Crack Response to Blast Vibrations and Moisture Induced Volumetric Changes in Foundation Soils

By

C. H Dowding, Professor, Civil & Environmental Engineering, Northwestern University
C. Aimone-Martin and V. Rosenhaim , Aimone-Martin Assoc. Socorro, NM, and
J. Meissner, student, Northwestern University, Evanston, IL.

Abstract

In this paper vibratory crack response is compared to that produced by volumetric changes in foundation soils induced by natural events. These natural phenomena include changes in the water table, changes in soil moisture, and formation of ice lenses to name a few. Previous papers have compared vibratory responses of cracks to atmospheric effects such as those produced by the passage of weather fronts and daily changes in temperature and humidity. Periodicity of these atmospheric effects is on the order of a day to half a dozen days. Thus it is possible to observe atmospheric effects with measurement over a period of weeks to several months. On the other hand, crack response produced by volumetric changes in foundation soils occurs over a period of many months and/or may be seasonal in nature if not longer in the case of drought. Thus its measurement requires long periods of observation (many months to significant fractions of a year) or observation during critical seasons. Since it occurs over long periods of time, its observation may be obscured by climatologically induced crack response. These soil volume changes are compared with climatic data to describe the correlative nature of crack response in time with the soil volume change phenomena and likely climatic causes.

Introduction

Past work (Oriard, 2002, 1999; Dowding, 2008, 1996; Stagg et al 1984) has shown that there are many environmental factors that produce long-term deformation and cracking of buildings. In general, they can be separated into the following three broad classes:

* Foundation movement
* Physico-chemical and thermal response of building materials
* Structural distortion from overloading, creep, etc.

Responses to changes in the foundation soil are usually so slow that it is difficult to notice their day to day change and the monitoring period must extend to significant fractions of a year and beyond to detect these changes. This long period of observation is necessary to detect long term trends as well as aperiodic extreme events such as formation of ice lenses and drought induced volumetric changes of soil.

This paper compares volumetric changes in foundation soils and crack responses for two case studies. Both involved structures founded at the surface (on grade), on flat, concrete slabs (slab on grade -- hereafter in this paper), the most responsive of foundations to volumetric changes of shallow soils. In both cases changes in soil volume were measured with anchor systems, which is relatively unusual for crack response study. The first case involved a slab on grade house in North Carolina (Pineville) and the second a garage in Indiana (Universal). In both cases long term soil volumetric changes and foundation movement were measured by mechanical gauges and anchor systems and optical surveying. These movements were then correlated in time with changes in the level of the water table and/or estimates of changes in soil moisture. Crack response was measured by inductance sensors (Pineville) and micrometers and inductance sensors (Universal). Physio-chemical and thermally induced movement of instrumented cracks occurred during monitoring and were also measured by the crack sensors.

The Pineville case will be presented first in a traditional fashion where long term, climatologically induced crack response is compared to short term or dynamic, blast induced crack response. The long term crack response will then be compared with the long term volumetric changes in the foundation soil and a crude estimate of changes in soil moisture based upon a crude estimate of accumulated water based upon rainfall information and estimated evaporation. The Universal case is presented second for comparison. The crack in the slab on grade garage was only fitted with micrometer based crack sensor. Since it was read manually, data only exist for long term response. The associated house was founded at three different depths, which allowed a unique observation of the affect of the depth of foundation on long term deformation of the house foundation.

Figures for the first - Pineville - case are presented on page 5, before the text for the second – Universal – case. The paper then closes on page 11 with the conclusions, references, figures for the second case and the appendix in that order.

Dynamic Response of Pineville Slab-on-Grade House is Typical

The house shown in Figure 1 was monitored with the hybrid combination of the ITI Autonomous Crack Measurement (ACM) system and LARCOR standard vibration monitoring seismograph (AMA et al, 2002). This combination allows recording of vibratory response time histories of both crack and structural response to either ground motions or air over-pressures as well as well as long-term, climatological crack response. ACM crack response is measured with a Kaman inductance micro meter displacement sensor. See Aimone-Martin, Dowding (2005) or other ISEE articles for a detailed description of the hybrid ACM-seismograph system used in these studies.

The exterior wall of the slab on grade, wood-frame, one-story house was covered with brick. Response of the super structure was monitored on both the exterior brick façade as well as the interior walls. Response of the midwalls along with an interior gypsum drywall crack was monitored on the interior of the structure. The crack shown in Figure 2 is located at a top corner if the first window to the right of the house corner in the foreground. Ground motions produce structural responses, which in turn drive the crack response.

Response of the crack to climatological effects (both atmospheric and soil) for the full study is compared to the time histories of temperature and humidity in Figure 3. The width of existing wall cracks is highly sensitive to changes in ambient temperature and humidity. As is typical, dynamic response of cracks to blasting is small compared with the slow, opening and closing with diurnal (or 24-hour) fluctuations in temperature and humidity, passage of weather fronts and seasonal effects. To show this comparison, long-term changes in crack widths were measured and recorded on an hourly basis. Changes in crack widths were plotted against cumulative time (in hours) where a positive increase in crack response represents opening.

