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Foundation Performance in an Expansive Clay

Comportement de fondations sur des argiles gonflantes

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SYNOPSIS

Information from eight extensive case studies of buildings situated in the Eagle Ford Geologic Formation which have exhibited post-construction floor and foundation movements of 50 to 250 mm is presented. The structures are tilt-wall one-story office/warehouse and two and three story office buildings of concrete and masonry construction. The buildings have pier and beam foundation systems founded 4.5 to 10.5 m below grade with both suspended and "floating" ground supported floor slabs. Although engineered and constructed in accordance with local industry standards, the functional performance of the buildings has not been acceptable.

The studies are subdivided into two groups of distress types; those attributed to contractor error; and those design related. Documented contractor errors consist of improperly constructed voids under grade beams, belling of the top of the pier and separation of structural elements from ground supported features. Design errors consist of under-prediction of soil movement and pressure, placement of granular soils below grade, inadequate prediction of the total zone of soil movement, and lack of understanding of subsurface conditions. The thrust of the paper concerns design errors and suggested design modifications.

INTRODUCTION

Foundation performance related to expansive clays have been studied and discussed throughout the world. By analyzing the performance of a foundation system, and understanding the interdependency of the structural system, site geology, building use, and environmental factors, modifications to the design can be performed to enhance or reduce the cost of subsequent systems.

This paper presents the observed performance of various foundation systems in one particular expansive clay shale. The purpose of the paper is to illustrate, by way of case studies of distressed structures, the highly expansive nature of this formation. An extensive description of the site geology and soil characteristics is provided in order to help identify formations with similiar characteristics. If the potential for and magnitude of expansion can be identified, then engineering judgement can be used to minimize its effect on a structure.

SITE DESCRIPTION AND GEOLOGY

The study area is located in Irving, Texas, U.S.A., a suburban community located immediately west of Dallas. Climate is temperate. Topography in the study area consists of rolling hills, with slopes of 10 to 30 degrees. Principal vegetation consists of range grasses and mesquite trees.

Geologically, the site is underlain by the Britton Member of the Eagle Ford Formation, a marine, montmorillonitic clay shale of Upper Cretaceous age. The shale is thinly laminated, gray to bluish-gray in color and weathers to tan to olive tan and gray with ironstaining along joints and fissures. Depth of weathering varies from 10 to 40 feet below grade. Groundwater is not present in significant quantities, although intermittent perched water is occasionally encountered along the weathered/unweathered interface during the rainy seasons.

SOIL CHARACTERIZATION

Weathering of the Eagle Ford results in a tan to olive-tan and gray residual clay. The clay retains the shales' laminated fabric, and is jointed and fissured on spacings of 25 to 100 mm. The joints and fissures are commonly ironstained and occasionally silt lined. The clay structure is shown in Fig. 1.

The upper 1 to 3 meters of clay soils are subjected to variations in seasonal soil moisture, but these values are less than the average for the Dallas metroplex of 4 to 5 meters. This reduced seasonally active zone is considered to be primarily a result of the sloping site topography, and the relative low permeability of the clay soils.

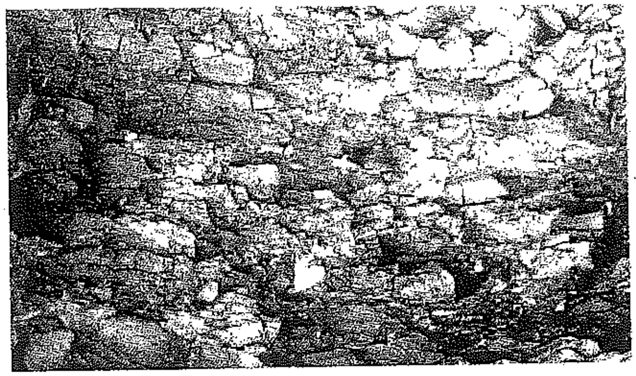


Fig. 1 Residual clay of the Eagle Ford Formation. Note the jointed and fissured structure and ironstained surfaces.

The natural moisture content of the clays below the seasonal influence is 4 to 7 percentage points below their plastic limit. The moisture content generally decreases with depth, as is common in weathered shales. An example of a typical Log of Boring is shown in Fig. 2. Analysis of the log of boring illustrates moisture above the plastic limit to a depth of about 1.5 m, and soil moisture below the plastic limit below 1.5 m. This boring was drilled near the end of the rainy season. Also shown on the log is the maximum pressure (P_s) and the percent swell at overburden, (S_p) results of two constant volume swell (CVS) tests. The procedure for the CVS test is described by Johnson (1978). P_s at the two depths tested is in excess of the overburden pressure, if K_o is assumed to be equal to 1.

