DAMAGE PREVENTION

Analyzing Underground Water-Pipe Breaks In Residual Soils

By Paul F. Hudak, Barry Sadler and Bruce A. Hunter

Though less dramatic than other geologic events, expansive soils are among the world's most costly hazards. Each year in the United States, expansive soils cause over $2 billion in damage to roads, buildings and other structures (Keller, 1996; Montgomery, 1997). Some estimates are as high as $6 billion/year (Pipkin and Trent, 1994). Financial losses from expansive soils are approximately equal to those from all other geologic hazards combined (Montgomery, 1997). The potential for damage is especially severe in montmorillonitic clay soils that undergo significant changes in moisture content over time. These conditions apply to many parts of the southwestern United States. While much of the previous work on expansive soils has addressed road and building foundation problems, the present study focuses on structures fully enclosed in soil. Specifically, the objective was to evaluate the spatial distribution of water pipe breaks relative to soil conditions and climate patterns in University Park, Texas.

Background

Expansive soils contain clay minerals that undergo significant volume changes with changes in moisture. Swelling is caused by the attraction of water molecules to plates of expanding clay minerals such as montmorillonite. Layers of water molecules and hydrated cations are added between plates as the clay expands or swells (Keller, 1996). Generally, expansive clays have a high plasticity index, reflecting a tendency to take up much water while in the plastic state (Brown, 1979). (The plasticity index is the numerical difference between the liquid and plastic limits. Respectively, the plastic and liquid limits are the moisture contents at which the soil changes from a semi-solid to a plastic, and from a plastic to a liquid.)

Montmorillonite is associated with most expansive soils. With the addition of water, this clay mineral may expand 15 to 20 times its dry volume (Brown, 1979). However, 25 to 50 percent expansion is more common in soils that contain various minerals and organic matter (Keller, 1996). Unfortunately, a volume increase of only 3 percent is potentially dangerous and requires special design considerations (Brown, 1979). A confined clay deposit containing montmorillonite can exert pressures of several tons per square meter (Brown, 1979).

Much of the previous work on expansive clays has focused on building foundations and roads (Ambrose, 1981). For example, the University of Texas at Arlington (UTA, 1978) studied the effects of expansive soils and remedial measures on residential, monolithic slab foundations in the Eagle Ford and Taylor Formations of north-central Texas. The study involved ten damaged houses, overlying expansive soils derived from shale and marl bedrock. Allen and Flanigan (1986) sampled 228 foundation failures over several soil associations in Dallas County, Texas. Most of the damage was associated with soils having a high shrink-swell potential. In a study conducted by the City of Carrollton, Texas, 26 to 36 percent of the ten-year old homes surveyed had suffered damage to sheet rock and brick veneers that was attributed to expansive soils (Allen and Flanigan, 1986).

Pipes and other structures that are buried in montmorillonitic soils also are subject to damage caused by large hydration pressures (Day, 1994). With numerical modeling, Sorochan and Kim (1994) showed that wetting an expansive soil creates vertical and horizontal stresses that can ultimately crack objects enclosed in the soil. Moreover, the pressure component associated with swelling increases with an increasing vertical load. The load prevents loosening of the soil, leading to a stress increase in the backfill around the structure. This is especially true of water and sewage lines, where even minor damage can create leaks. Once a leak occurs, the water saturates the material next to the leak, compounding the problem by causing continued expansion or movement.