Weather “front” effects are represented by the changes that occur over a periods of several days. The most significant periods of frontal humidity are associated with rainfall on the order of 0.5 in or more over one to three days. Timing of several of these rainfall events in terms of hours into the program is 1248, 1488, 1752, and 1848 with 50, 12, 30, & 15 mm of rain respectively. During these periods of high humidity atmospheric moisture is absorbed within the wood framing, which expands the wood fibers along with the attached wall covering (e.g., interior drywall) causing the crack to respond.
The largest period of rain involved a total of 160 mm (6.33 in.) over a period of 28 days starting around 1800 hours. The net effect was a 243 micro-meter (μm) or 9753 micro-in (0.009753 in) change in crack width (opening) over a 28-day period to around 2500 hours. This change in crack width is 69 times greater than the largest blast-induced change in crack width of 3.6 μm (141.55μ-in or 0.0001415 in).

Shallow Anchor Allows Measurement of Soil Shrinkage/Swelling

An inexpensive single-point anchor device shown in Figure 4 was installed on August 29 (~0 hours) in the front yard of the instrumented structure at the location of the boring made to measure the geotechnical properties. This device measures expansion/contraction of the near-surface soils containing clay with changes in ambient rainfall and soil moisture levels. A diagram of the anchor system is shown on the right in Figure 4 and photographs of the installed device are given on the left. The device was fabricated with a 25 mm (1-in) OD interior PVC rod embedded in grout at the base of a 150 mm (6 in) drilled borehole. A threaded bolt was inserted through the interior PVC pipe. The rod is assumed to remain stationary. The elevation of the center rod pin is not affected by changes in soil moisture levels near the hole collar. A 125 mm (5-in) OD casing forming the hole collar was inserted approximately (1.2 m) (4 ft) from the ground surface. Two opposing bolts were placed on the casing wall beneath the interior rod bolt. Measurements of the separation distance between the reference bolts on either side of the interior rod have been taken since September 25.

Figure 5 compares time series of three parameters: top, response of the crack over time, middle, expansion/contraction of the surface soils as measured by the anchor, and bottom: an estimate of the retained moisture of soil. The period of maximum swelling occurs at the same time the crack responds the most. As the reference bolts in the anchor move closer together (e.g., relative position decreases), the outer collar moves upward in response to surface swell from soil wetting. Thus a smaller value implies more swelling and the greatest swelling occurred in November (hours 1600 – 2400), the period of greatest rainfall. Moisture retained in the shallow soils in the bottom plot is estimated from precipitation reported at the Charlotte airport as described below.

The bottom plot in Figure 5 represents a crude estimate of the increase in stored water in the soil profile based upon measured rainfall (wetting), a non site specific estimate of the evaporation losses for a typical southern site (drying) and an estimate of the rate of downward percolation (drying). These latter two effects lead to drying of the soil. The cumulative volume of water retained in the shallow soil is then the running sum of these daily volumes. Details of this estimate are described in the Appendix. The necessity to estimate the two drying rates make reduce the accuracy of this estimate. More stored water raises the potential for swelling of dry, expansive soils. The largest, sustained increase in retained or stored water occurs at the same time of the greatest swelling of the soil, hours 1850 through 2450.

Soil Properties and Swell Potential

Soil properties at the test house are tabulated in Figure 6. A complete soil analysis accompanies the figure on the right. Consolidometer swell tests were conducted with a 14 kPa (2 psi, 300 psf, or 0.15 tsf) load. This load is typical of slab foundation pressure of one-story structures similar to those surrounding the Pineville quarry. Samples were consolidated with a 300 psf normal load then inundated with water and allowed to swell under the 14 kPa load to measure heave, or percent swell. Samples were subsequently reloaded until the sample achieved the original, pre-test specimen height. The pressure required to reduce the total heave to zero is recorded as the swell pressure. The upward swell pressure, 45 kPa (6.6 psi or 947 psf), when compared with typical downward foundation soil pressures of 14 kPa provides a measure of potential swell that could occur if local area soils were to become saturated.

Swell potential is routinely estimated from soil index test results. They are based on variety of soil properties such as colloidal clay content, plasticity index (PI) and shrinkage limit (SL) which is computed from liquid and plastic limits. Based on the clay size fraction and SL, this soil is classified with a very high swell potential. Figure 6 compares swell potential estimated from the liquid limit and in-situ dry density (Holtz and Kovacks, 1981) for three soil samples surrounding the quarry. Soil near the test house, B-1, is shown to have a high swell potential, which verifies the measurements.

Dynamic Response of Crack Is Small Compared to Shrink/Swell Effects

Maximum surface ground heave 5.5 mm (0.22 in) in Figure 5 response to weather front activity and rainfall measured over a 220-day period was 0. 5 % in the absence of a surface load compared with 0.4 % heave measured in the lab under a 14 kPa (2.1 psi or 300 psf), vertical load. This measured field response confirms the laboratory measurements and that swelling clays exist in the area.