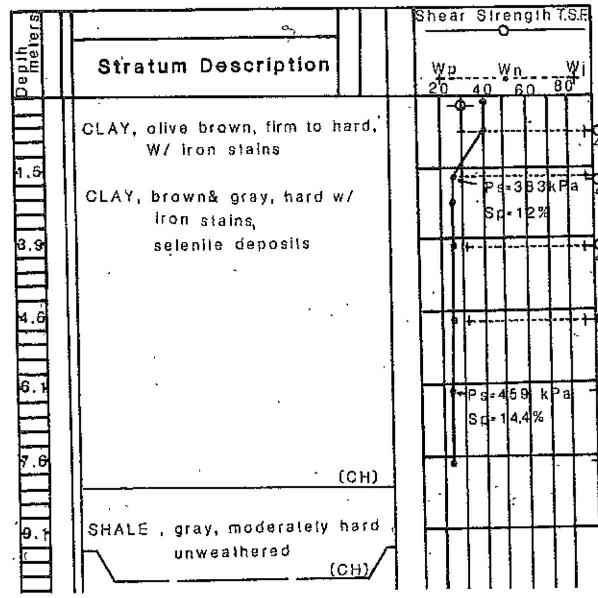


Fig. 2 Typical Soil & Soil Moisture Profile.

The weathered shales classify as CH soils, in accordance with the Unified Soil Classification System. The consistency varies in the zone of seasonal moisture, becoming hard below this zone. A summary of some of the pertinent soil properties is provided in Table I.

A limited amount of testing for clay mineral content has been performed and is shown in Table II. The tests indicate the percent clay fraction (minus 2 microns) is 50 to 60 percent

TABLE I
SUMMARY OF SOIL PROPERTIES

PROPERTY	UNITS	SAMPLE POPULATION	RANGE	MEAN	STANDARD DEVIATION	COMMENTS
Liquid Limit, w_l	--	71	49-94	76.8	8.43	
Plastic Limit, w_p	--	71	19-42	30.4	4.77	
Plasticity Index, I_p	--	71	33-70	46.5	8.30	
Dry Unit Weight, $_d$	gm/cm^3	52	1.41-1.86	1.61	0.098	Natural Moisture below plastic limit
Wet Unit Weight, $_w$	gm/cm^3	52	1.83-2.18	2.03	0.068	Natural Moisture below plastic limit
Dry Unit Weight, $_d$	gm/cm^3	19	1.29-1.68	1.47	0.088	Natural Moisture above plastic limit
Wet Unit Weight, $_w$	gm/cm^3	19	1.80-2.10	1.94	0.092	Natural Moisture above plastic limit
Specific Gravity, G_s	--	14	2.79-2.93	2.85	0.03	
Saturation, S	%	20	87-97	92.0	0.03	Zone below seasonal influence
Swell Pressure, P_s	kPa	22	95.8-790.1	464.5	182.0	CVS test
Percent Swell, S_p	%	22	3.2-18.1	11.5	3.7	CVS test

TABLE II
CHEMICAL COMPOSITION
(determined by x-ray defraction)

FACTOR (expressed as %)	CLAY	CLAY	SHALE
Depth (m)	2.1	4.2	7.6
minus 2 microns	51.8	61.3	51.8
montmorillonite	36	34	14
illite	8	10	11
mica	1	1	1
kaolonite	17	22	41
chlorite	4	3	1
quartz	23	19	21
feldspar	3	2	2
calcite	2	3	8
dolomite	1	1	1
gypsum	1	2	1
other	5	5	3

for both the clay and shale. The percent of montmorillonite and kaolinite in the clays, expressed as a percent of the clay size particles, is 34 to 36 percent and 17 to 22 percent, respectively. One sample of the unweathered shale tested showed a significant difference in percent montmorillonite (14 percent) and kaolinite (41 percent) versus the weathered soils.

BUILDING DESIGN

Two types of foundation and floor systems are discussed;

1. a pier and beam structure with a suspended floor slab; and

2. pier and beam with "floating" ground supported floor slab (composite construction).

Either system requires accurately predicting the active zone (the zone subject to movement) and the potential vertical movement (PVM). In the following case studies, the performance of both suspended and "floating" floor systems are analyzed.

The composite foundation is the more commonly used type for low-rise commercial construction.

The piers are extended to a stable zone, with the structural loads suspended above the expansive soils. The floor slab is then designed to "float" independently of the structural system.

Numerous methods are utilized to reduce the movements of a "floating" floor slab to within acceptable limits. The methods used fall into two philosophical categories: dry and wet. The "dry" philosophy relies on keeping any expansive soils under the slab at the same moisture as at the time of construction. The "wet" philosophy, on the other hand, essentially pre-moistens or pre-swells the expansive soil prior to placement of the "floating" slab. The philosophy utilized for any particular structure is dependent upon the geological formation, functional use of the building, and owner preference.

All of the ground supported floor systems studied, were "stabilized" using the dry philosophy consisting of removal of a depth of expansive clay and replacement with inert fill.

