Foundation Design of an Industrial Plant in Stillwater, Oklahoma

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ABSTRACT

The geotechnical considerations in the design and construction of an industrial plant in an expansive soil environment are discussed in this paper. The soils at the site exhibited a high swelling potential that necessitated a defensive design approach. The behavior of these soils was quantified from a limited number of controlled swelling tests. The data were supplemented by using published correlations between the swelling behavior of soils and the results of soil index tests that are routinely performed during soil investigations. Correlations were found very useful in corroborating quantitative test results from controlled tests. Several measures were included in the design to protect the foundations and the structure against the potentially damaging effects of subgrade swelling. One of these measures included the use of a collapsible fiberboard carton under the slabs to accommodate expansion of subgrade soil without exerting any significant upward pressure. The collapse mechanism of this fiberboard carton was determined in the laboratory under simulated field conditions by using a simple, practical test setup. The test results confirmed that the fiberboard would collapse before swelling pressures reached the acceptable design pressure. The test results show that relatively easy-to-perform tests and routine soil index tests can be very useful in developing an understanding of the behavior of swelling soils and in selecting the proper design details that will minimize the potential problems associated with such soils.

Certain clay-rich soils in temperate and tropical climates undergo volume change with change in water content. When this volume change is appreciable, foundation design deserves special attention in order to protect the foundation and the structure from damage. This can be achieved in two ways: the foundation system may be designed to accommodate the anticipated heave or the structure and the foundation may be designed to withstand pressures that can be caused by this swelling. A combination of the two approaches may be used to achieve an economy in the design.

Irrespective of the design approach, it is essential to understand the behavior of the soil and to make quantitative estimates of anticipated heave and pressures that swelling can cause on the structure foundation. Further, it is advantageous if such estimates can be derived from soil properties that are easily determined with a reasonable degree of reliability using simple, routine tests.

Similarly, it is important to know how the defensive measures included in the design will ameliorate the effects of swelling under actual field conditions. Because these measures are implemented beneath the foundation, their performance can be evaluated either by observation of adjacent similar constructions or by simulation in the laboratory.

Geotechnical considerations in foundation design for a recently constructed industrial plant in Stillwater, Oklahoma, are presented in this paper. The plant is founded on swelling soils with design parameters derived from a limited number of controlled swelling tests and correlations with results of soil index tests. Several defensive measures were included in the design to minimize the potential effects of swelling on the structure, including the placement of a fiberboard carton form under the slabs to accommodate anticipated heave. Performance of the cardboard was evaluated by using a simple laboratory test that proved to be extremely useful in the design.

SITE CONDITIONS

Moore Business Forms, Incorporated, owns an industrial plant facility located in the town of Stillwater, Oklahoma. A portion of the plant was constructed several years ago, and new facilities were added to it to expand the firm's manufacturing capabilities. Located adjacent to the existing plant structures, the new plant includes a process building, a tank farm, and other appurtenant structures (Figure 1).

The site is located in a temperate climate with a mean annual temperature of 60.8° F and a mean annual precipitation of 32.18 in. (1). The maximum reported mean temperature is 94° F for the month of July, and the bulk of the rainfall occurs from May through August.

The soils on the site consist of approximately 28 ft of sandy, silty, reddish-brown clay that overlies a heavily overconsolidated thick stratum of clay known locally as "red-bed." The upper clay soils exhibit swelling tendencies when wet and have been overconsolidated through a desiccation process. The heavily overconsolidated red-bed behaves similarly to a soft rock and shows no perceptible swelling tendencies.

GENERAL DESIGN CONSIDERATIONS

The project design criteria established a number of specific requirements for acceptable foundation performance. Some of these requirements, which in-