Figure 7 compares the long-term, atmospheric climatological response for a few days surrounding the 2/05 blast. Daily changes in crack width over a twelve day period are compared with dynamic crack motions for the blast on 02/25/07 that occurred during this time period (shown by the arrow). The maximum one-day change of 84 μm (3368 μ-in) exceeds the largest change in zero-to-peak crack width during the blast pulse of 3.6 μm (141.55 μ-in).

As shown in Figures 5 and 7, the crack response to diurnal temperature and humidity is over 24 times greater than that produced by the 02/05 blast. Quarry blasting some 760 m (2500 ft) away produced a maximum Peak Particle Velocity (PPV) of 2.667 mm/s (0.105 ips) and a maximum airblast of 125 dB (average 116 dB) on 2/05. This maximum blast induced ground motion produced a zero-peak crack response 3.6 μm (141.55 μ-in), which is 1.4% of the maximum weather response (peak-peak) during the study.

Figure 1: Pineville Test Structure. Crack in Figure 2 is on inside of first window on the right wall at the nearest (right front) corner.

Figure 2: Crack in the interior gypsum drywall showing crack sensor and null sensor.

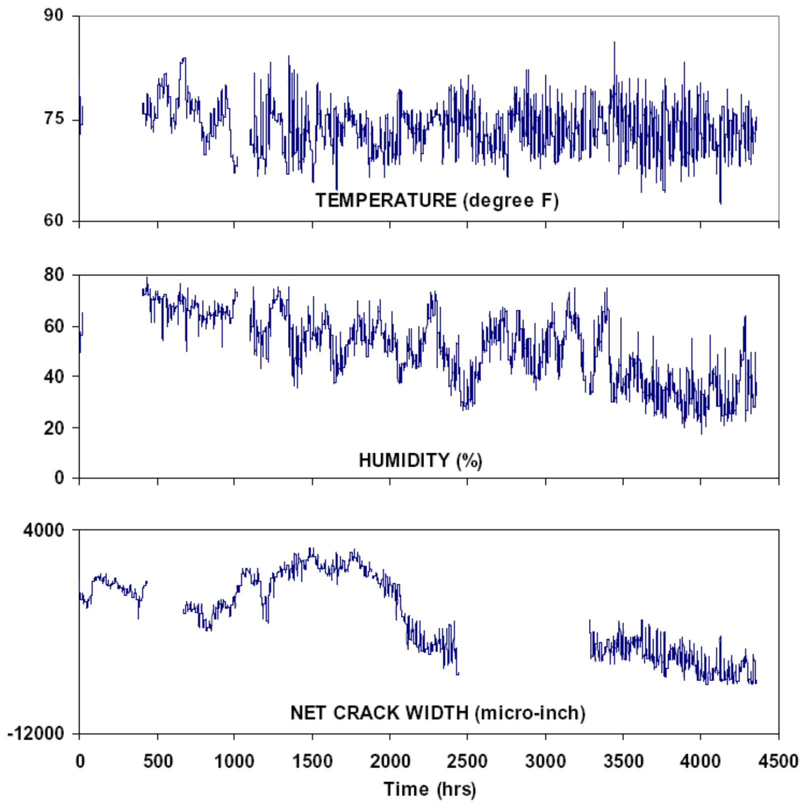
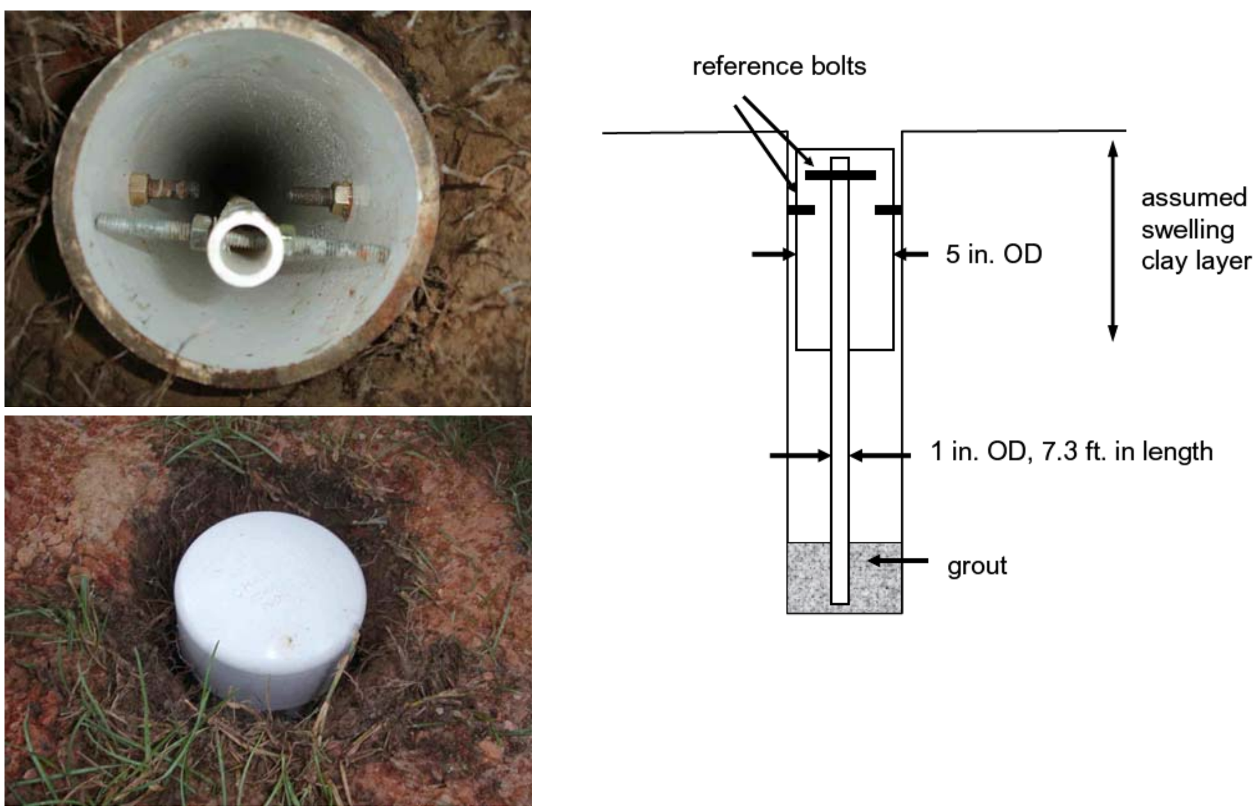