Study Area

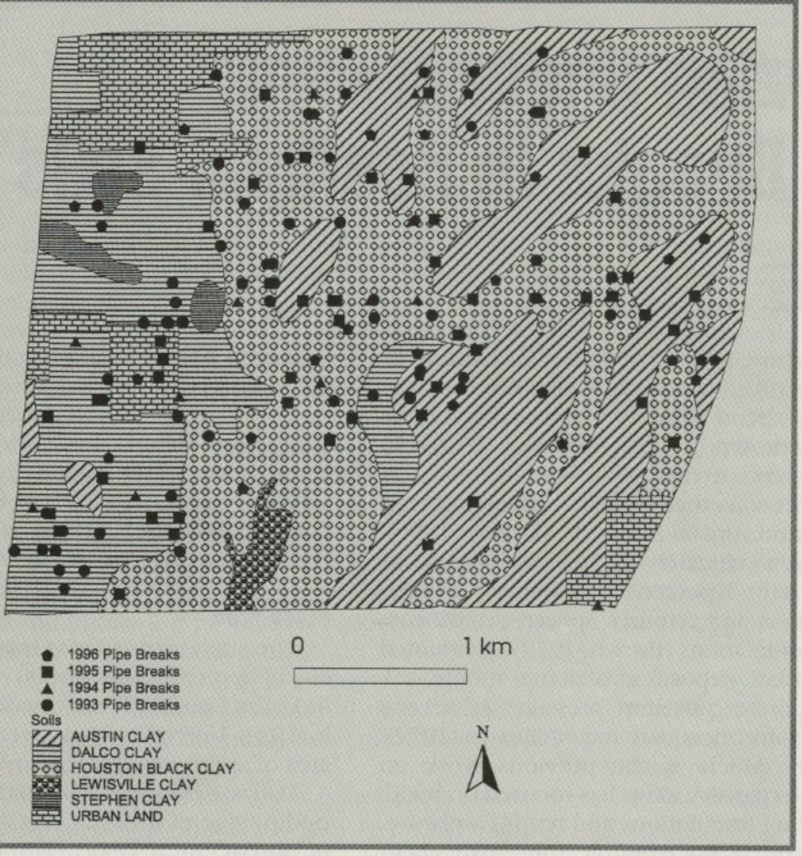
The study area is University Park, a city of approximately 22,000 residents in Dallas County, Texas. Incorporated in 1924, University Park occupies an area of approximately 9.6 km^2.

Dallas County is situated at the updip edge of the Gulf Coastal Plain, in north-central Texas. The underlying rock formations dip gently to the east-southeast, at a rate of approximately 10 m/km (Shuler, 1918). Outcropping rocks in Dallas County are Upper Cretaceous in age, deposited under shallow marine conditions. In the study area, these rocks include indurated chalks and shaly limestones of the Austin Formation. Thin bentonitic beds also are present throughout this formation (Barnes, 1972). The Austin Formation is rippable for construction.

Residual soils developed on the Austin Formation contain expansive clay minerals. These dark plastic clays are one of the most recognizable characteristics of the Blackland Prairie, within which the study area resides. Potential vertical rise in soils of Dallas County can approach 15 cm starting from a dry condition with zero loading. A vertical rise of 8 to 13 cm is common for a surcharge loading typical of slab-on-grade structures and dry soil conditions (Allen and Flanigan, 1986). Movements of these magnitudes are well above what is usually considered tolerable for the average stiffened slab-on-grade foundation. Free swell in these soils can exceed 6 percent, and absorption pressures greater than 430 KN/m^2 are routinely recorded (Allen and Flanigan, 1986).

Figure 1

Soils Distribution and Location of Pipe Breaks



The United States Soil Conservation Service (Coffee et al., 1980) has mapped six soil units within the study area (Figure 1). These are the Austin Clay, Houston Black Clay, Stephen Clay, Dalco Clay, Lewisville Clay and Urban Land. Austin soils are nearly level to gently sloping (0 to 2 percent slopes) soils on uplands. Typically, the surface area is dark grayish brown silty clay about 25 cm thick. To a depth of 81 cm, the soil is brown silty clay. White platy clay is common below a depth of 81 cm. These soils formed in material that derived from soft chalky limestone of the Austin Formation.

Houston soils are deep and nearly level to gently sloping. Typically, the surface layer is very dark gray to black clay, about 15 cm thick. To a depth of 97 cm, the soil consists of black clay. From 97 cm to 132 cm, very dark gray clay is predominant. Beneath 132 cm, to a depth of 178 cm, dark grayish brown clay with light olive brown mottles is common. Houston soils formed in clayey marine sediment on uplands.

Stephen soils are shallow and gently sloping. Typically, the surface is very dark brown silty clay that is about 36 cm thick. White, platy and massive chalky limestone is present below a depth of 36 cm. These soils formed on chalk deposits of the Austin Formation.