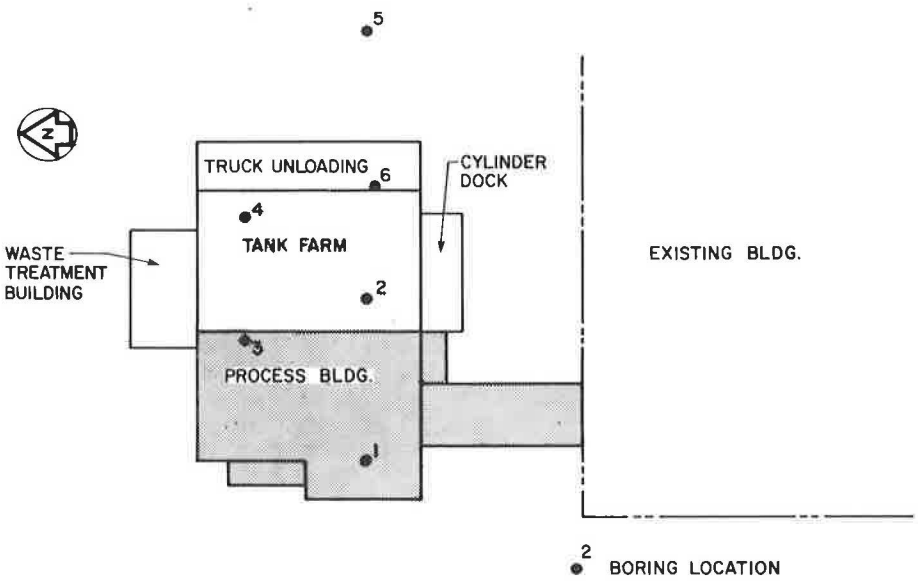

FIGURE 1 Site plan.

fluenced geotechnical investigations and design, are as follows:

1. The finished grade elevation for the process building was established several feet above the existing ground; this required structural fill under the foundation. Cost comparisons indicated that use of the on-site clay soils would be preferred because any granular soil had to be imported from a source away from the site at a significantly higher cost.
2. The process building housed sensitive and heavy equipment, which required that foundation movements be minimal, if any, and that the effect of unknown movements associated with swelling or shrinkage be minimized.
3. It was determined feasible to support the tank farm foundation directly on subgrade. Any differential movement caused by seasonal swelling and shrinking or gradual cumulative swelling could be accommodated by the flexibility inherent in the metal structures and piping with no distress or impact on the performance.

It should be pointed out that the existing plant structure was supported on belled caissons founded in red-bed.

Subgrade Soil Investigations

Several borings were drilled in the general site area during the preliminary planning stage of the project. Once the structure layout was prepared, nine additional borings were drilled to define the soil conditions under the planned structures and to collect soil samples for laboratory tests; the location of six of these borings is shown in Figure 1. The drilling was performed during December 1982, using a 4.5-in. inside-diameter continuous flight hollow stem auger. Standard penetration tests were performed in all borings at 5-ft intervals, and intact soil samples were collected using thin-walled Shelby tubes. The drill cuttings were removed by forced air, and the samples were wrapped in plastic to minimize any change in natural moisture content on exposure. Each boring was advanced a minimum of 5 ft into the underlying red-bed, and the rock cores were recovered for inspection and laboratory testing. Several grab samples were collected to determine compaction requirements for the soil proposed for the structural fill.

Laboratory Tests on Soils

A laboratory testing program with a limited scope was undertaken to determine swelling characteristics and other soil properties. A list of tests that were performed on soil samples, which were conducted using standard test procedures, is given in Table 1.

TABLE 1 Laboratory Test Program

Test Type	No. of Tests: Soil	No. of Tests: Red-Bed
Water content	15	6
Unit weight	7	6
Atterberg limits	12	
Shrinkage limit	1	
Grain size	6	
Specific gravity	1	5
Free-swell index	13	
Controlled swelling	2	
Consolidation	1	
Unconfined compression		4
Triaxial compression	4	2

The test results are included in Tables 2 and 3 and in Figures 2 through 4. Free-swell index tests and controlled swelling tests were performed according to Bureau of Reclamation practice (2). A brief description of test procedures is presented here. No swelling tests were performed on red-bed as it showed no perceptible swelling tendency upon wetting.

Free-Swell Test

This test was performed by slowly pouring 10 cm^3 of dry soil passing a Number 40 sieve into a graduate filled with water. The soil mixture was allowed to come to rest at the bottom, and the swollen volume was noted. The free-swell index value was determined

TABLE 2 Summary of Test Results

Sample No.	Soil Type	Fines (%)	Sand (%)	Colloids (%)	Liquid Limit (%)	Plasticity Index (%)	Free-Swell Index (%)	Potential Degree of Expansion	Water Content (%)	Dry Density, lb/ft^3
BH1-1							40			
BH2-2	CH	90	10	40	76	51	80	Very high	19.0	
BH2-4	CH				59	40	50	Very high	17.3	114.7
BH3-2	CH	83	17	32	60	41	50	Very high	12.0	
BH3-4	CH				63	41	50	Very high	15.0	117.9
BH4-2	CL	82	18	27	42	25	30	High	11.0	115.0
BH4-3	CL	70	30	26	40	24	20	Medium high	12.0	
BH5-1	CH				71	51	60	Very high	15.6	
BH5-3	CH				59	37	40	Very high	13.8	
BH7-2	CH	91	8	40	80	57	50	Very high	17.3	
BH8-2	CH	93	6	31	61	38	60	Very high	18.1	
BH9-2	CH				73	52	60	Very high	23.0	
BH9-4	CL				37	21	0	Medium high	9.1	130.5

