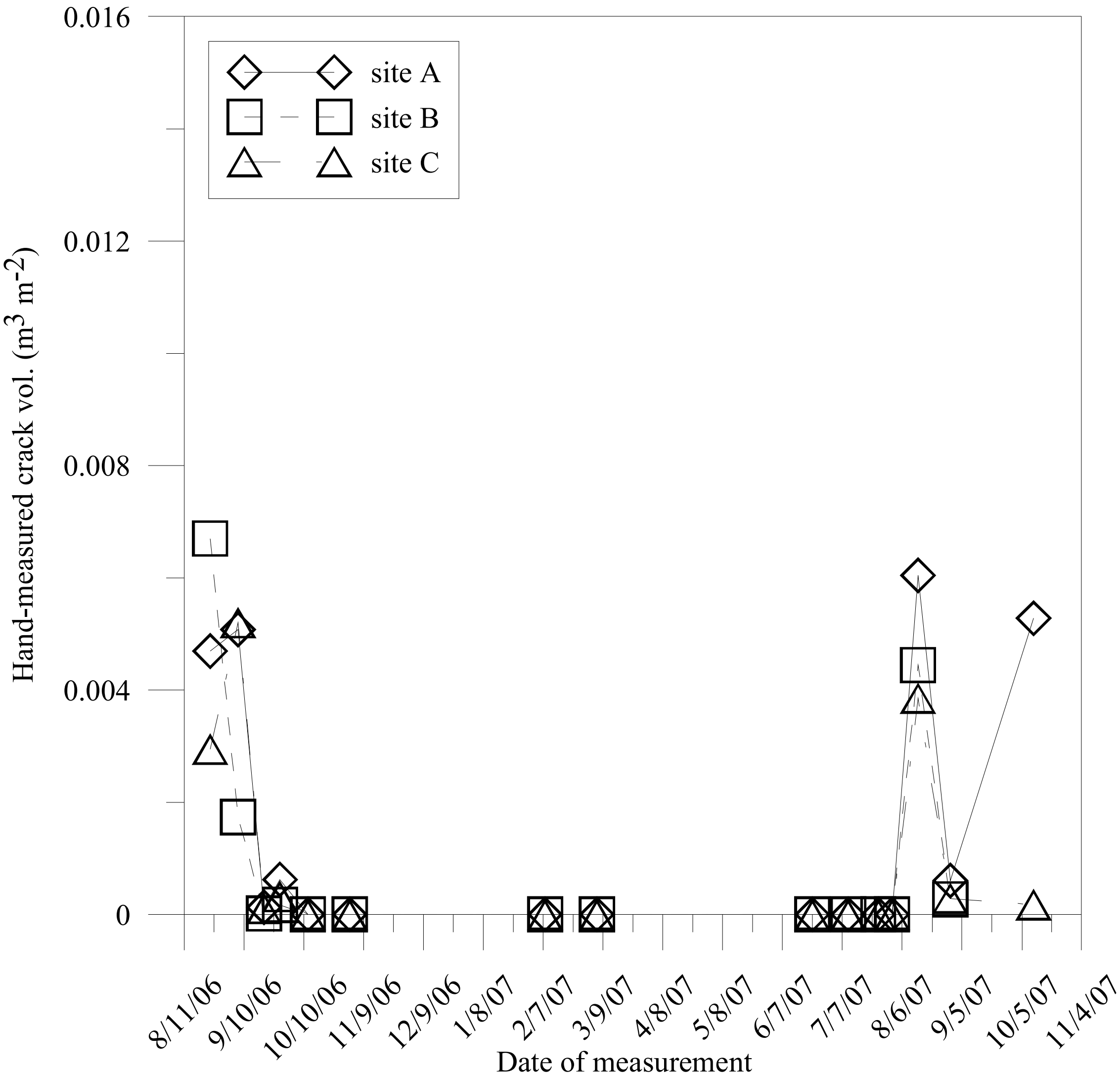


**Fig. 6.** Results of hand-measured crack volume for the Ships location in $m^3$ of crack volume per $m^2$ of soil surface.