Figure 3 - left: Response of the crack in Figure 2 (bottom) compared to the variations in outside temperature (top) and outside humidity showing large change at 2000-2500 hours (80-100days)

Figure 4 –below : Inexpensive anchor. Outer PVC pipe moves with soil while the inner rod is anchored to the soil at the grout depth. Thus the relative movement between the inner, small diameter pipe and the outré, larger pile is the expansion (swelling) or contraction (shrinkage) of the soil at elevations between the anchor and the reference bolts.



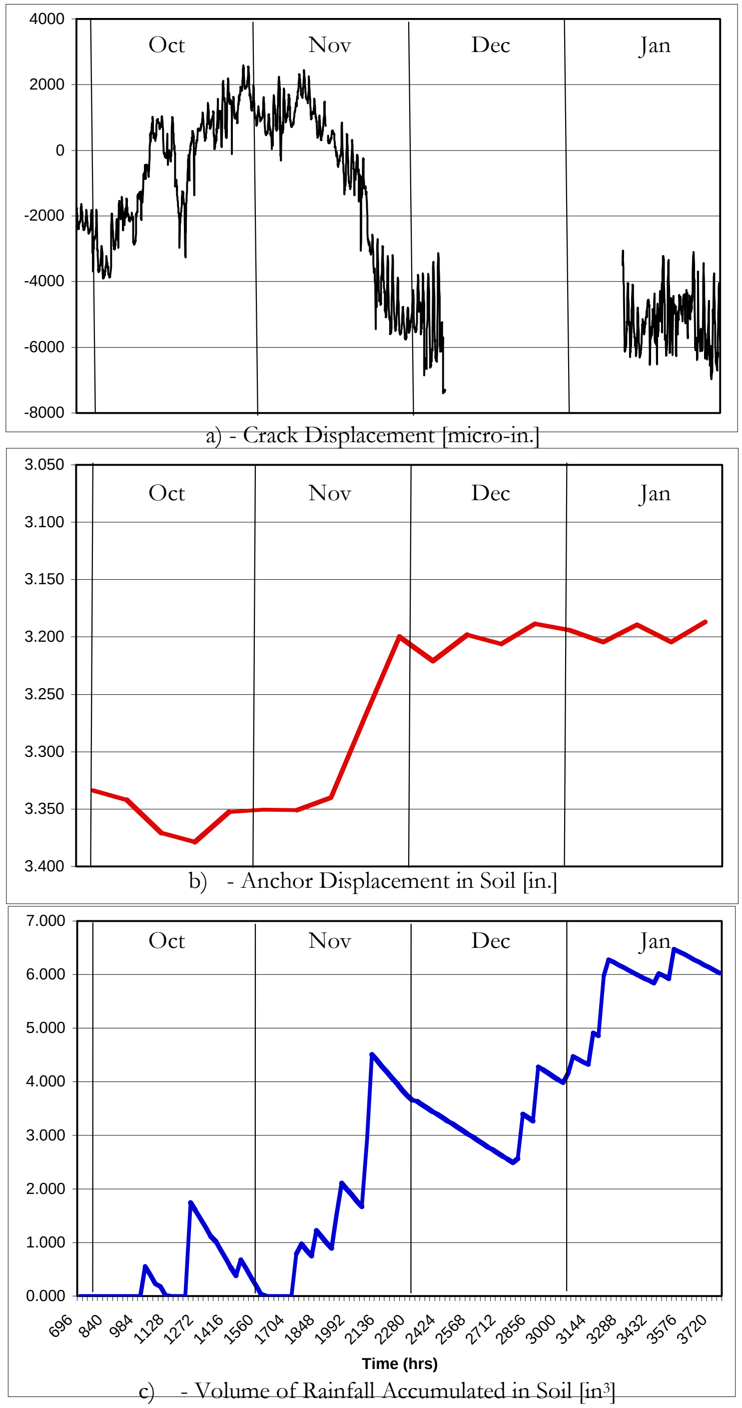
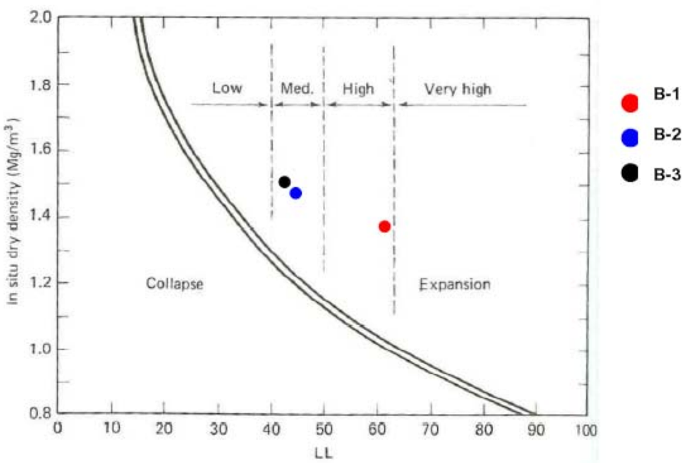