TABLE 3 Summary of Expansion and Uplift Tests

	Sample No.			
	BH1-1	BH1-1	BH2-2[a]	Remarks
Soil type	CH	CH	CH	
Dry density (lb/ft^3)	124.1	115.9	109.5	
Water content (%)	11.9	15.7	17.4	
Saturation (%)	84.4	88.7	90.1	
Expansion when wetted (%)	4.69		–[b]	Seating load of 1.13 psi
Load to consolidate to original height (psi)	55.0			
Swelling pressure when wetted (psi)		8.3 (55)	53	Sample BH1-1 expanded 1.13 percent under 8.3 psi Swelling pressure (55 psi) interpolated graphically
Expansion when load released (%)		2.77		

[a]Sample BH2-2 was tested for consolidation using ASTM procedure. A load of 53 psi represents the total incremental load when sample showed an expansion of about 0.5 percent and started consolidating under higher loads.
[b]No test data available.

as the ratio of increase in the volume and initial dry volume.

Load Expansion Test

This test was performed by using a standard consolidometer with a porous stone at each end. The specimen, prepared from a Shelby tube intact sample, was placed in the consolidometer and loaded to 1 psi. The sample was saturated under this load, and the increase in height (volume) was recorded. When the swelling was complete, additional loads were applied in increments to determine the load required to bring the specimen to its original height. The data give an indication of the potential expansion under a nominal load of 1 psi.

The second specimen was tested to determine the maximum load required to prevent expansion. The sample was placed in the consolidometer and sufficient load was added during sample saturation to prevent an increase in volume. Because of difficulties experienced during testing, a small volume increase was noted and the results were extrapolated to estimate the maximum potential swelling pressure corresponding to a zero increase in volume. When further swelling under the load (8.3 psi) ceased, the sample was unloaded in decrements to allow expansion and the increase in volume was recorded.

The third sample was loaded in the consolidometer to determine its compression characteristics. The sample exhibited strong swelling tendency when exposed to water and continued swelling under each increment of load until a load of 53 psi was reached. The test proved to be very useful in estimating maximum swelling pressure.

Because only one test was performed for each set of conditions, data were correlated with index test results using published correlations by others (2) and are shown in Figures 3 and 4. In view of the large variations normally encountered in soil properties, the correlations between the index tests and the swelling tests were quite encouraging.

LABORATORY TEST ON CARDBOARD CARTON FORM

A 4-in. high, wax-impregnated fiberboard carton was provided under the grade beam supported slab to accommodate expansion of subgrade soils without exerting large pressures against the slab. According to the fiberboard manufacturer, the carton had a puncture strength of 275 psi and could support up to 1,000 psf of distributed load when dry. (Although these are desirable characteristics for handling, supporting of workmen, and the weight of wet concrete, there was a genuine concern about the fiberboard's collapsibility under limited moisture exposure conditions and a load of 3 psi or less that could be safely resisted without any distress by the 12-in. thick slab.)

A relatively simple test was devised to study the collapse mechanism of the fiberboard carton. A 12- x 12-in. rectangular cell 36 in. high, was constructed of 1/4-in. thick acrylic plastic (Figure 5). The cell was supported on a wooden base and reinforced at the bottom. A 6-in. thick layer of soil was placed at the bottom of the acrylic container. The soil was reddish-brown clay obtained from the site and was placed and compacted in four layers at the field placement water content. A dry density of 111.5 pcf was achieved at a moisture content of 18 percent using standard proctor compaction effort. A piece of fiberboard carton, 12 x 12 in. in size, was placed over the compacted soil layer. The two open sides of the carton were protected against excessive