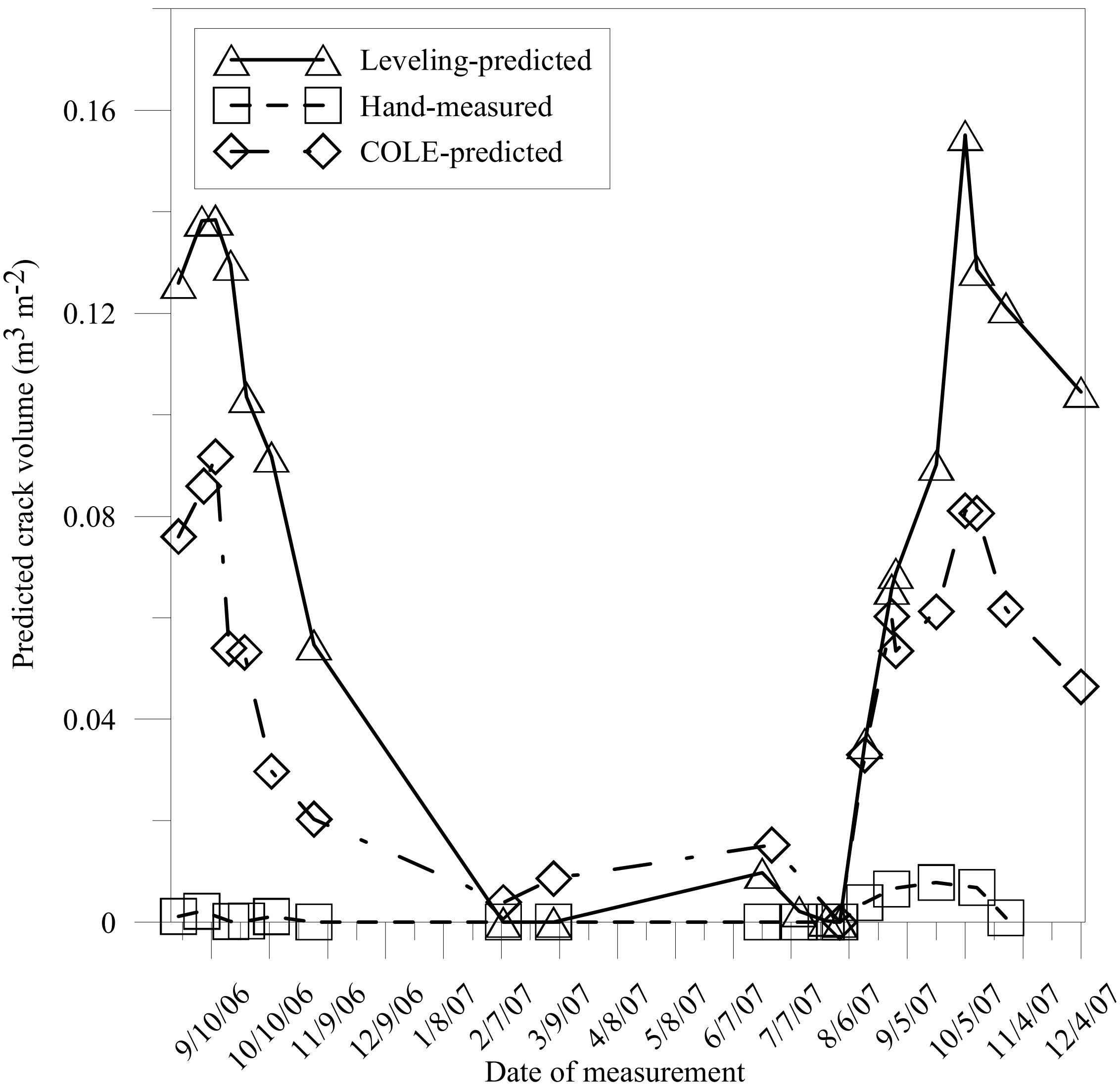


**Fig. 7.** Shows the comparison of how leveling-predicted, hand-measured, and COLE-predicted crack volume was predicted on different days of measurement for the Burleson location.

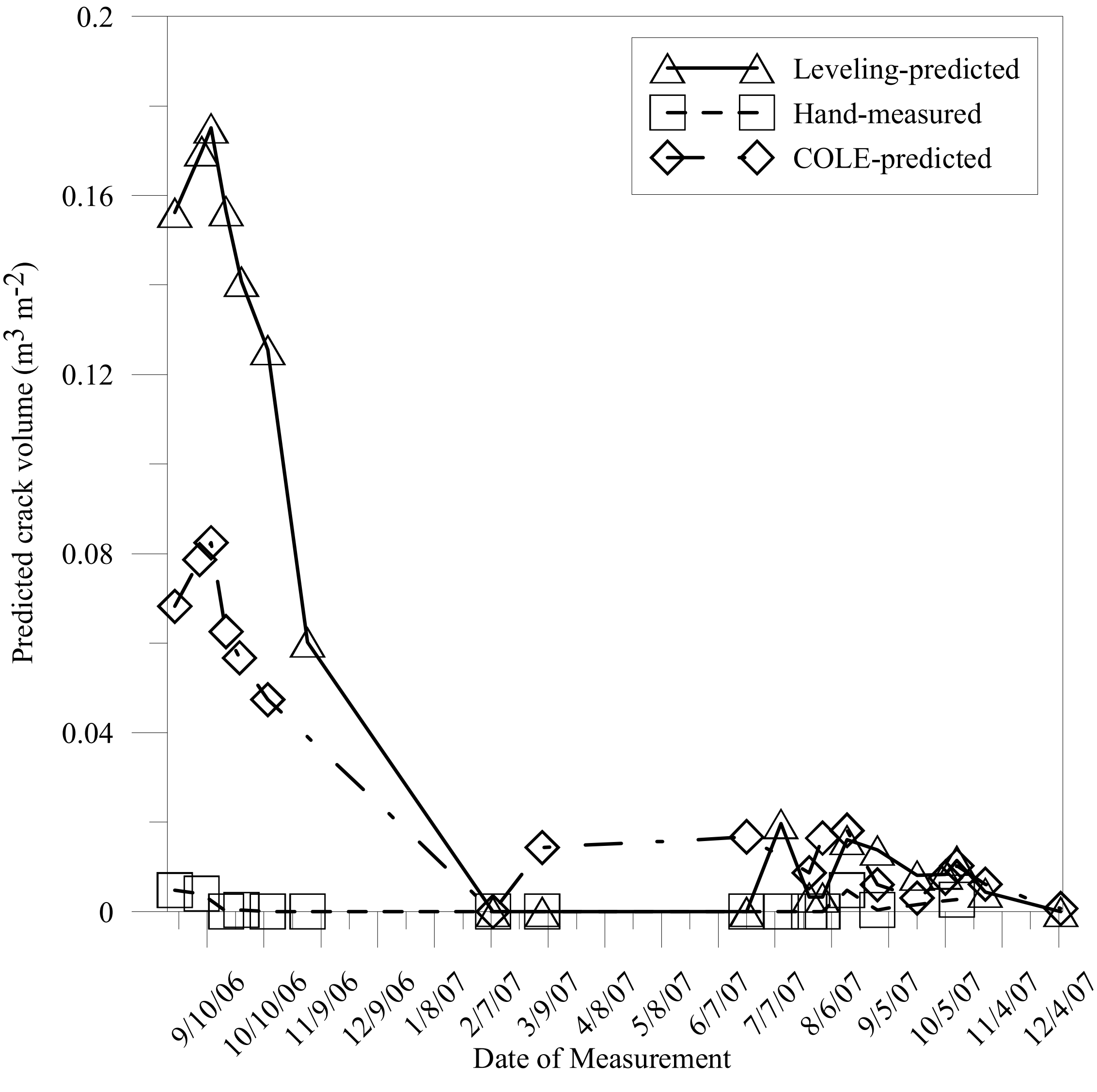


**Fig. 8.** Shows the comparison of how leveling-predicted, hand-measured, and COLE-predicted crack volume was predicted on different days of measurement for the Ships location.

The hand-measured crack volume for the Ships location was also ten times less than the leveling-predicted crack volume.