FOUNDATION MOVEMENT, CONTRACTOR RELATED

Contractor related errors which lead to distressed structures can be grouped under three general headings;

1. collapsed grade beam void boxes;

2. mushroomed or improper construction of piers; and

3. overlapping of slab on grade portions of the structure (i.e. paving, sidewalks, etc.) with suspended structural elements.

Due to the highly expansive nature of the Eagle Ford Formation and the pressures associated with swelling, any construction deficiency resulted in foundation movement and distress. Examples of each type of contractor related distress are presented in the following case studies. The studies are subdivided and identified by type of distress.

<u>Grade Beam Void Construction</u>

One of the more common factors in severe distress is the improper construction of the grade beam void. Within the Dallas/Fort Worth area, wax impregnated cardboard forms are generally used beneath the grade beam to create the void between piers. The forms are designed to withstand the weight of wet concrete during construction of the void. When the cardboard form becomes wet prior to concrete placement, the forms collapse allowing concrete to cure on top of the underlying soil. An example of a collapsed void box during construction is shown in Fig. 3. Due to the high swell pressures associated with the residual clays, failure of the grade beam in bending occurs upon swelling of the underlying soils. An example of the resulting structural distress is shown in Fig. 4. The beam shown experienced a maximum differential movement of 81 mm over a span of 6.7 meters.

<u>Pier Construction</u>

Proper construction of piers in expansive soils is required. Mushrooming of the top of the piers or construction of any horizontal projection allows the underlying clay to exert significant vertical pressure, with the potential for distress.

An example is a 3 level steel frame building, with brick veneer. The foundation consists of straight shaft piers socketed into the gray shale, with a top bearing plate for support of the structural steel column. The architectural covering around the column was detailed to be the same diameter as the pier.

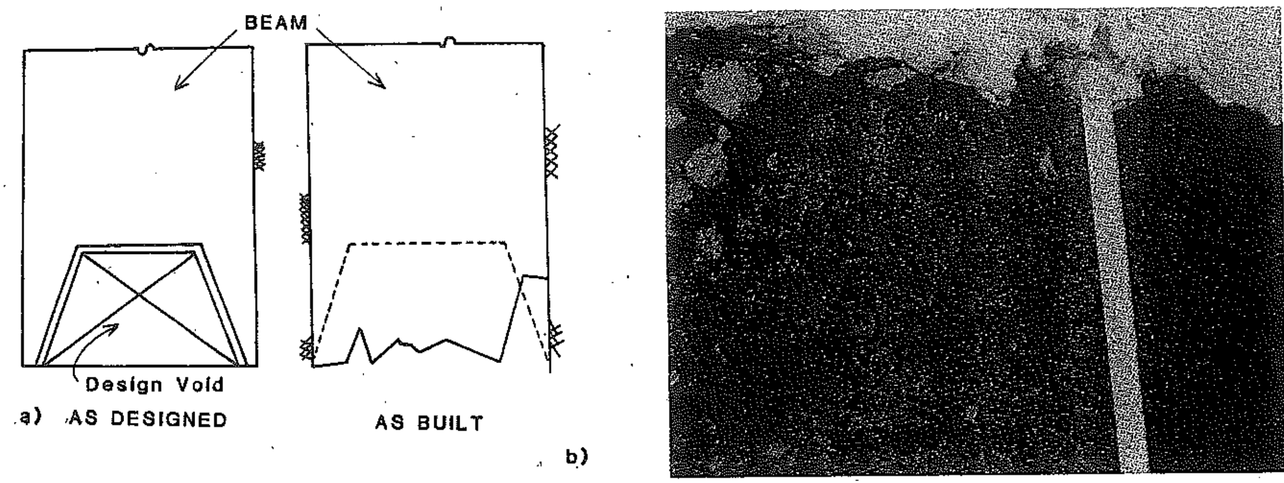


Fig. 3 Collapsed grade beam void. a) Sections of design and as built grade beam. b) Photograph of hardened concrete in design void space.

The top of the pier was constructed as detailed, but at a lower elevation than required. In order to extend the pier to the ground surface, a square cap was poured, and new bearing plate set. The cap extended beyond the diameter of the pier, and was underlain by residual soil. Expansion of the residual soils resulted in separation of the cap and pier.

A section of the designed and constructed pier is shown in Fig. 5a and Fig. 5b, respectively. Measured movement of one column is shown in Fig. 6. Of a total of 70 piers, 18 piers and columns moved, with movements measured at 9.5 mm to 101.6 mm. By calculating the dead load of the structure and dividing by the area of the "cap", soil pressures on the bottom of the "cap" were calculated to be 134.0 kPa to 243.1 kPa. This compares to soil pressures calculated by using the equation suggested by Komornik and David (1969) of 52.6 kPa to 62.6 kPa.