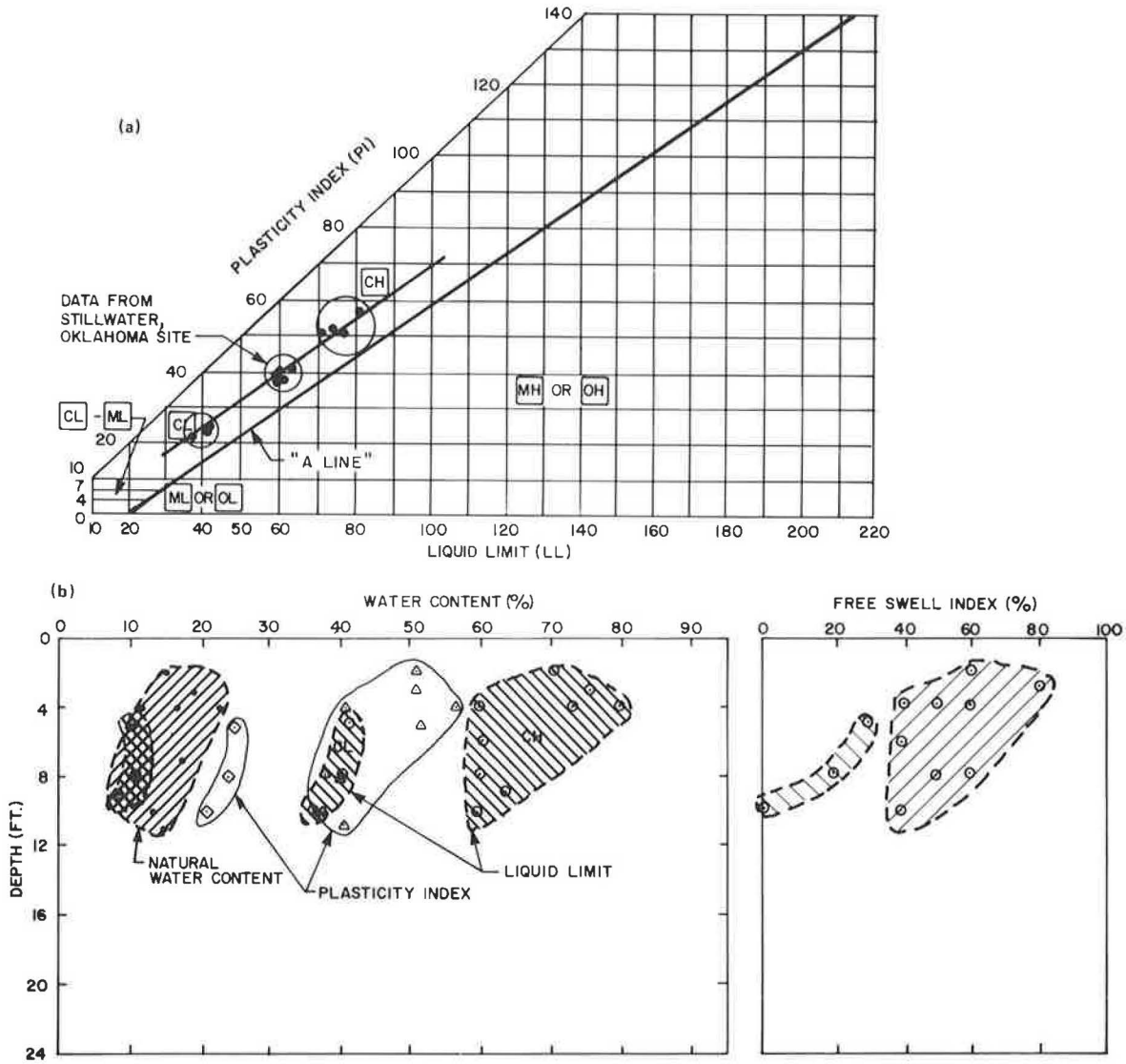

FIGURE 2 Index test results: (a) plasticity chart and (b) depth profile.

moisture soaking by a 2-in. plastic sheet taped to the top of the carton. Next, 12-in. thick concrete was poured on the carton form using a concrete mix similar to the design mix (water/cement ratio of 0.54). The setup represented the site conditions fairly well. A 4 mil plastic sheet was placed between the concrete and the acrylic container to eliminate bonding and friction. The four sides were also coated with white petroleum jelly so that the 4 mil plastic sheet would not adhere to the acrylic walls (Figure 6).

The deformations of the cardboard were observed under the weight of wet concrete for the next 6 days. The measured deformation and the shape of the deformed carton are given in Table 4 and shown in Figure 7a, respectively. On the 6th day, additional load was placed on the concrete to bring the total load on the carton to 2.16 psi. No additional deflection was noticed during the next 2 hours, and it was decided to expedite the test by increasing the load to a final value of 3 psi. The load was increased to 3.16 psi (the maximum acceptable upward pressure on the foundation slab was 3 psi). Within 20 minutes of the loading, the deflections increased suddenly and approached 3 in. within 4 hr of loading; these data are given in Table 5. The observations continued for the next 8 days at which time the test was terminated when further increase in deflection was small. The final collapsed shape of the carton is shown in Figure 7b.