Figure 5: Comparison of crack response (top) with distance between bolts, which indicates swelling when the distance declines (middle) and a crude estimate of the volume of retained water in the shallow soils (bottom). Retained water is the sum of wetting by measured rainfall and drying by estimated evaporation and downward percolation. See Appendix for details.



sample interval (ft) 2.5 - 4.5
description red silty clay
moisture content (%) 22.0
dry unit weight (pcf) 85.9
moist unit weight (pcf) 101.5
liquid limit 62.0
plastic limit 40.0
plasticity index 22.0
percent gravel (%) 0.0
percent sand (%) 26.1
percent silt (%) 20.8
percent clay (%) 53.1
void ratio 0.927
strength (psf) 13640.0
percent swell (%) 0.4
swell pressure (psf) 947.0
USCS classification MH

Figure 6: Comparison of soil properties at B-1 the test site with other nearby soils shows those at B-1 to indicative of a soil with a high swell potential(after Holtz and Kovacks, 1981) . A complete soil analysis accompanies the figure on the right.

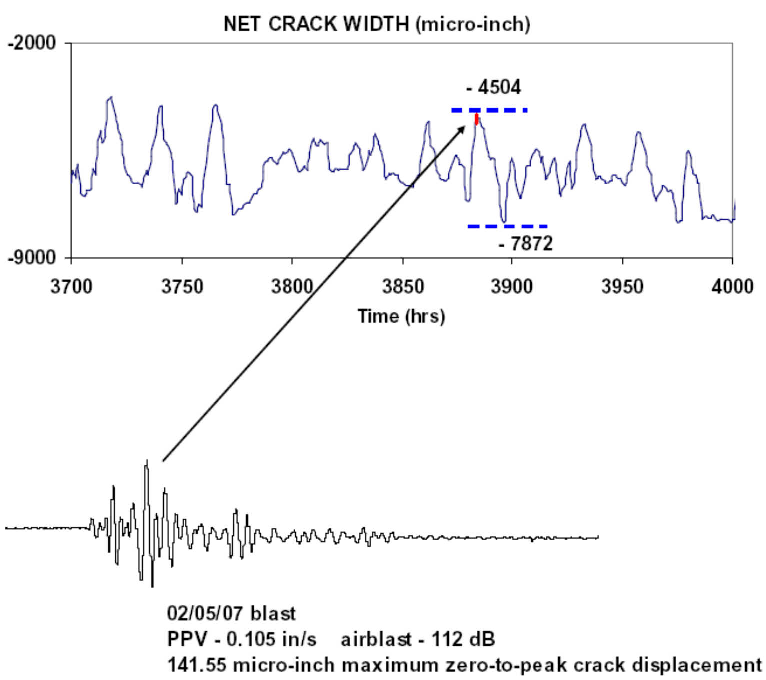


Figure 7 Compares the daily diurnal changes in crack response before and after the 02/05 blast that produced the 2.7 mm/s (0.105 ips) PPV motion showing how large is just the daily crack responses compared to the vibratory responses.

Response of Universal Slab-on-Grade Garage Was Measured Manually

The crack in the garage at the Universal Indiana site in Figure 8 (left side) was monitored manually with the micrometer (middle). This crack in the center of the half height brick wall (right) was also present on the inside. While micrometers are capable of detecting changes as small as 0.002 mm (.0001 in), difficulties in precise placement and reading by interpolation limited their actual precision to 0.05 mm (0.005 in). This precision is some 20 times better than that possible with many commercially available crack gauges. Foundation response of the house associated with the garage in Figure 9 was measured with special optical survey techniques described below.