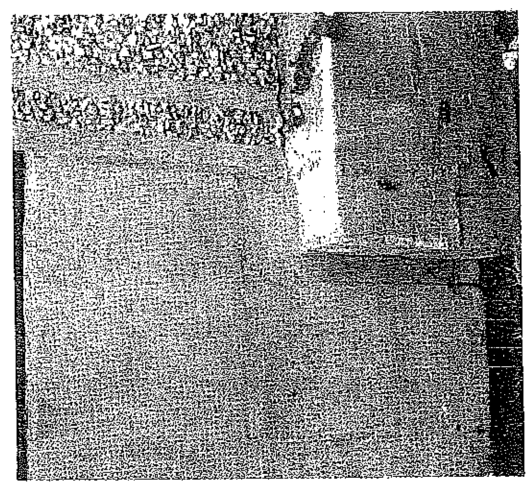
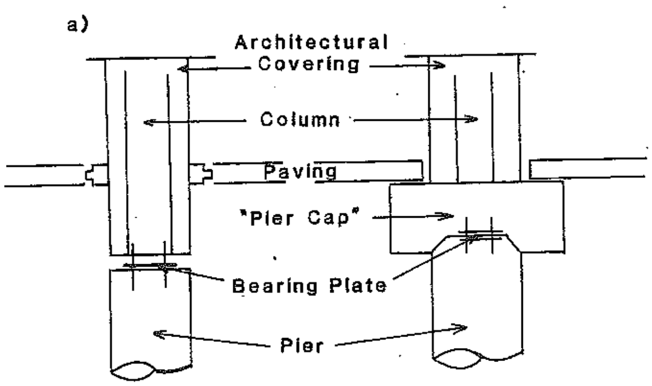


Fig. 4 Failure of the grade beam at pier connection due to uplift forces on underside of the beam shown in Fig. 3.



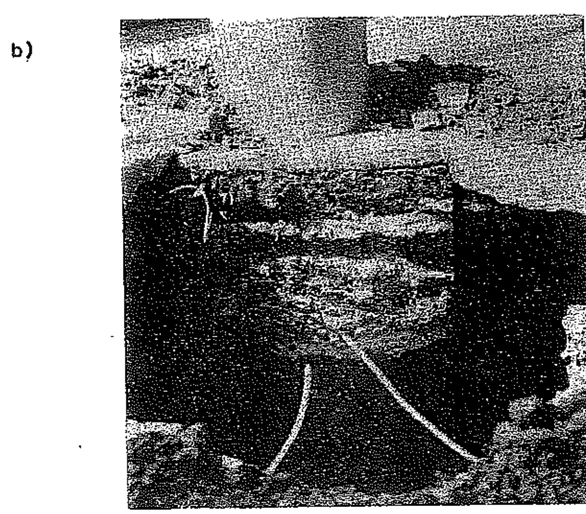


Fig. 5 Design versus constructed pier. a) Sections of design and as built pier. b) Photograph of pier and cap.

Fig. 6 Pier/column separation attributed to swelling soils underlying "pier cap" shown in Fig. 5.

Separation of Structural Elements

A pier supported structure must be separated from slab-on-grade features. Due to the high swell pressures even relatively minor details have resulted in distress.

This particular example consists of a 3-story office building with a pier and beam foundation and suspended floor. Structural loads are transmitted by steel frame to the foundation. Brick veneer was used for architectural covering. Concrete paving extended up to the building.

Approximately three years after completion of construction, cracks were noted in the exterior wall at three levels. Differential movement of the pavement on the order of 76 mm to 127 mm was noted. Figs. 7 and 8 illustrate the areas of distress in the brick veneer at the first floor level and in the adjacent concrete pavement, respectively.

A test pit revealed that the grade beam was widened during construction by placement of a 63 mm thick mortar or grout covering on the exterior face of the grade beam. The mortar covering overlapped the expansion joint between the grade beam, and the adjacent pavement. Soil expansion resulted in upward movement of the concrete pavement. The uplift pressure exerted

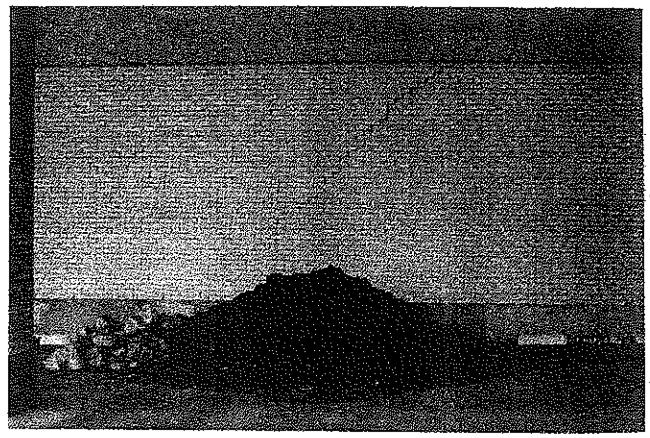


Fig. 7 Cracked brick veneer on a pier and beam foundation.