Dalco soils are moderately deep and nearly level to gently sloping (0 to 3 percent slopes). Typically, the surface layer is black clay, about 66 cm thick. To a depth of 89 cm the soil is dark gray clay. The underlying material, to a depth of 203 cm, is white, soft chalky limestone. The limestone is platy to a depth of 104 cm and massive below that depth. Dalco soils formed on uplands, in material derived from chalky limestone of the Austin Formation.

The Lewisville Clay is deep and gently sloping. The surface layer of this soil is dark grayish brown silty clay, about 33 cm thick. To a depth of 71 cm, the soil is light olive brown silty clay. Light yellowish brown silty clay is present to a depth of 119 cm. Below that, to a depth of 203 cm, the soil is light yellowish brown silty clay with fine textured, light gray mottles. Lewisville soils formed in Pleistocene alluvium on stream terraces.

Finally, Urban Land consists of extensively built up areas where 75 percent or more of the surface is covered with buildings and pavement. These soils were altered or covered during urban development (Coffee et al., 1980).

Table 1 lists relevant engineering properties of each soil in the study area. Drawing conclusions from this table, all the soils have a high corrosion potential, and a moderate to very high shrink-swell potential. A low shrink-swell potential implies a volume change of less than three percent in an unconfined clod of soil as the moisture content increases from air-dry to field capacity (Coffee et al., 1980). Moderate shrink-swell implies a 3 to 6 percent volume change, high shrink-swell corresponds with a 6 to 9 percent volume change, and a very high rating indicates a volume change more than 9 percent. The Houston and Dalco soils have the highest shrink-swell potential, resulting from high plasticity indices. Both of these soils plot in the high compressibility range on a standard plasticity chart (Figure 2).

The high corrosion potential of the soil units stems from a predominance of clay constituents, and a related tendency for moisture retention and electrical conduction. Respectively, high, moderate and low corrosion potentials correspond to earth resistivity measurements of less than 2,000 ohms/cm^3, 2,000 to 5,000 ohms/cm^3, and more than 5,000 ohms/cm^3 (Coffee et al., 1980).

The climate of the study area compounds the potential hazards of expansive soils. The area has a temperate climate, with long hot summers and moderately wet springs and falls. Prolonged hot, dry periods with little or no rainfall followed by cool, wet periods provide an ideal environment for expansion (Keller, 1996). In climates with long dry periods, fine-grained soils often shrink to a minimum volume, producing vertical cracking that extends to considerable depths. When significant rainfall occurs, the ground swells as water is absorbed, producing considerable vertical or lateral pressures on structures (Ambrose, 1981). Cracks can facilitate rapid seepage of water into lower soil horizons.

High summer temperatures cause moisture losses in the study area. The average temperature in Dallas County is 29° C in the summer and 9° C in the winter (Coffee et al., 1980). Temperatures exceeding 38° C are a typical occurrence every summer. The highest temperatures are associated with fair skies, light westerly winds and low humidity, as continen-