Both blast vibration induced and long term crack response inside the house associated with the garage was measured with the Kaman based micro-meter displacement ACM system. This system and the Universal case are described in detail in Dowding (2008 and 1996). Space does not permit presenting this information here.

Swelling and Shrinking of Universal Foundation Soils

Swelling/shrinkage of the foundation soil was measured with the two anchor systems shown in Figure 10: a commercially available Borros point and a concrete dowel. These devices allow expansion/contraction between the bottom anchor and the upper pipe flange to be measured with a micrometer with a resolution of 0.05 mm (0.005 in) as described above . As soil between the anchor and the flange expand, or contracts, the distance "a" on the drawing changes. This distance was recorded manually one to two times per month. Borros points are normally employed where rock is not near the surface and can be pushed into the ground without a boring. The rock anchors were installed some 2.9 m (9.5 ft) (distance e) below the ground surface and normally measured the volumetric change over a distance of 2.7 m (9 ft)

Frost Heave of Soil

Soil can heave substantially during the winter as shown in Figure 11 (right) by the frost heave spikes that are superposed on top of the seasonal volume change induced movement of the soil anchor (middle right). The spike during 1987 correlated in time with the passage of a cold front as shown by the one week period of below freezing temperatures in the accompanying outside temperature time history (bottom). The same correlation exists for the second spike during 1986. Although the temperature records for 1986 are incomplete, there were more below freezing temperatures for that year than 1987, which was unusually mild year. Thus even in the unusually mild winter of 1987, the soil near the test house heaved in response to freezing as much as 3.8 mm (0.15 in). In a more normal year, the heave is more likely17.7 mm (0.7 in), as shown by the 1986 spikes. Unfortunately, no soil properties were measured as for Pineville, and only Soil Conservation Service classification is available: Ragsdale silty loam.

Long Term Response of Cracks in Slab-on Grade Garage

Garage crack movements (top right) are compared to the soil anchor movement (middle right) in Figure 11. Timing of their greatest change coincides with the January, 1987 frost heave spike. The correlation seems reasonable as the garage walls are founded on 365 mm (1.2 ft) deep strip footings in a climate where frost penetration is some 1 to 1.25 m (3.3 to 4.1 ft). The shallow footing is exposed in Figure 8 (right). Thus, during winter frost penetration, frost heave can jack the slab differentially and distorts the garage foundation and walls. As can be seen in Figure 11, this distortion produces crack movement of some 500 µm (20,000 µ-in 0.02 in.) during a mild winter. A more typical winter, such as 1986, could have produced crack movements 4 times larger as estimated from the ratio of soil anchor movement for the two winters.

Changes in Water Table Correlate with Soil Shrink/Swell Behavior

As shown in Figure 11 (bottom left), the water table at the test house fluctuates seasonally some 1.5 m (5 ft) between a winter high and a summer low. Seasonal water table fluctuation correlates quite well in time with the seasonal 16.5 mm (0.65 in.) settlement and subsequent rise of the top of the soil anchor (middle left). Soil anchors measure relative movement between the anchor in rock and the top cap at the ground surface as shown in Figure 9. The soil settles during the summer because it shrinks upon drying much the same way mud shrinks and cracks upon drying. The soil also rises or swells during the fall when the water table rises and the soil becomes more moist as it did in the Pineville case.

Changes in the elevation of the water table were monitored with an observation well constructed as shown in Figure 9 (right). Depth of the water below the ground surface was measured monthly with a measuring tape The wells, excavated to rock, are only 3 m (10 ft) deep as the bedrock surface is shallow beneath the test house and garage.

Foundation Movement

Absolute movements are most efficiently measured by optical surveying techniques which depend upon an immovable bench mark and a precise monitoring location. The 3.3 m (10 ft) proximity of rock and three soil anchors grouted to rock near the house provide an unusually close and stable benchmark system. The most precise monitoring locations were provided by the stainless steel balls that were screwed into the frame of the house. Elevation changes were measured monthly with typical optical survey instruments of that era. However, a machinist's scale was employed as the target to allow distinction of elevation differences as small as 0.3 mm (0.012in).

Vertical movements of the test house frame, which reflect movement of the foundation are compared to the movement of the soil anchor in Figure 11 on the left. Two extremes of the measured response were chosen for comparison: movement over the shallowly founded eastern portion of the test house and over the more deeply founded, western full basement. Elevations of the three different foundations are shown as dotted lines in Figure 9. The more shallowly founded portion of the house responded the most for three reasons. First, the soil is thicker below the shallow footing and, therefore, there is a greater volume to shrink/swell. Second, the soil beneath the basement is almost always below the water table and thus always saturated, whereas much of the soil beneath the shallow section is subjected to the seasonal change in moisture content caused by the fluctuating water table. Finally, there were large trees on the eastern side of the house near the shallowly founded portion. The roots of these trees are capable of locally lowering the water table during the dry summer months.