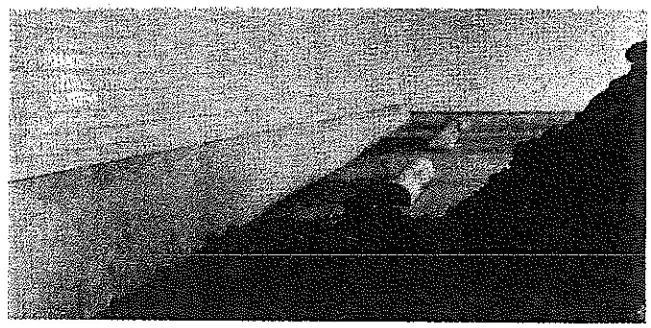


Fig. 8 Differential movement of a pavement adjacent to grade beam and wall shown in Fig. 7.

by the soils on the pavement was transferred to the brick veneer by the thin mortar covering. The pressure was sufficient to move the brick and rotate the structure. Fig. 9a and b illustrate the "as built" and the subsequent location of the pavement, covering and veneer after expansion.

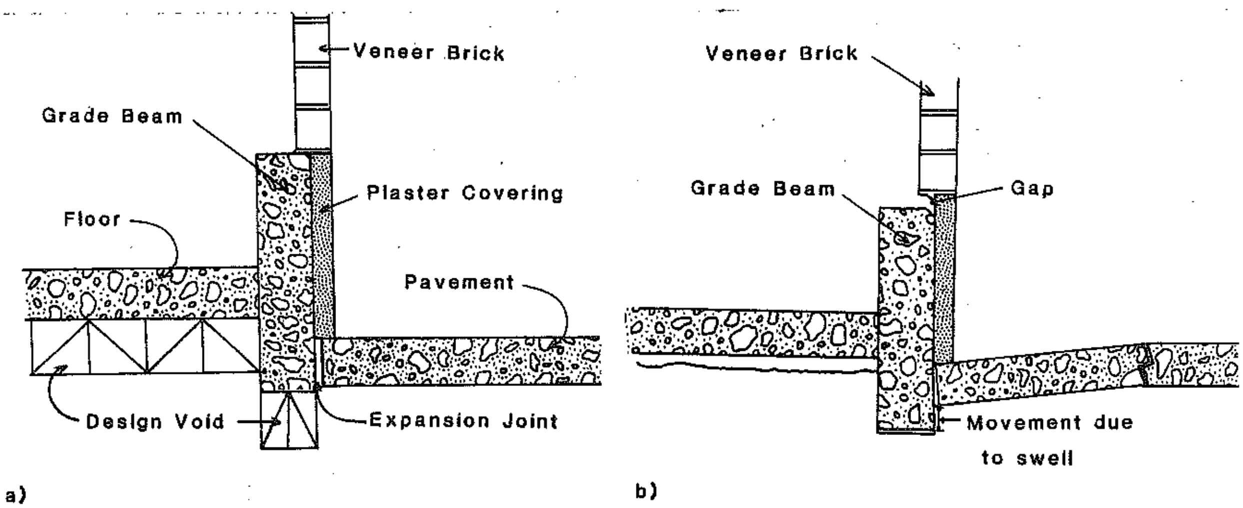


Fig 9 Grade beam and pavement sections for the building shown in Figs. 7 and 8. a) As built b) After soil expansion.

FOUNDATION MOVEMENT, DESIGN RELATED

The preceding studies illustrate foundation and building movement related to construction deficiencies. Although these types of deficiencies are important from the owner's perspective and in analyzing distress, they are generally not controllable by the geotechnical engineer. Of greater significance to the engineer is foundation and building performance related to design.

Studies of distressed structures in this formation have shown common design related factors which have attributed to foundation and building movement. They are:

1. Underprediction of the potential vertical movement and depth of expansion (active zone);
2. Removal and replacement of near surface soils with inert, non-expansive clayey sands; and
3. Recognition of both surface and subsurface drainage conditions;

Each of these items are discussed in the following sections.

Potential Movements and Depth of Active Zone

Both empirical and site specific methods of prediction of the total potential movement are available. A summary of some of the methods used to predict movement are available in the literature (Johnson, 1978). The method used must, however, be consistent with the site geology, and/or laboratory conditions used to develop the predictive method.

By way of example, the observed versus predicted movement at three sites studied are shown in Table III. The empirical methods used to calculate the observed movements were reported by McDowell (1959), Vijayvergiya and Ghazzaly (1973), and Van der Merwe (1964). The swell test prediction was developed using the CVS test (Johnson, 1978). The depth of observed saturation and preconstruction test data were used to predict the measured movements for each of the methods reported.

Analysis of Table III shows the McDowell and Vijayvergiya methods underpredicting the movements by 160 to 540 percent. The CVS test overpredicted the movement by 22 to 24 percent. The Van der Merwe method underpredicted the observed movements by 21 to 44 percent.

Based on these and other investigations, the CVS test appears to more accurately predict the movements than any of the empirical methods analyzed. Not all empirical methods have been used. Other types of site specific swell tests such as the Improved Simple Odometer Test (Jennings, et al, 1973) and swell at overburden tests (U.S. Army Corps of Engineers, 1961) have not been correlated with observed movements. Soil suction test data is currently being evaluated.