Table 1

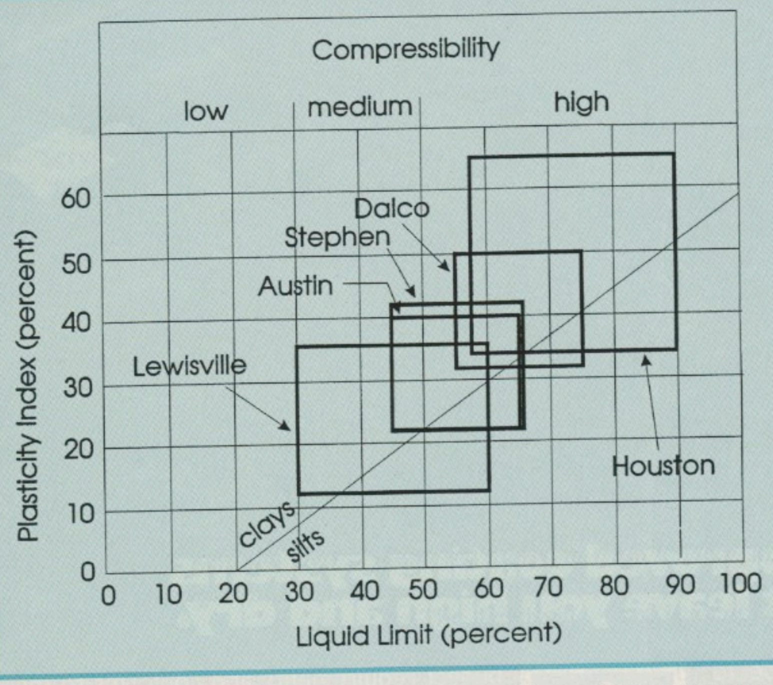
Soil Properties*

Soil	Plasticity Index	Liquid Limit	Shrink-Swell Potential	Corrosion Potential
Austin Clay				
0–25 cm	25–40	45–65	high	high
25–81 cm	22–38	45–65	moderate	high
Houston Clay 0–198 cm	34–65	58–90	very high	high
Dalco Clay 0–89 cm	32–50	55–75	very high	high
Stephen Clay 0–36 cm	22–42	45–66	moderate	high
Lewisville				
0–38 cm	20–36	41–59	high	high
38–104 cm	25–36	48–60	high	high
104–191 cm	12–34	30–55	high	high

* *modified from Coffee et al. (1980)*

Figure 2

Range of Plasticity Indices and Liquid Limits for Soils in Study Area (chart modified from Ambrose 1981)



tal tropical air masses infringe upon the area (Rohli and Grymes, 1997). On average, 8 to 10 days in August reach 38° C, 6 to 8 in July, 1 to 2 in September, and 1 to 2 in June. In the winter, runs of extremely cold weather are of short duration, lasting only a few days. The frost line is less than 5 cm below ground level, and therefore freezing is not a factor in subsurface pipe breakage.

Compounding the drying effect of high temperatures, there are typically low amounts of rainfall in the study area from mid to late summer. Mean annual rainfall is approximately 86 cm (Coffee et al., 1980), although annual totals have varied from less than 51 cm to more than 127 cm (Rohli and Grymes, 1997). The most common storms are thunderstorms that occur frequently in the spring and early summer. In the late summer and early fall, hurricanes moving inland from the Gulf of Mexico may cause infrequent, but heavy rainfall. Longer duration lower intensity storms are triggered in the fall and winter by southward moving continental polar fronts.

During a typical year, precipitation totals tend to show a bi-modal peak (Rohli and Grymes, 1997). The first occurs in late spring when frontal passages are frequent. Rainfall is further enhanced because the ground warms significantly while the atmosphere is still cool. The second peak is in autumn, due to intrusions of tropical systems ranging in strength from weak easterly waves to hurricanes. Moisture shortages typically develop during the summer as a result of extended periods when high evapotranspiration rates exceed rainfall. Gross annual lake-surface evaporation in Dallas County is approximately 162 cm (Allen and Flanigan, 1986). Deficits and droughts represent an important component of the climatology of the area (Rohli and Grymes, 1997).

Rainfall runoff is a key input to surface water reservoirs in north-central Texas. Most of the water consumed in this region comes from artificial reservoirs. Park Cities Municipal Utility District supplies drinking water to elevated tanks in University Park, the focus of this study. The City maintains the water distribution system within its jurisdiction. Typically, the pipes are buried about 50 cm below ground level. Throughout the study area, the high water table is more than 2 m below the land surface (Coffee et al., 1980).

Pipe diameters in the distribution system range from 10 to 84 cm, with 15 cm most common. The 10 cm diameter pipe is made of PVC, and the other sizes are cast iron. Pipes having diameters equal to or greater than 61 cm are encased in concrete. Breaks in the cast iron pipe are repaired by inserting a ductile, galvanized iron segment.

Methods

Data from the Public Works Department of University Park, the Soil Conservation Service and the National Oceanic and Atmospheric Administration (NOAA) were compiled to evaluate the spatial distribution of water pipe breaks in relation to soils and climate in the study area.