The three different methods of estimating crack volume were compared against each other to determine if they could be related. The hand-measured crack volume was graphed against the leveling-predicted crack volume to see if they had a linear relationship for the Burleson Site locations and the Ships Site locations. The hand-measured and leveling- predicted crack volume for the Burleson Site locations could not be linearly related with an average $r^2$-value of 0.10 (Fig. 9). The hand-measured and leveling-predicted crack volume for the Ships Site locations also showed to not be linearly related with an average $r^2$-value of 0.12 (Fig. 10).

These two soils went under various wetting and drying cycles which could be a factor that caused the two methods to be unrelated. To determine if this did have an effect on the measurements the values were broken down into wetting and drying cycles based off of the moisture values. The hand-measured compared against the leveling-predicted crack volume for the Burleson Sites after being broken down into wetting and drying cycles showed that the wetting cycles did have an effect on hand-measured crack volume (Fig. 11). The wetting cycle showed that during times that crack volume is being measured based off of the leveling-predicted crack volume low or no amounts of crack volume are measured by hand. During a wetting cycle what is happening is that the

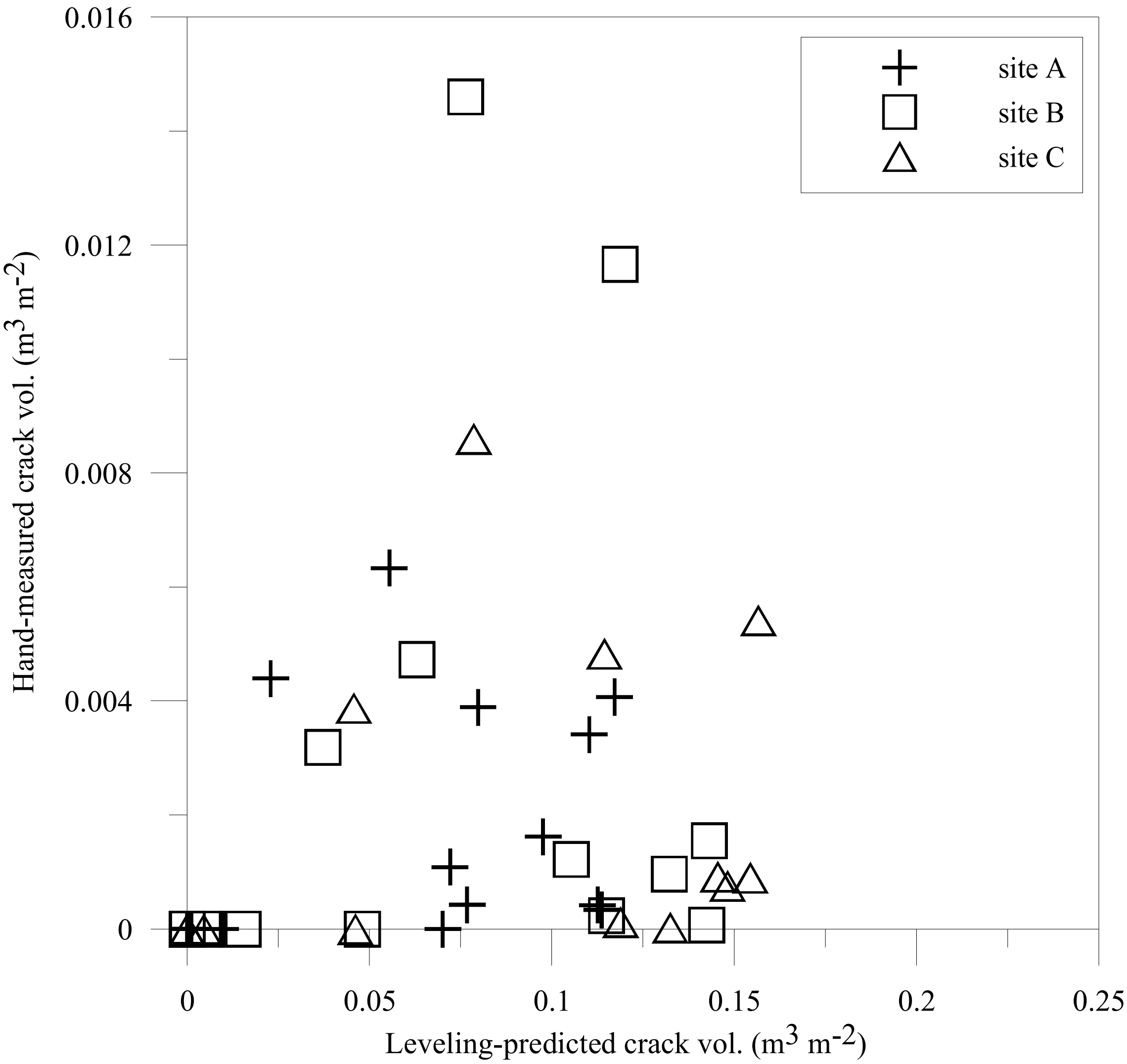


**Fig. 9.** A comparison of the hand-measured against the leveling-predicted crack volume for the Burleson location to determine a relationship.