Blast induced response of the cracks inside of the house were typically small compared to the atmospheric and moisture change induced soil response. Please refer to Dowding (2008 and 1996) for details. Space does not permit a presentation here.

Conclusions

Changes in soil volume induced by changes in soil moisture from natural causes can be significant. They are so slow that it is difficult to notice their day to day change and the monitoring period must extend to significant fractions of a year. Soils with a high swelling potential can expand significantly after periods of heavy rainfall as shown in the Pineville case. Soils shrink and swell as demonstrated by the volumetric response to the rise and fall of the water table at the Universal test structure. Moisture changes induced by water vapor migration during the winter can induce large soil volume changes as shown in frost heave measured at the Universal test structure. There are many other natural causes of volumetric changes in soil as discussed in any soil mechanics text.

Naturally occurring moisture induced changes in soil volume in turn induce foundation movement. This foundation response is greatest for shallowly founded structures, particularly those with slab-on –grade foundations. This foundation movement in turn can cause distortions in the structure, which in turn produce crack responses.

Crack responses that correlate with naturally occurring changes in soil volume described in these cases are large compared to typical blast induced crack responses as shown by the responses measured in the Pineville case.

References

Aimone-Martin, C.A. and C.H. Dowding (2005) "Blast-Induced Structural and Crack Response of a Brick Residential Structure near an Aggregate Quarry," *Proceedings of 31*st *Conferences on Explosives & Blasting Technique*, International Society of Explosive Engineers, Cleveland, OH.

Dowding, C.H. (1996) Construction Vibrations, Prentice Hall, Englewood Cliffs, NJ, USA, 610 pgs. Now available through Amazon.com and the International Society of Explosive Engineers.

Fetter, C.W. (2001) Applied Geohydrology, Prentice Hall, Upper Saddle River, NJ, USA, 598 pgs.

Holtz, R.D. and Kovacks, W.D. (1981) Introduction to Geotechnical Engineering, Prentice Hall, Englewood Cliffs, NJ, USA, 733 pgs.

Oriard, L. L. (1999) The Effects of Vibrations and Environmental Forces, International Society of Explosives Engineers, Cleveland, OH, USA, 284 pgs.

Oriard, L. L (2002) Explosives Engineering, Construction Vibrations and Geotechnology, International Society of Explosives Engineers, Cleveland, OH, USA, 680 pgs.

Figure 8 Slab-on-grade garage (left), outside crack (chalk line on right photo), and micrometer and measurement points to sense shearing as well as opening and closing.

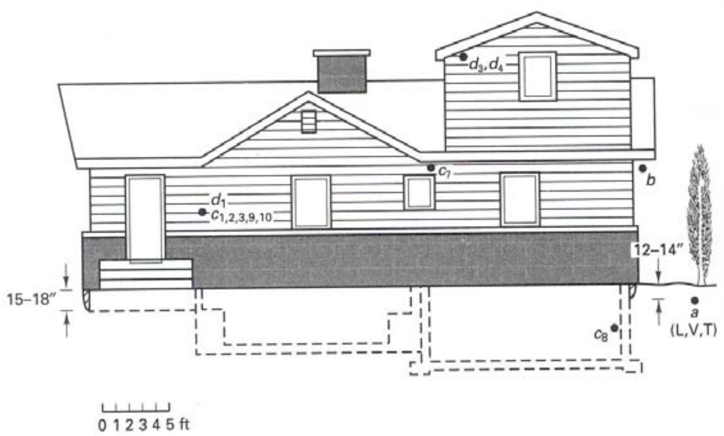


Figure 9: House associated with garage showing the variable foundation depths. The shallowest founded portion (left) displayed the most response to moisture induced volume changes in the soil.

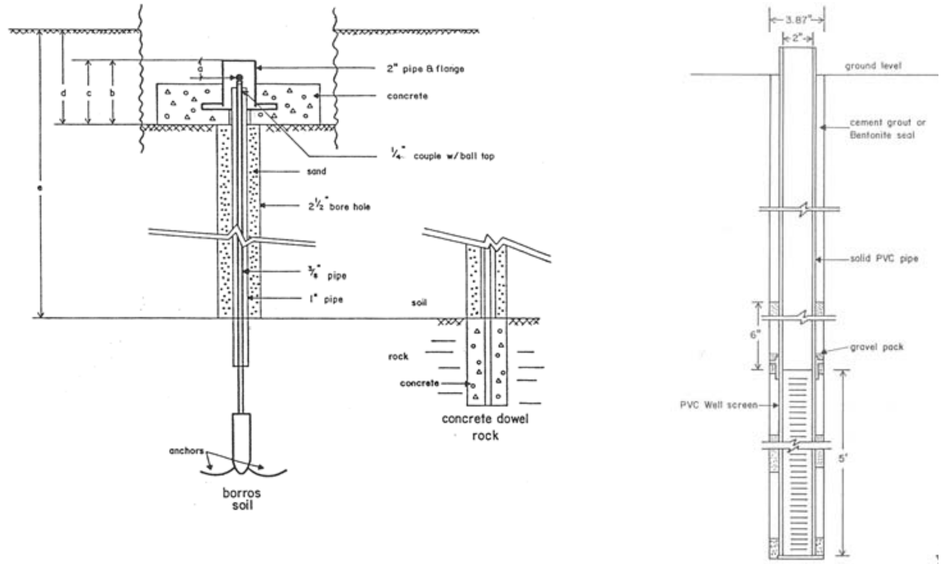


Figure 10: Other versions of inexpensive anchor systems and well for observing changes in the water table. Borros point (left) and rock dowel (center) and PVC well (right).