The test was considered successful and demonstrated that the fiberboard would support the wet reinforced concrete until such time that the concrete gains sufficient strength to support itself, but would collapse if the load increased to 3 psi. The collapsed carton will continue to accommodate as much as 3.5 in. of swelling.

FOUNDATION DESIGN

The foundation for the process building consists of grade beams supported on belled caissons seated in firm red-bed. The grade floor slab that supports heavy and sensitive equipment is designed as a two-way slab supported on grade beams. The slab in the remaining areas is supported directly on subgrade and is free to move upward or downward with subgrade. This slab may experience some differential

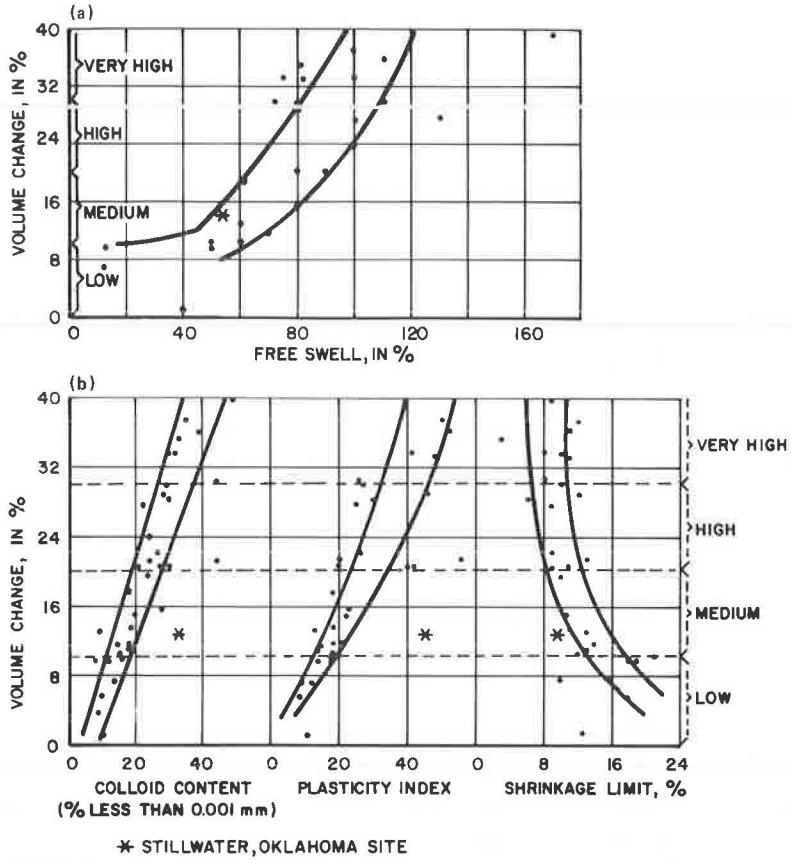

FIGURE 3 Swelling potential related to index properties.

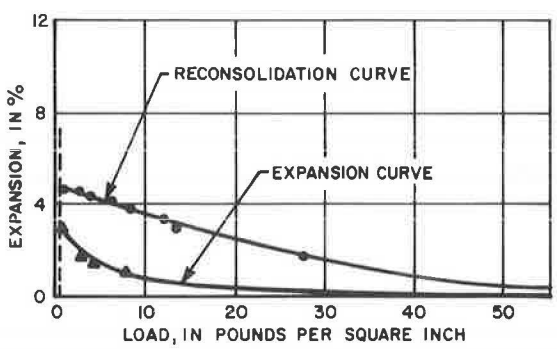

FIGURE 4 Effect of sequence of loading and wetting on expansion.

movement and does not support any equipment that will be affected by these movements.

The net bearing capacity for caissons was estimated to be 27.36 kips/ft^2 using a cohesion value of 3,040 psf and a bearing capacity factor of 9.0 (the contribution of skin friction was ignored for conservatism). Using a maximum allowable design load of 10 ksf, this resulted in a safety factor of 2.74. An upper limit of uplift force on caisson was estimated as follows (3):

$$Q \text{ uplift} = (\Pi)\ (d_s)\ (L)\ (Ca) \qquad (1)$$

where d_s is the diameter of the caisson shaft, L is the length of the caisson shaft, and Ca is the average adhesion value between the soil and the caisson.