Movements in extreme excess of predicted values result in foundation movement, generally as a result of insufficient void under grade beams, tilt wall panels, and suspended floor systems. The pressures exerted on grade beams have been sufficient to cause stretching of the piers and/or failure of the foundation system in tension. An example of the rotation in the superstructure is shown in Fig. 10. This particular example consists of a pier and beam foundation suspended 20.3 mm above the underlying soil. Straight-shaft piers, 406 mm in diameter, extending 1.8 m into unweathered shale (top of shale at 7.3 m below grade), and reinforced with 1.2% steel, were used. Within

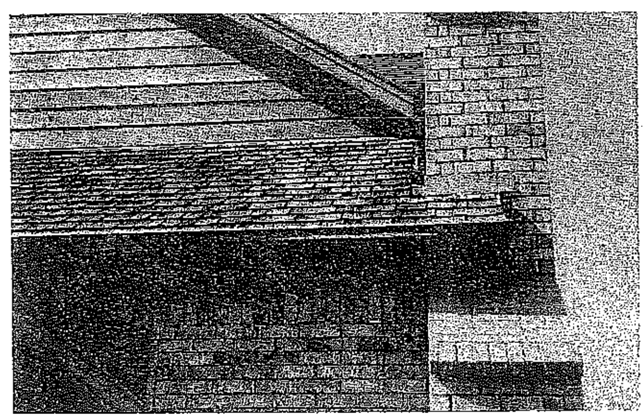


Fig. 10 Rotation of superstructure as a result of inadequate grade beam void. Rotation is equivalent to 114 m in 6.1 m height. Note gap at brick/roof connection.

TABLE III

PROJECT	OBSERVED MOVEMENT (MM)	DEPTH OF CLAY (M)	DEPTH OF SATURATION (M)	C.V.S.* ( )	PREDICTED MOVEMENT (MM) for Method McDOWELL (1959)	Vijayvergiya, ect. (1973)	Van der Merwe (1964)
A.	287	7.3	3.7	356	96	53	160
B.	190	9.8	3.4	---	119	89	150
C.	170	3.5	3.5	208	41	79	170

* Constant Volumn Swell, (Johnson, 1978)

approximately 15 months, soil movement adjacent to the grade beam measured 292 mm. The pressures exerted were sufficient to shear the pier steel and cause the rotation illustrated.

Accurate prediction of the active zone is required to predict the potential movement, determine the founding depth for underreamed piers, and to predict ultimate negative skin friction of pier shafts. Due to the high P_s values, the jointed and fissure clay structure, and extensive landscaping, the active zone has been observed to extend up to 9.2 m below grade. This zone is related to the P_s values, in-situ stresses, and availability of the deep migration of irrigation water.

Fig. 11 illustrates a site where post construction deep saturation occurred. A measurable increase in soil moisture occured to 8 m, coupled with a decrease in P_s values. Below the increased soil moisture zone, the P_s values increased to more typically measured values. A plot of in-situ stress, assuming K_o equal to 1, is also shown. A more elaborate evaluation of K_o does not appear to be justified, however intuitively it is anticipated K_o varies with time and soil moisture condition.

The structure consists of a two-story office building. The first floor is ground supported and detached from the grade beam and foundation. Foundation support consisted of belled or underreamed piers founded 6.4 m below grade. To date, maximum differential floor movement has been measured to be 190 mm. Pier movement varies from 6 to 135 mm.

Some of the pier movement is attributed to negative skin friction along the shaft, however, the increase in soil moisture and extreme reduction in the measured P_s is considered to be indicative of deep movement. Similar results have been observed on projects in the immediate vicinity.