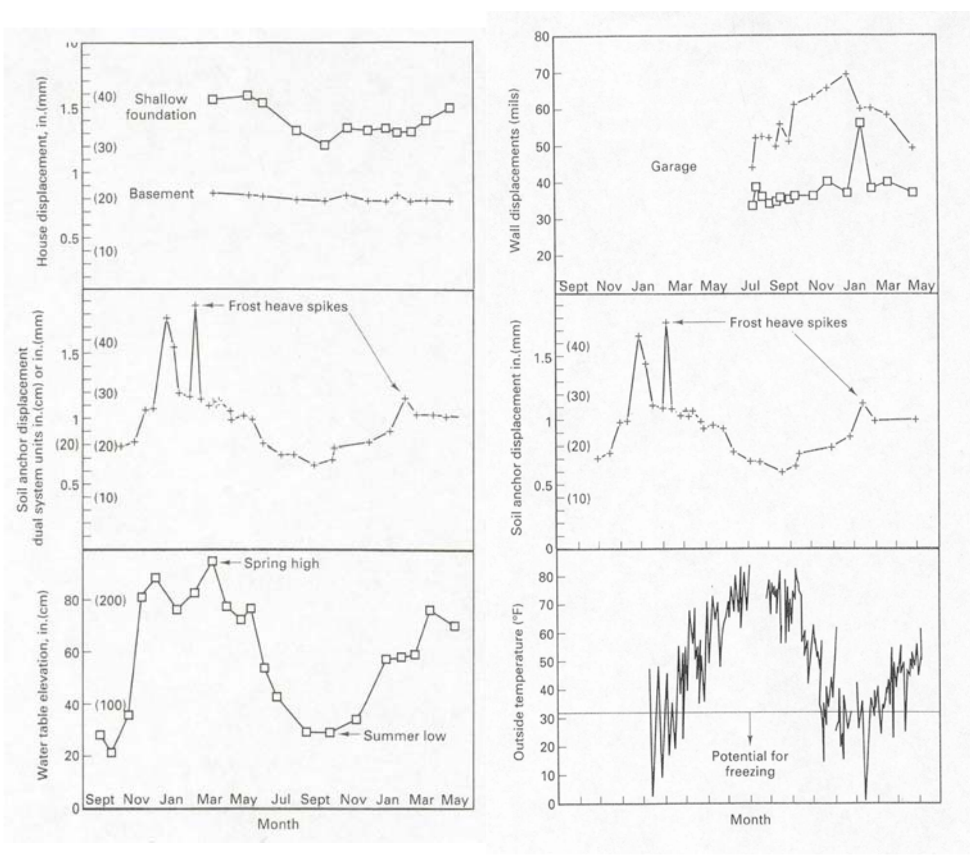


Figure 11: Vertical house movement (top left) and response of crack in slab on grade garage (top right) compared to soil volume change (middle graphs) and changes in water table (bottom left) and air temperature (bottom right)

Appendix: Details of Estimating Moisture Retained in the Shallow Soils

The volume of water/moisture accumulated or retained (VAcc) in given day can be crudely estimated as the Vol. Rainfall (VRF) minus Vol. Evapotranspiration (VET) minus the Vol. of Downward Percolation(VDP). The cumulative volume of water in the soil is then estimated as follows:

$$\sum_{i=day} VAcc_i = \sum_{i=day} VRF_i - VET_i - VDP_i$$

where VRF is the volume of rainfall on a given day (sometimes equal to 0), VET is the daily Evapotranspiration rate (specific to month of the year as shown in the table below), and VDP is the downward percolation per day (specific to the given soil). Values employed for the VET in the table below were assumed to be those recommended for a "southern" climate by Fetter (2001)

Month	VET [in^3/day]
October	0.13
November	0.08
December	0.03
January	0.02

The VDP is calculated as follows based upon the assumptions that the
permeability, K, is 10^{-6} cm/sec,
downward percolation gradient , i , is 1.0 and
area is one in. x one in. (thus 1 inch of rainfall produces 1 cubic in of water)

$$VDP = KiA = (1 \times 10^{-6}\frac{cm}{s})(1\frac{cm}{cm})(\frac{1in}{2.54cm})(in^2)(\frac{86400s}{1day}) = 0.03\frac{in^3}{day}$$

Thus the bottom plot in Figure 5 in the body represents a crude estimate of the increase in stored water in the soil profile. More stored water raises the potential for swelling of dry, expansive soils. The largest increase in retained or stored water occurs at the same time of the greatest swelling of the soil.