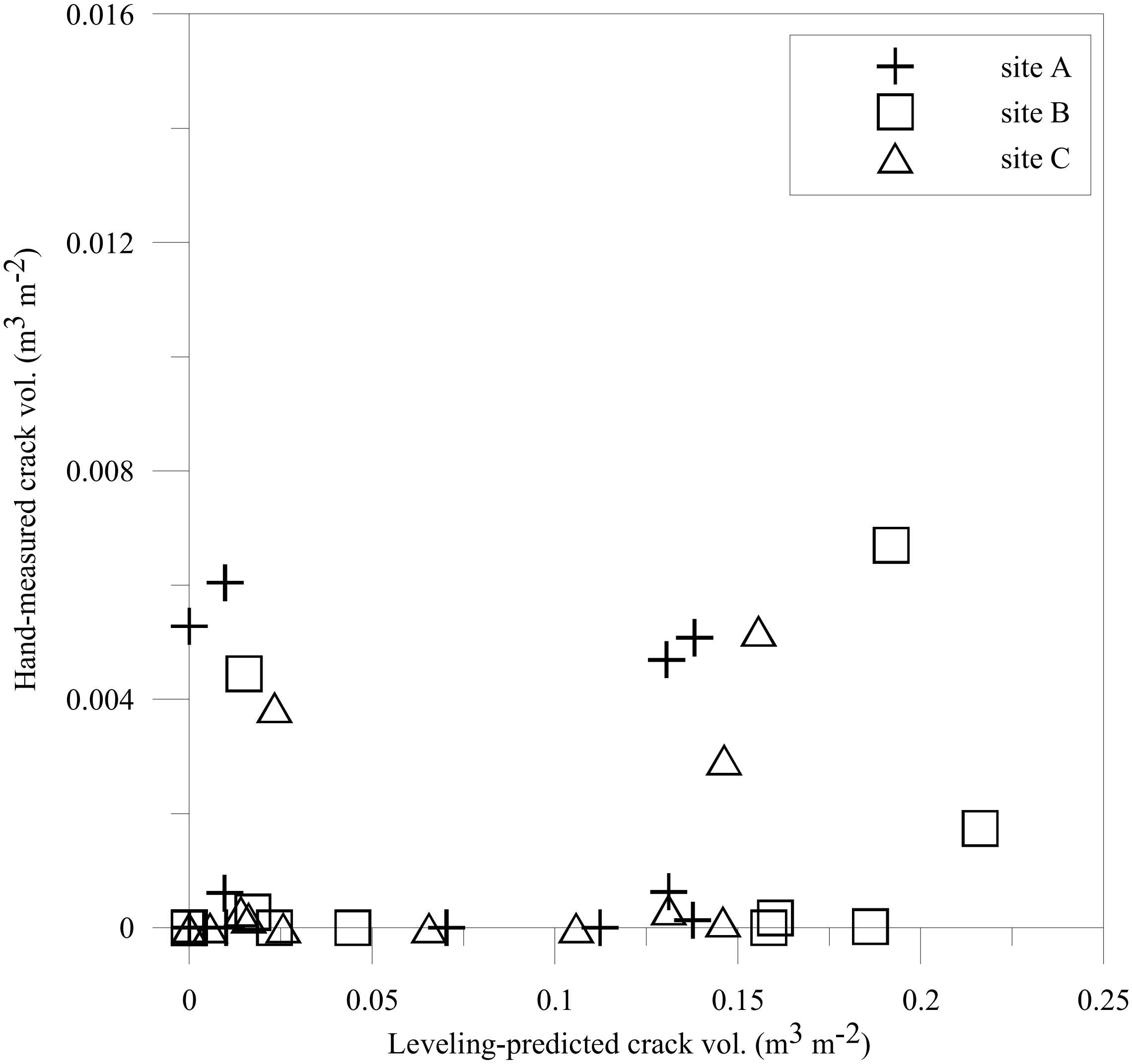


**Fig. 10.** A comparison of the hand-measured against the leveling-predicted crack volume for the Ships location to determine a relationship.

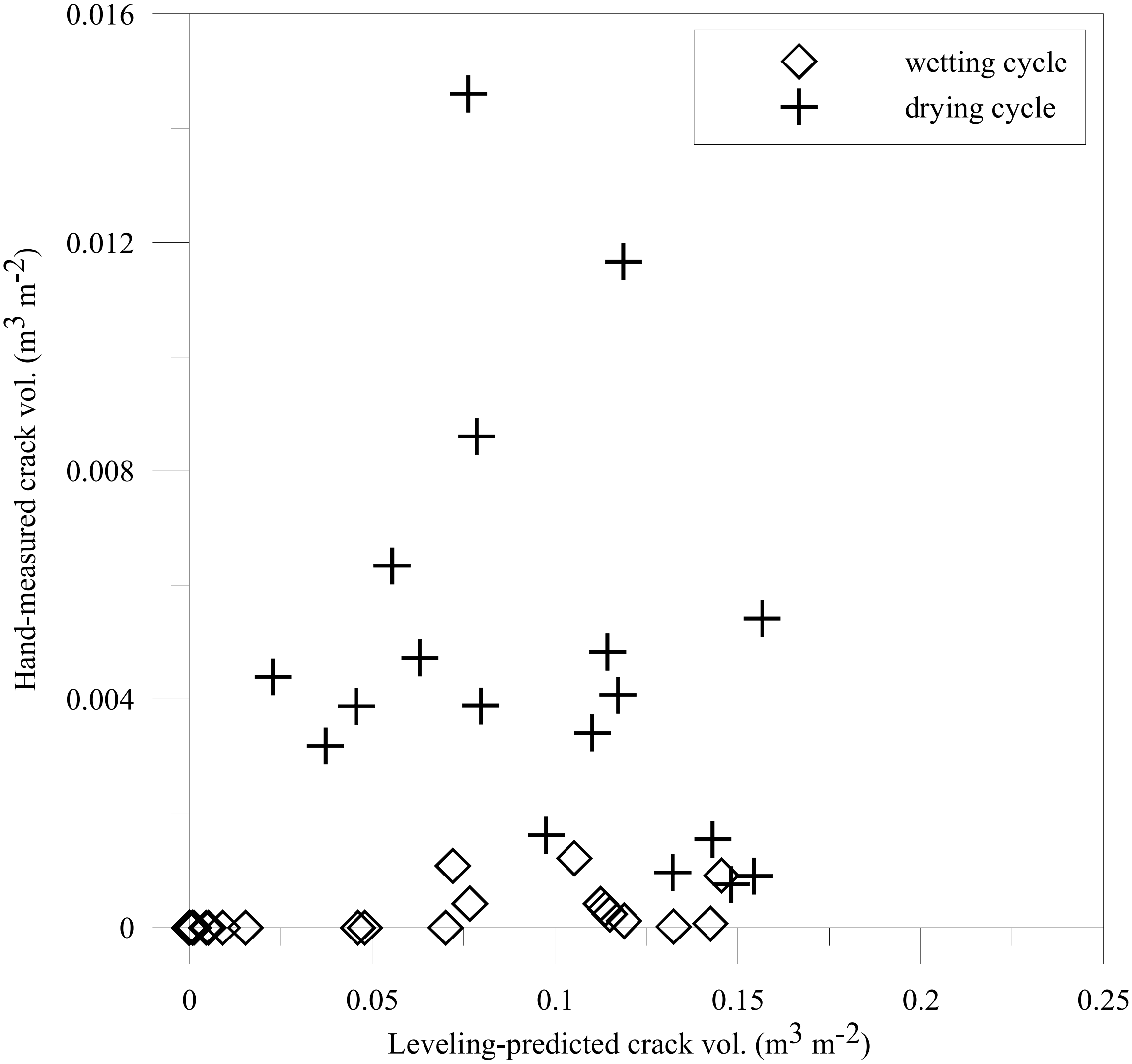


**Fig. 11.** A comparison of the hand-measured against the leveling-predicted crack volume for the Burleson location broken down into wetting and drying cycles to determine a relationship.