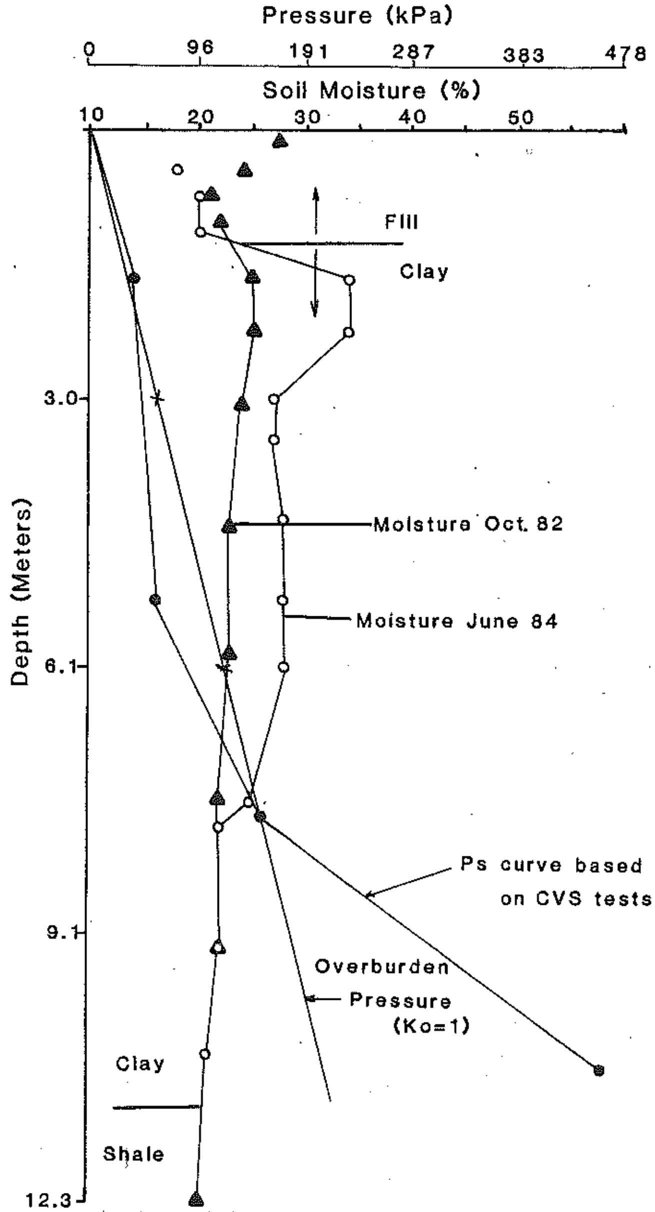


Fig. 11 Moisture increase with time. Increase in moisture and decrease in swell pressure associated with deep saturation of available surface water.

Removal and Replacement of Soil

Various techniques are utilized within the industry for the purpose of reducing the potential movements so that a ground supported floor slab may be utilized. Within the sites investigated in the Eagle Ford Geologic Formation removal of 0.9 to 1.5 m of clays and replacement with an inert clayey sand fill has been utilized. The inert fill has been reported to be for the purpose of removing the active zone, providing a surcharged load to the underlying clays to reduce the potential for movement, and to isolate the floor slab from the potentially expansive clays. Due to the swell pressures associated with the residual clay, the depth of active zone, and the tendency for water to pond in the inert fill, this type of stabilization technique has had detrimental effects.

As discussed in the previous section, the P_s values below the zone of seasonal moisture variation are significantly high to negate any surcharge effect from the addition of a limited amount of fill. In addition, because the active zone is moisture related and not related to the seasonal moisture variation, deep seated movement will occur if moisture is available. Deep seated soil movement will significantly affect the ground supported floor slab and foundation system. Last but not least, the presence of sandy soils surrounded by clay soils causes what is locally termed a "bird bath". Surface water can then pond in the inert fill. This water is then continuously made available to the underlying expansive clays.

A significant number of structures have undergone severe distress as a result of surface migration of water into inert fills placed at or

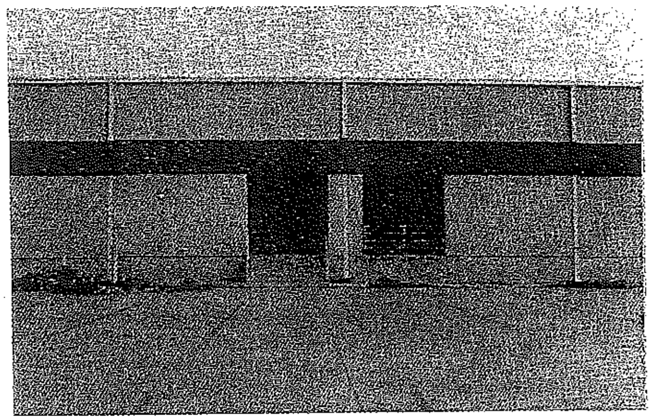


Fig. 12 Tilt wall movement associated with severe floor movement. Note accent stripe. Movement at pier connection shown in Fig. 13.

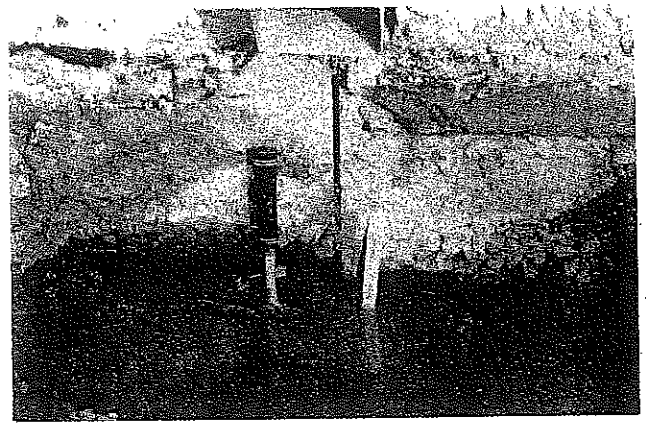


Fig. 13 Movement of adjacent panels shown in Fig. 12. Left panel moved about 51 mm. Head of hammer is on top of pier.