An adhesion value of 2,000 psf was considered a reasonable upper limit assuming the soil absorbed sufficient moisture during swelling and, thus, softened. For a 20-ft long shaft, this provides an uplift force of 40 Πd kips per caisson. The diameter of the bell was checked to assure sufficient resistance against uplifts as follows:

$$Q \text{ uplift} - Q \text{ dead} = q_d/F)\ \Pi/4\ (d_b^2 - d_s^2) \qquad (2)$$

where

q_d = net bearing capacity = C.Nc. (cohesion x bearing capacity factor)
d_b = diameter of the caisson bell,
d_s = diameter of the caisson shaft,
F = safety factor, and
Q dead = permanent dead load.

The diameter of the caisson shafts varied from 24 to 36 in. and the bell diameter varied from 4 to 8 ft. The total length of caissons, including the belled portion, varied from 9 to 21.5 ft. A layout plan for the cassions, which were reinforced for the entire length, is shown in Figure 8.

An estimate of the heave under the foundation was made using data from laboratory tests under different in situ confining pressures. It was estimated that the soils could heave as much as 1.3 in. under the foundation. Such a heave would have no effect on the two-way supported slab because the fiberboard carton form would accommodate up to 3.5 in. of heave. It was estimated that the grade beams could experi-

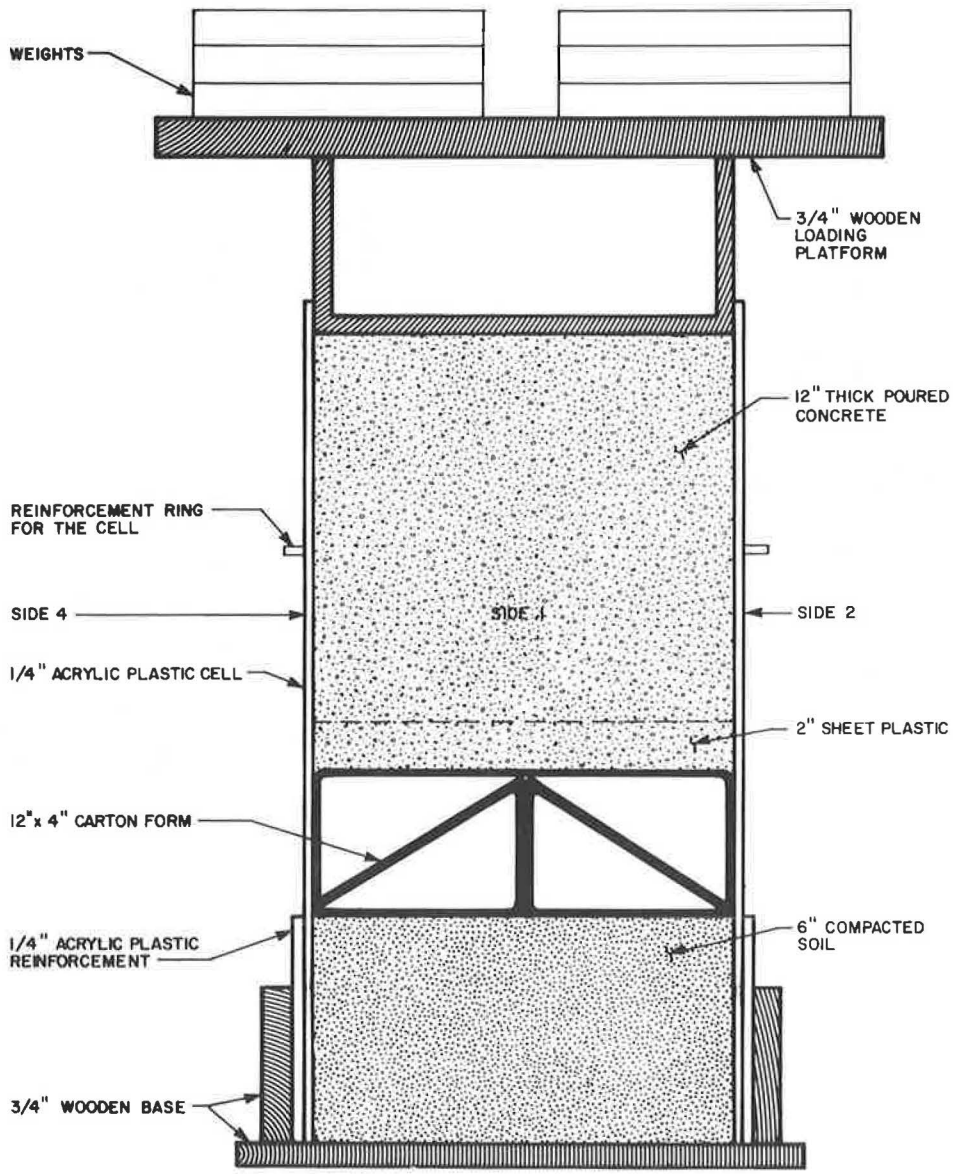

FIGURE 5 Carton form test setup.