cracks at the surface may close due to a rain while there is still cracking occurring throughout deeper portions of the soil profile. The drying cycle was still not able to relate the two methods with an $r^2$-value of 0.07. The hand-measured compared against the leveling-predicted crack volume for the Ships Site locations after being broken down into wetting and drying cycles showed the same effect on hand-measured crack volume as the burleson location (Fig. 12). The wetting cycle showed that during times that crack volume is being measured based off of the leveling-predicted crack volume low or no amounts of crack volume are measured by hand.

The COLE-predicted crack volume values followed the same trend as the leveling-predicted crack volume but predicted the crack volume to be approximately half the amount of the leveling-predicted crack volume. Comparing the leveling-predicted against the COLE-predicted crack volume for the Burleson Site locations shows that the two methods are linearly related with an average $r^2$-value of 0.73 (Fig. 13). Comparing the leveling-predicted against the COLE-predicted crack volume for the Ships Site locations shows the two methods can also be linearly related for the Ships location with an average $r^2$-value of 0.89 (Fig. 14). This good relation between the two methods of estimating crack volume shows that COLE is a good indicator of a soils shrink swell potential. Although COLE under predicts crack volume compared to leveling-predicted crack volume it is still unknown whether or not Leveling-predicted crack volume is more accurate than COLE-predicted.

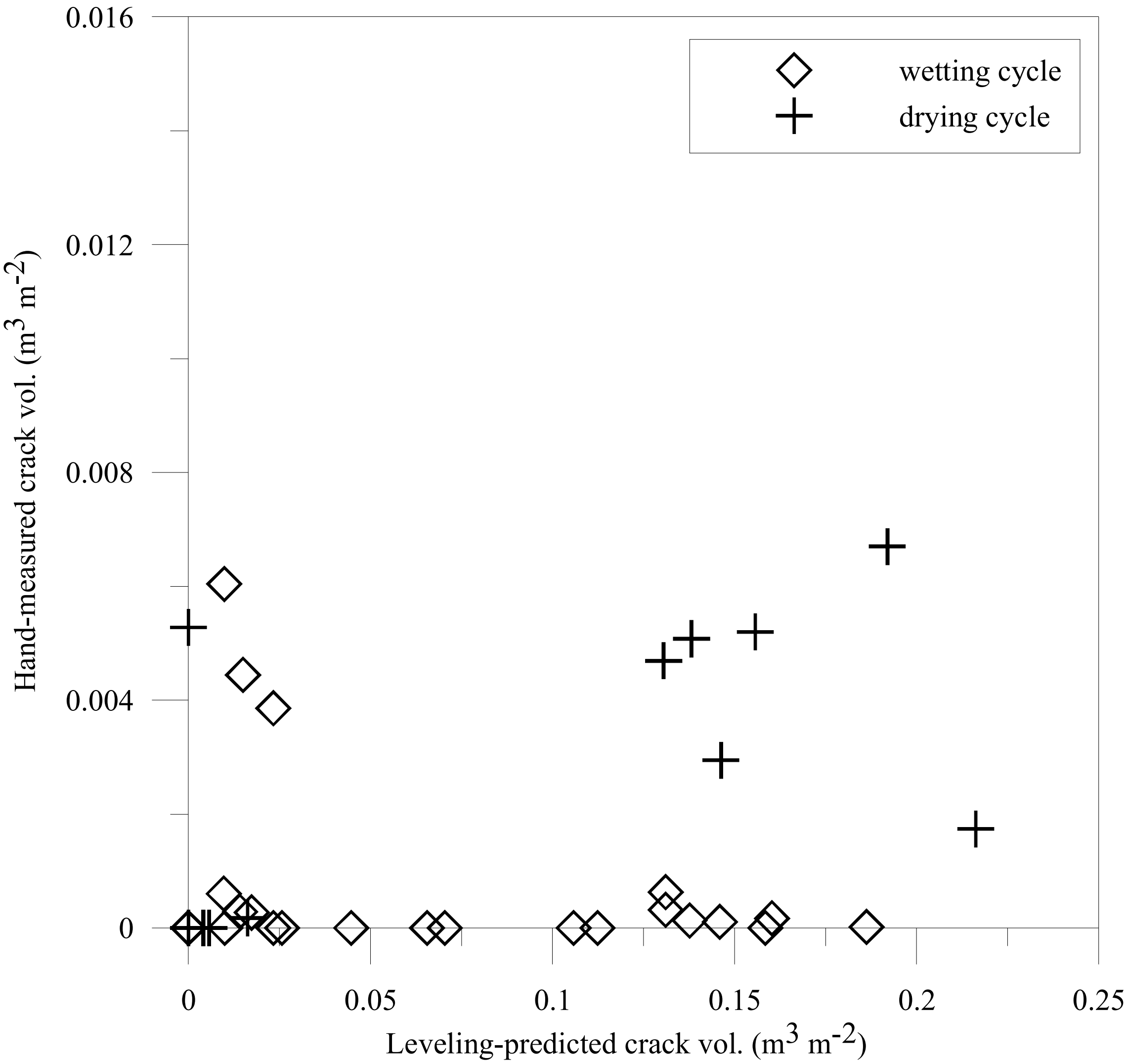


**Fig. 12.** A comparison of the hand-measured against the leveling-predicted crack volume for the Ships location broken down into wetting and drying cycles to determine a relationship.