A geographic information system, ARC/INFO (ESRI, 1995), was used to digitize soil boundaries from maps in the Dallas County Soil Survey (Coffee et al., 1980). A second layer of data, the pipe network, was created from blueprints provided by University Park's Public Works Department. Arcs

Table 2

Pipe Break Data, 1993–1996

Soil	Total Pipe Length (m)	(Cast Iron)	(PVC)	Total Breaks	(Cast Iron)	(PVC)	Total Break Density*	(Cast Iron)	(PVC)
Austin Clay	41,835	37,433	4,402	36	35	1	8.6	9.4	2.3
Houston Clay	57,365	51,975	5,390	76	62	14	13.2	11.9	26.0
Dalco Clay	32,173	27,469	4,704	43	32	11	13.4	11.7	23.4
Stephen Clay	2,416	2,223	193	0	0	0	0.0	0.0	0.0
Urban Land	10,964	10,765	199	6	5	1	5.5	4.7	50.3
Lewisville	239	239	0	0	0	0	0.0	0.0	n/a

** number of breaks per 10,000 m of pipe*

ere assigned identification codes ased on pipe diameter. A street netork with addresses was clipped om the Tiger File for Dallas County .S. Bureau of the Census, 1996).

Next, the data layers were transrmed to State Plane coordinates and onverted to ARCVIEW (ESRI, 1996) hape files. A fourth layer (pipe eaks) was created by matching eak addresses in files of the Public orks Department to digital address- in the street network. Pipe break data were compiled for the period from 1993 to 1996. The data layers were then overlaid to determine the number of breaks, break density and pipe characteristics for each soil unit. Finally, temporal patterns of break occurrence were tabulated and compared with local records of precipitation and temperature.

Results and Discussion

Piping resides within all of the soils exposed in the study area. Breaks were recorded in four of the six soils over a four-year period (Figure 1, Table 2). The highest density of breaks (for all pipe) was in the Houston and Dalco Clays (Table 2). Those soils also have the highest plasticity indices (Table 1). A tendency for soils with higher plasticity indices to exert greater stress on pipes is consistent with previous observations for building foundations (Ambrose, 1981).

The Austin Clay, with a plasticity index and liquid limit similar to the

Figure 3

Pipe Breaks Per Month (1993–1996)

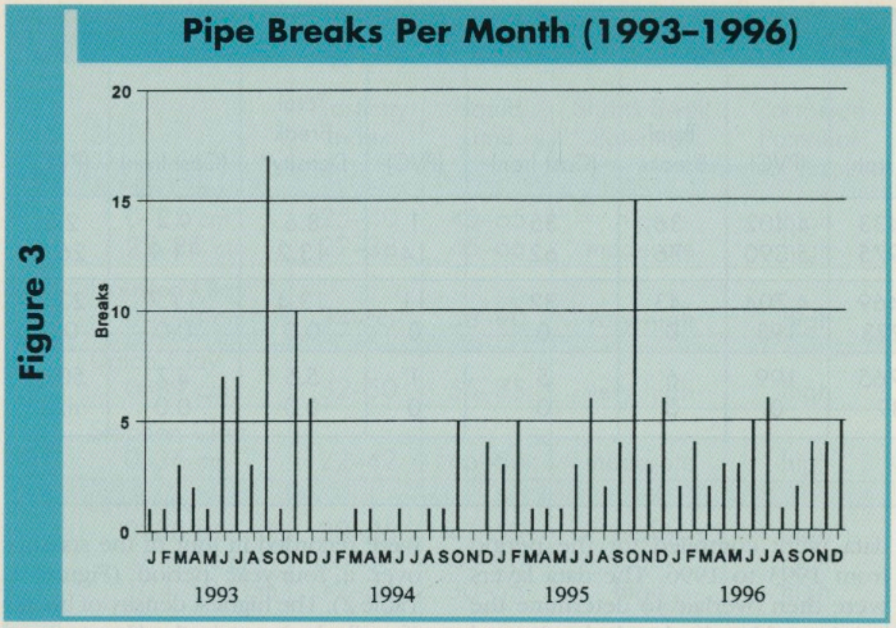
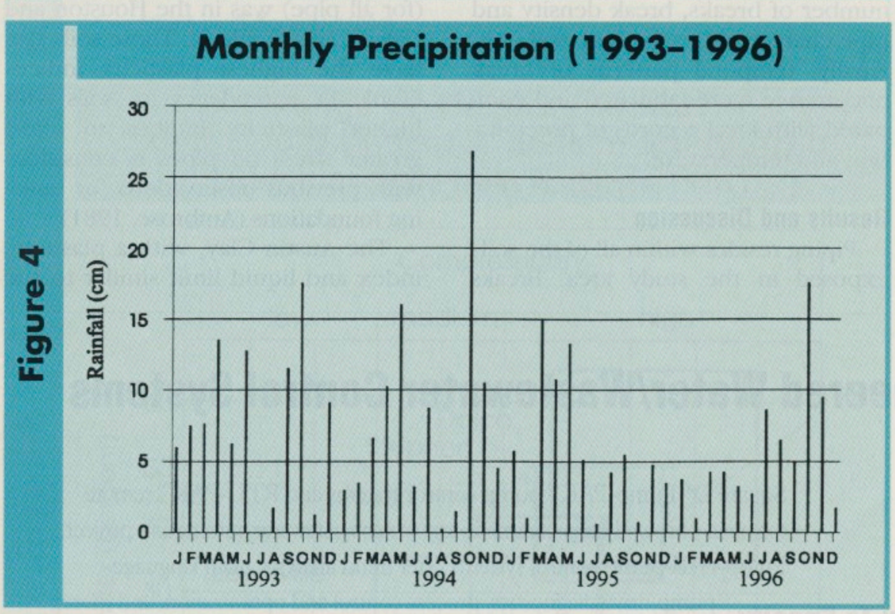