TABLE 4 Fiberboard Carton Test Load, 1.16 psi (Weight of Concrete)

		Maximum Deflection of Carton Form, in.				
Date	Time	Side 1	Side 2	Side 3	Side 4	Remarks
June 23, 1983	8:45 a.m.					Placed concrete
	9:15 a.m.	0.45	0.12	0.5	0.12	
	9:45 a.m.	0.52	0.12	0.62	0.20	
	4:00 p.m.	0.52	0.20	0.67	0.20	
June 24, 1983	8:30 a.m.	0.63	0.25	0.75	0.25	
	4:30 p.m.	0.63	0.25	0.75	0.25	
June 26, 1983	12:00 noon	0.67	0.30	0.80	0.30	
June 27, 1983	11:00 a.m.	0.67	0.30	0.80	0.30	
June 29, 1983	9:05 a.m.	0.72	0.32	0.82	0.32	At 11:30 a.m., load increased to 3.26 psi

FIGURE 6 Deformation of carton form—test setup before placing of concrete.

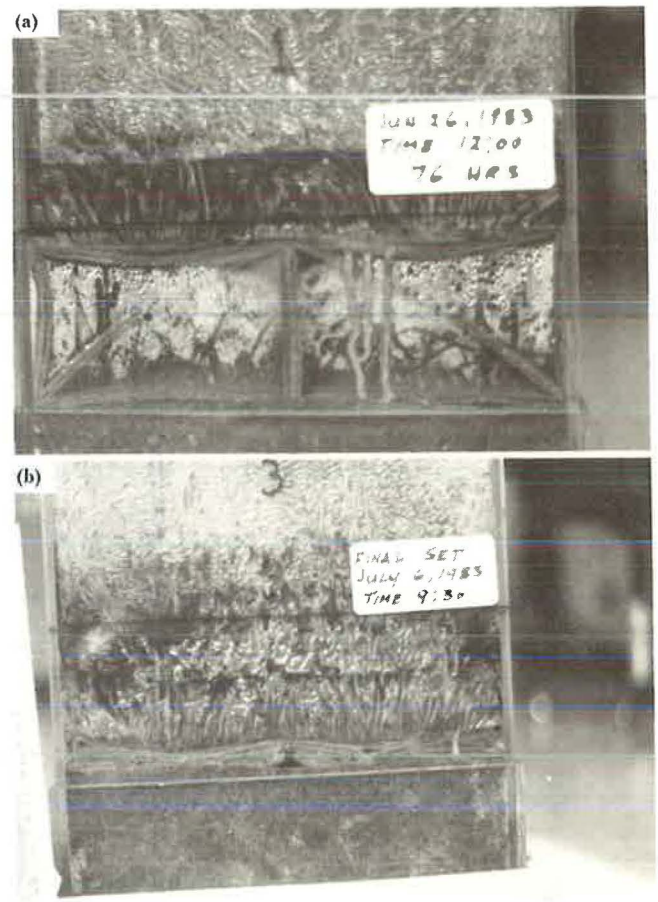

FIGURE 7 Deformation of carton form under a load of (a) 1 psi and (b) 3 psi.

TABLE 5 Fiberboard Carton Test Load, 3.16 psi

Date	Time	Maximum Deflection of Carton Form, in.				Remarks
		Side 1	Side 2	Side 3	Side 4	
June 29, 1983	11:50 a.m.	2.90	2.55	2.92	2.52	
	11:55 a.m.	2.95	2.55	3.00	2.52	
	12:40 p.m.	2.95	2.55	3.05	2.52	
	4:30 p.m.	3.00	2.62	3.07	2.60	
July 4, 1983	9:00 a.m.	3.30	3.00	3.47	3.10	
July 6, 1983	9:25 a.m.	3.32	3.05	3.52	3.15	Test terminated

ence as much as 6 to 10 psi of upward pressure during extreme conditions, but those conditions are unlikely to occur due to other defensive measures included in the design.

The following features were included in the design to further protect the structure against harmful effects of swelling and shrinkage:

1. All exterior grade beams were placed 4 ft below grade. This depth was judged to be slightly more than the depth of seasonal moisture variation. Thus, the subgrade soil is reasonably well protected from the seasonal change in the environment.