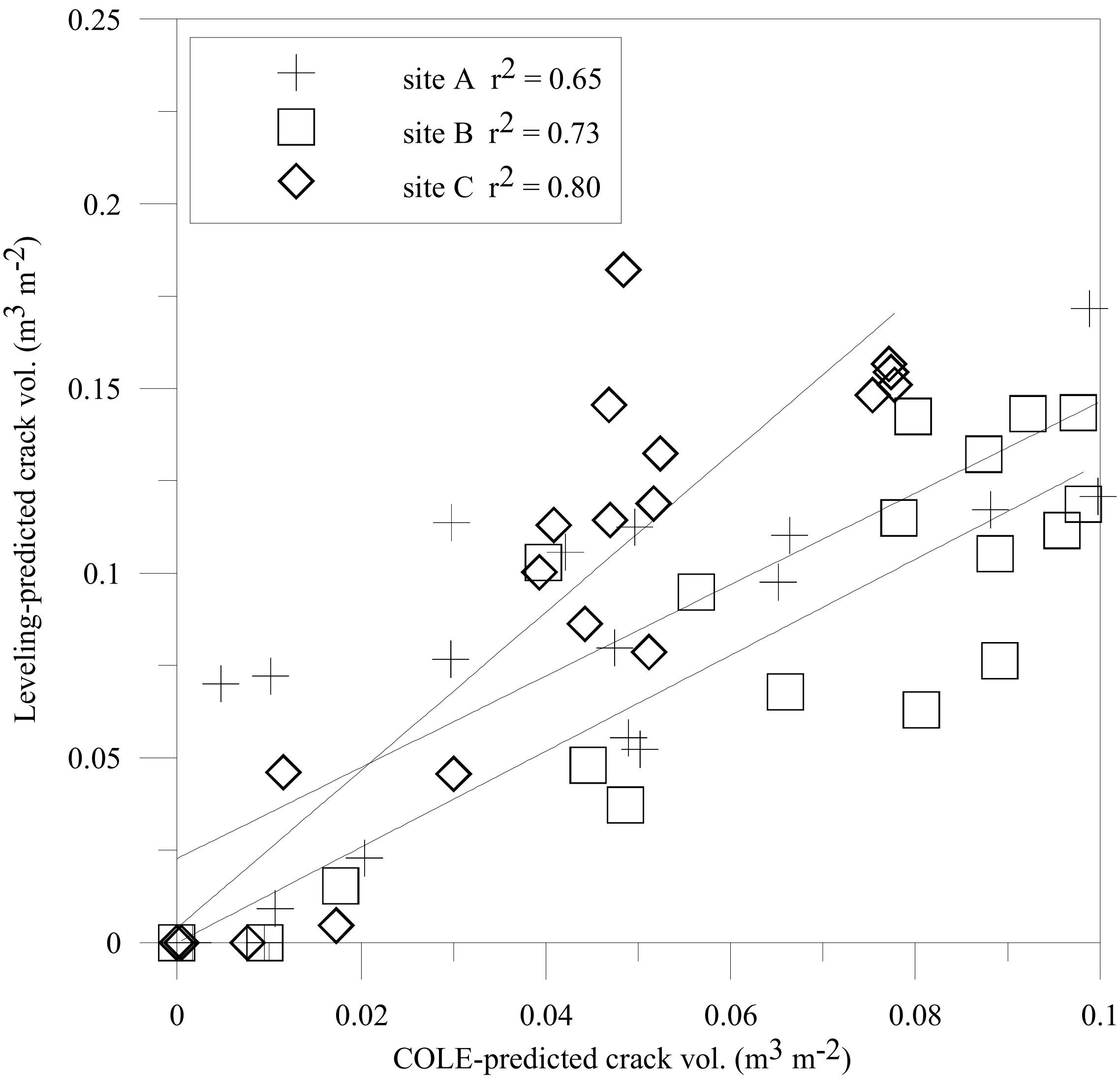


**Fig. 13.** A comparison of the COLE-predicted against the leveling-predicted crack volume for the Burleson location to determine a relationship.