below grade. The most severe movements generally occur at the edge of the building and migrate towards the center. Floor slabs which have been tied or doweled into the grade beams or tilt wall panels generally exhibit a severe rise in the floor approximately 1.8 to 3.0 m feet away from and parallel to the tilt wall panel or grade. Floor slabs which are not connected to the grade beams and/or tilt wall panels generally exhibit severe movement adjacent to the grade beam, decreasing towards the center of the structure. Topographic surveys of the top of the floor slab show significant rises in the overall movements along the perimeter of the structure in relationship to the interior portions of the building. In severe cases the interior of the structure also moves. Floor systems tied to the grade beam and/or tilt up panels subjected to severe movement have resulted in structual distress. An example of tilt-wall movement is shown in Figs. 12 and 13. Movements occurred over approximately a 3 year period.

Surface and Subsurface Conditions

Foundation design in a dry, deep expansive soil requires an awareness of both the surface and subsurface drainage conditions. Ponded water adjacent to or under a structure in a dry expansive soil profile can result in deep seated movements.

An example of inadequate subsurface drainage as a result of design is shown in Fig. 14. In this example, the designers used 1.1 m of inert fill (clayey sand) to reduce the potential movements and stabilize the "floating" floor. The inert fill was extended 1.5 m beyond the limits of the building.

Within the Dallas area, the inert fill as specified is available as a non-uniform clayey sand/sand mixture. The sands are medium to fine. Due to the sand, the permeability of the fill is relatively high in comparison with the underlying clay soils. Surface water infiltrating through the inert fill perches on the fill/natural clay interface, and is available to the dry residual clays.

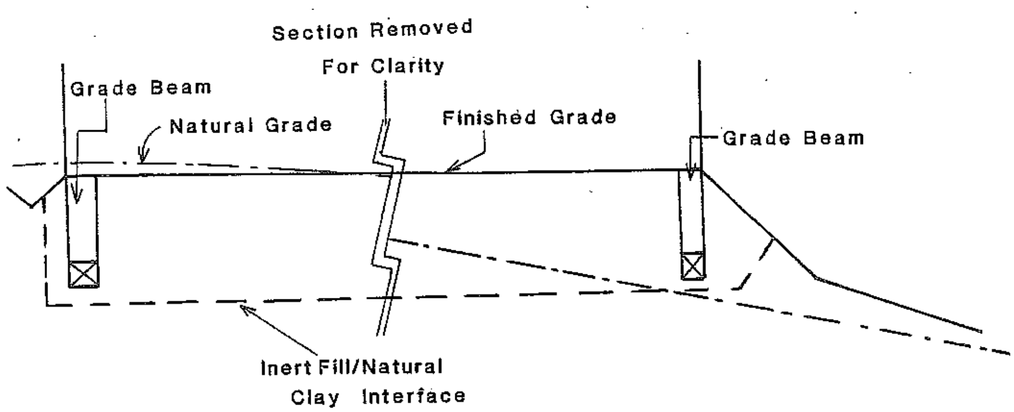


Fig. 14 Subsurface drainage modified by design. Design consisted of removal of clay soils and replacmeent with inert clayey sand fill.

Post construction floor movements of up to 292 mm have been measured in structures of this design. Pier movements ranging from 6 mm to 140 mm have also been observed.

Pier movement is attributed to swell below the founding depths and/or negative skin friction along the shaft, dependent upon the site specific geologic and design conditions.

Localized alluvial deposits overlying weathered clays can also provide avenues for surface water to infiltrate and pond. Due to the high swell pressure associated with residual Eagle Ford clays, movement of the clays below alluvial deposits as thick as 4.6 m have been observed.

CONCLUSIONS

1. The Eagle Ford Formation is a clay shale of Cretaceous age. Weathering of the shale results in an expansive clay which may exert pressures of 95 to 790 kPa, and volumetric swell of 3 to 18 percent. The natural moisture content of the weathered shale is generally below the plastic limit below the zone of seasonal moisture variation.

2. The seasonally active zone of soil movement is 1 m to 3 m, however the zone of movement is influenced by the availability of water to the deeper dry clays. Post construction active zones have been measured as deep as 9.2 m.

3. Proper construction of grade beam voids and piers is critical if the foundation is to perform as designed. This is probably more critical in this formation due to the high swell pressures and large volumetric swell.

4. Accurate prediction of the potential and probable post construction movements is required for design of a structure. For the studies sited, predicted movements based on constant volume swell tests were more accurate than the empirical methods proposed by McDowell (1959) or Vijayvergiya and Ghazzaley (1973).

5. Deep seated soil movement can result in foundation movement due to swell below the foundation depths, and/or negative skin friction.

6. The removal of a limited amount of clay and replacement with inert, non-expansive fill may result in development of perched water under the building as a result of subsurface drainage. Deep seated swell is attributed to the availability of this water.

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