2. All floor slabs not supporting critical equipment were designed to be independent of grade beams and can move up or down with the subgrade soil.

3. The structural fill placed under the structures was compacted at a moisture content that will result in minimum or no swelling. This moisture content was close to the natural moisture content of site soils but considerably higher than the optimum moisture content.

4. General drainage around the facilities was designed to drain away any precipitation rapidly and efficiently. Thus, subgrade soil was protected against saturation from extended ponding or rainfall.

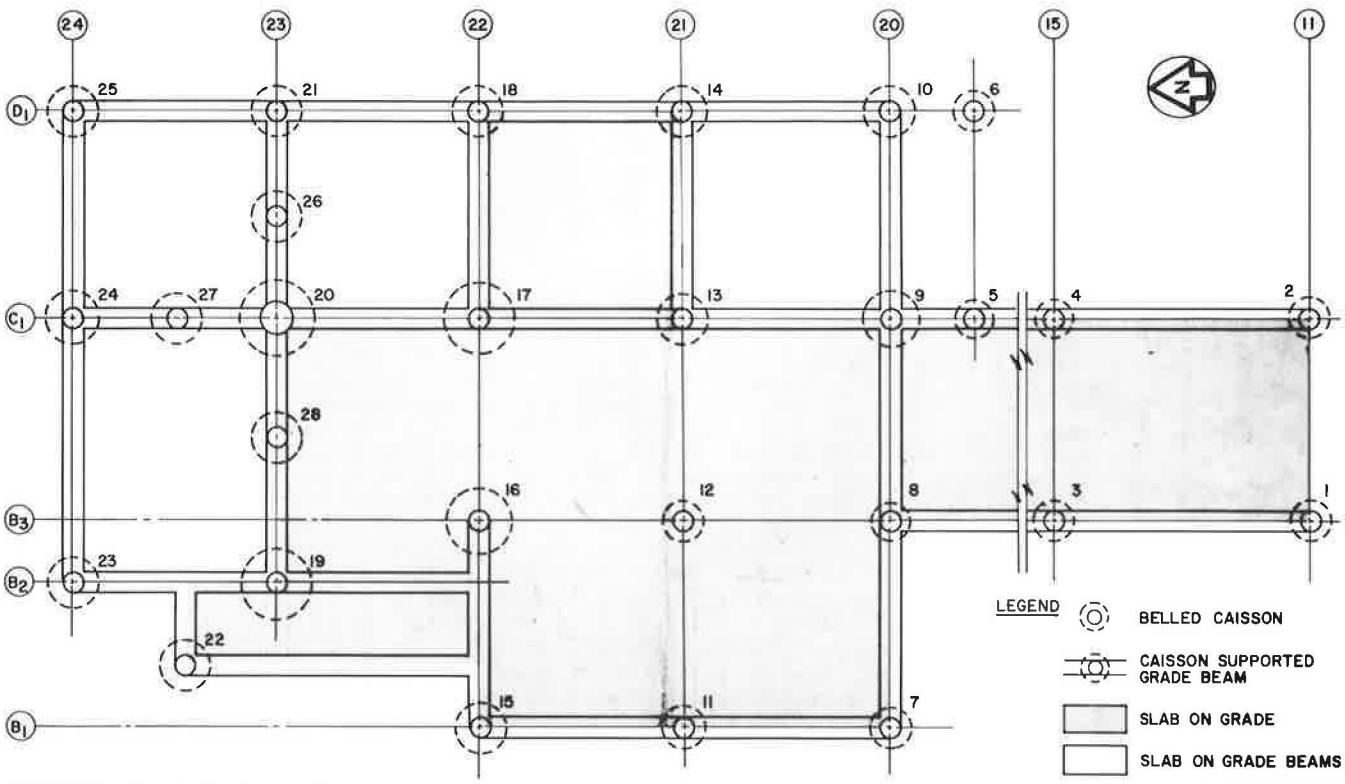

FIGURE 8 Foundation layout plan.

CONCLUSIONS

The soil properties were determined using a limited number of controlled tests supplemented with a sufficient number of simpler tests that can be performed much more rapidly and economically. Agreement was found between the correlations for the site soil and the published data. Performance of a fiberboard carton form was studied in the laboratory under simulated conditions. The tests were relatively simple and provided valuable information on the expected behavior of the fiberboard. Several defensive design features were included at a relatively minor cost that added much to protect the structure against the potential harmful effect of swelling soil.

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