Figure 4

Monthly Precipitation (1993–1996)



Stephen Clay, registered the third highest break density (Table 2). A comparatively small number of breaks were observed in the Urban Land unit. This can be attributed to a high percentage of compacted sandy fill versus native clay in that unit.

An absence of breaks in the Stephen Clay and Lewisville soil stems from the relatively small amount of pipe in those units. Also, a thin soil mantle in the Stephen Clay results in some pipes being buried in the more stable, underlying bedrock.

Higher break density values were observed for PVC than cast iron in the Houston Clay and Dalco Clay. However, a lower break density was computed for PVC in the Austin Clay. These observations suggest that under very high shrink-swell conditions, PVC pipe may be more vulnerable to breaking. Under moderate shrink-swell conditions, the break resistance of PVC exceeds that of older cast iron, perhaps due to the weakening effects of corrosion. The break density computed for PVC pipe in the Urban Land unit may be skewed. It is based on only a short length of PVC.

Breaks were more common in the smaller-diameter pipe. Of the 134 breaks documented in cast-iron, all but 4 were in 15-cm or 20-cm diameter pipe (the smallest cast-iron diameter categories). Thicker pipe walls and concrete encasing account for a lower break frequency in the larger-diameter pipe.

Most of the breaks occurred from September to December (Figure 3). Over the four-year study period, those four months yielded more breaks (86 breaks) than the other eight months combined (75 breaks). The higher break frequency from September to December may be caused by adding water to soils that were dried out during the summer. In January to May, soil moisture fluctuations are less extreme, leading to less shrink-swell. In some years, there are a significant number of breaks in June and July that may be due to short periods of rain that moisten dry soil. Apparently, shrinkage during dry months also contributes to pipe ruptures. From December, 1994 through June, 1996, there were eight months with an above-average (> 3) number of breaks. Each of those eight months had below-average (< 7 cm) rainfall.

Soils in the study area dry out during the summer due to extremely high temperatures and relatively low amounts of precipitation, especially in July and August (Figure 4). During those months, rainfall is insufficient to offset water losses to evapotranspiration. Lower temperatures in the other months cause less evapotranspiration that leads to less extreme soil drying.

The association between plasticity index and break density observed in this study suggests that expansive clays may play an important role in rupturing water pipes. Corrosion can also weaken cast iron pipe, making it vulnerable to breaking from hydrostatic water pressure. However, maintenance workers generally noticed little to no corrosion during repair jobs, including cast iron pipe dating back to 1939 (D. Simpson, personal communication). Because of their relatively high silicon content, cast irons resist oxidation and corrosion but are vulnerable to brittle deformation (Walton, 1971).

Chemically stabilizing the soils with lime, which has been moderately successful for building foundations (Allen and Flanigan, 1986), replacing the clay with nonactive structural fill and ductile piping may mitigate future problems in the study area. Corrosivity can be overcome by coating the pipe with protective material, attaching anodes to the metal, using more resistant material or using rubber/plastic connectors.

For a list of references, e-mail wemedit@aol.com or write Water Engineering & Management.

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