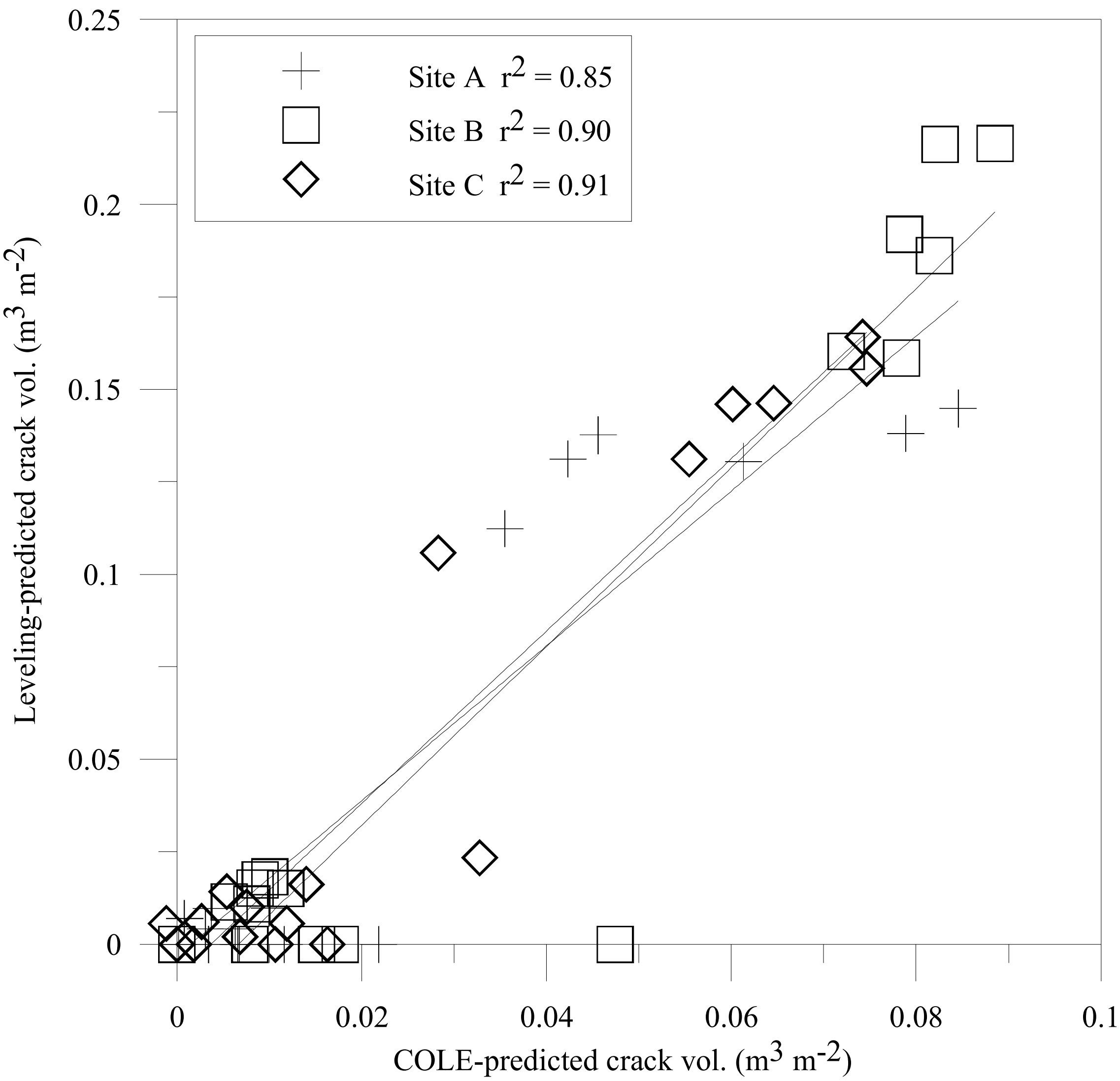


**Fig. 14.** A comparison of the COLE-predicted against the leveling-predicted crack volume for the Burleson location to determine a relationship.

**Comparing smectitic and mixed mineralogy**

To compare the shrinking and swelling of the two different Vertisols, one with smectitic mineralogy and the other with mixed mineralogy, leveling-predicted crack volume was compared in relation to volumetric moisture content for the two locations. When comparing leveling-predicted crack volume in relation to volumetric moisture content for the Burleson Site locations shows that the two have a linear relationship with an average slope of -0.216 (Fig. 15). When comparing leveling-predicted crack volume in relation to volumetric moisture content for the Ships Site locations shows that the two also have a linear relationship with an average slope of -0.529 (Fig. 16). The shrinkage response to change in volumetric moisture content for the Ships soil was significantly higher than the Burleson soil with a p-value $< 0.05$. This shows that the fact the Ships locations higher COLE values was a good indicator of the fact that the ships soil has a higher shrink-swell potential than the Burleson soil.

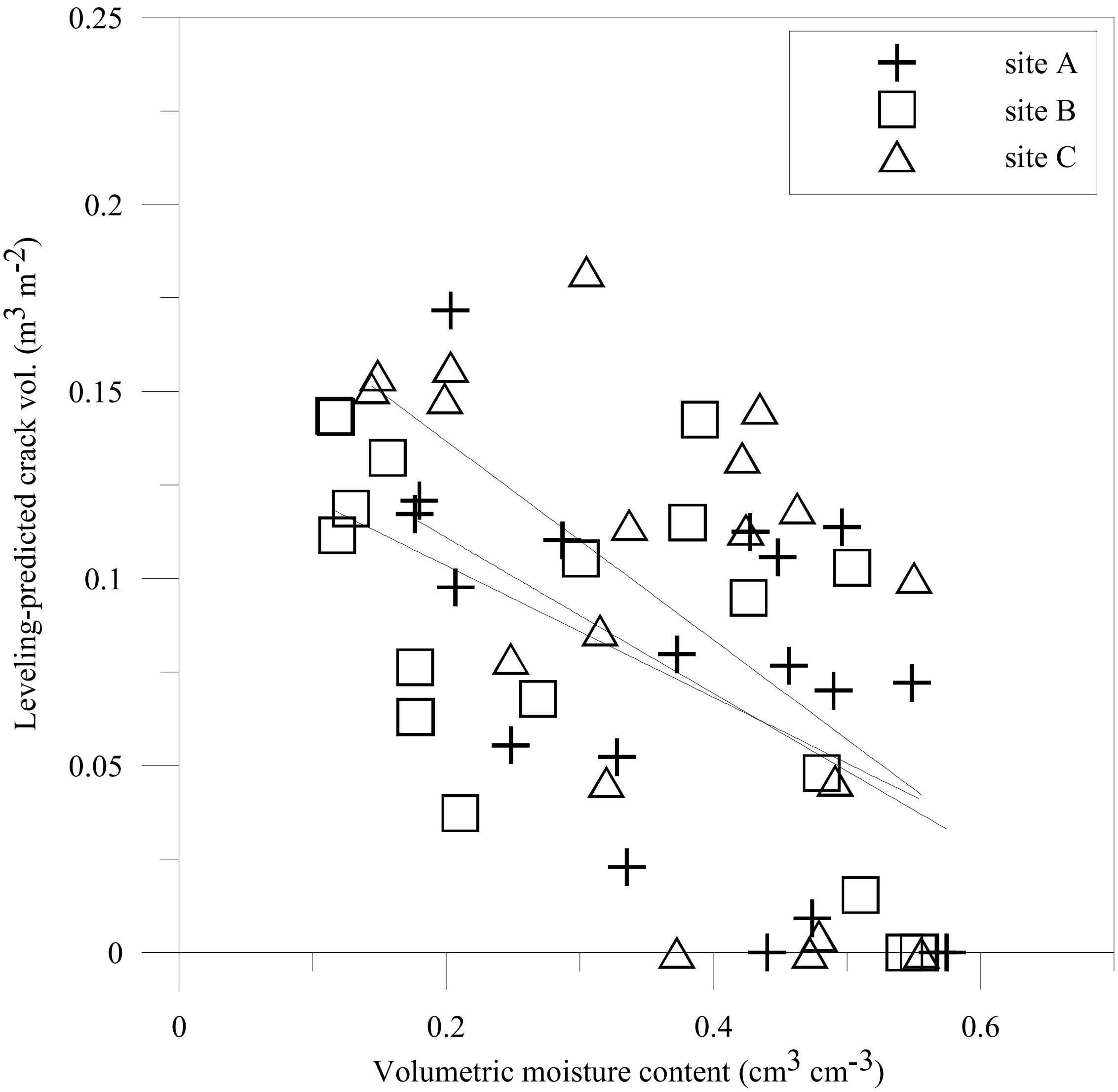


**Fig. 15.** Shows the shrinkage response of the leveling-predicted crack volume in relation to volumetric moisture content of the soil for the Burleson location.

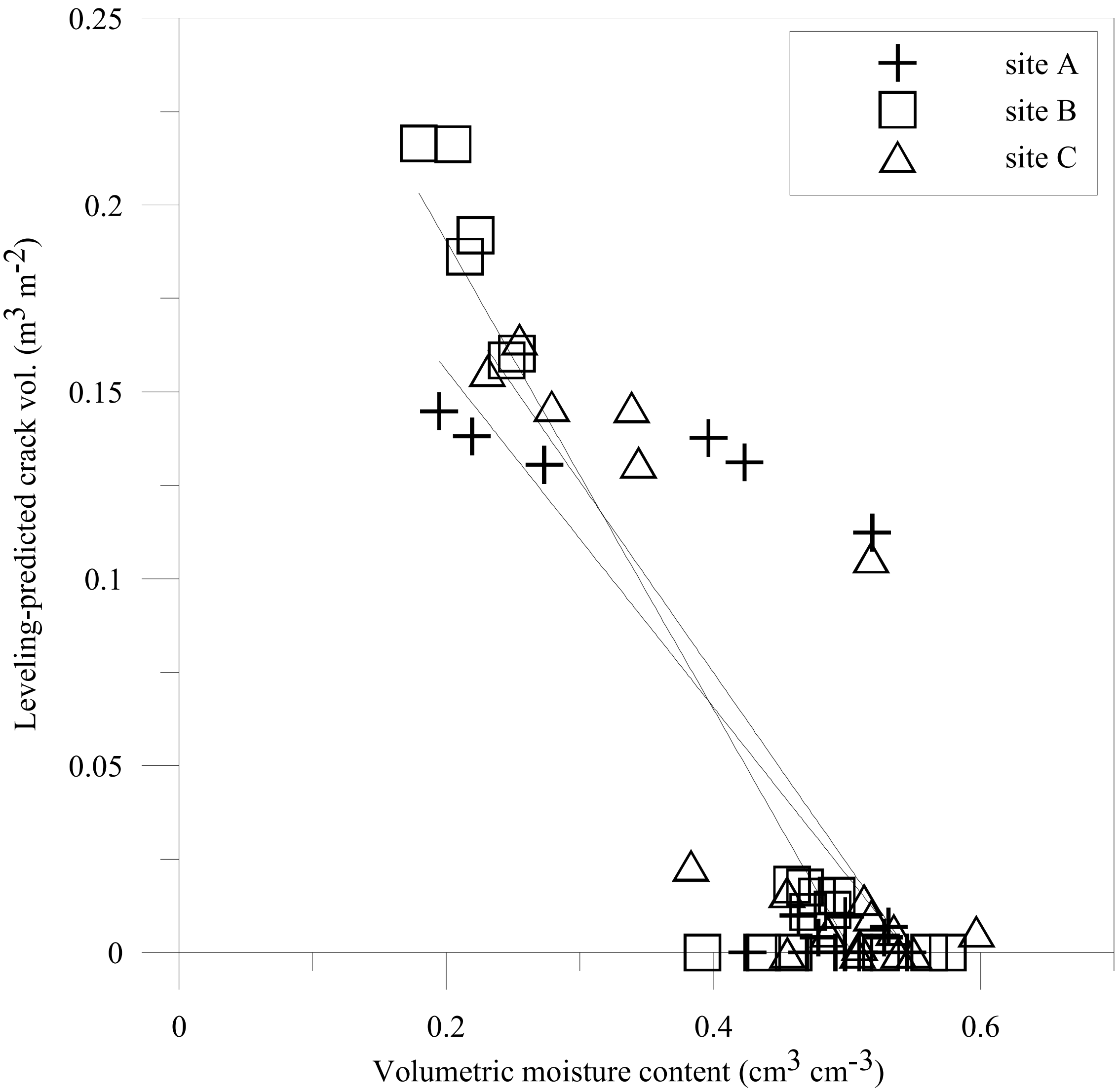


**Fig. 16.** Shows the shrinkage response of the leveling-predicted crack volume in relation to volumetric moisture content of the soil for the Ships location.

# CHAPTER IV

# SUMMARY AND CONCLUSIONS

The results of this research have answered some questions and opened the door to further research. The three different methods of estimating crack volume (leveling-predicted, hand-measured, and COLE-predicted) followed the same temporal trend but with values at different magnitudes. The leveling-predicted crack volume was ten times that of the hand measured crack volume and two times that of the COLE-predicted crack volume. When leveling-predicted crack volume was compared with hand-measured crack volume it was found that the two did not have a linear relationship and could not be related. After the values were broken down into a wetting and drying cycle it was found that when wetting zero cracks were being measured by hand when cracks were being measured by the leveling-predicted method. This shows that the hand-measurements are inaccurate under wetting conditions. The drying cycle was still unable to be linearly related to the leveling-predicted crack volume. When the leveling-predicted crack volume was compared with the COLE-predicted crack volume for both locations showed that the two methods had a strong linear relationship. These results show that leveling-predicted crack volume is a more practical and reliable methods of estimating crack volume.

When comparing the shrinking and swelling of the two different soil series, one with smectitic mineralogy and the other with mixed mineralogy, showed that you can't always base a soils shrink-swell potential from its mineralogy. Lab analysis showed that the Ships clay, with the mixed mineralogy, actually had higher COLE values that the Burleson clay, with smectitic mineralogy. When comparing leveling-predicted crack volume in relation to volumetric moisture content of the soil shows that the Ships clay had stronger shrinkage response to change in soils moisture than the Burleson clay being significantly different with a p-value $< 0.05$. These results show that COLE is a good predictor of a soils shrink-swell potential.

Further research is needed to understand the cracking cycle of shrink-swell soils and to determine whether leveling-predicted crack volume or COLE-Predicted crack volume is a more accurate method. These results will provide further researchers with insight as to how the three different methods of estimating crack volume compare and how to use COLE as a method of estimating soils shrink swell potential.

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