SOIL IMPROVEMENT BY PRECOMPRESSION AT A TANK FARM SITE IN CENTRAL JAVA, INDONESIA

Kul Bhushan, President, Group Delta Consultants, Inc., Aliso Viejo, CA, USA
Carlos V. Amante, Project Engineer, Group Delta Consultants, Inc., Aliso Viejo, CA, USA
Ramzi Saaty, Project Manager, Fluor Daniel, Inc., Aliso Viejo, CA, USA

ABSTRACT

The site of a tank farm is underlain by about 3- to 8-m thick, very soft, compressible clay layer. The site was successfully preloaded using wick drains and 10- to 13-m high surcharge. Settlements of 0.6-1.7 m were measured during surcharge and 19-73 mm under subsequent hydrotest.

1. Introduction

A number of case histories are available in the literature [1,2,and 3] presenting data on the use of surcharge for improvement of soft soils and failure of tanks constructed on soft soils. However, only limited data are available on settlement behavior during surcharge and corresponding post-surcharge loading during hydrotest. This paper presents the results of a surcharge and hydrotest program performed at the site of a tank farm located in Central Java, Indonesia. The tank farm is 25,300 square meters in area and consists of 17 steel storage tanks with diameter ranging from 8.8 to 31.2 m and height ranging from 4.57 to 16.5 m. The tank dimensions and locations are shown in Figure 1.

The tank farm is underlain by about 3- to 8-m thick, very soft and highly compressible clay layer. In 1992, the tank farm area was hydraulically filled with 1.0- to 2.5-m thick dredged river sands. The site was preloaded by soil surcharge to improve the soil bearing capacity and minimize post-construction settlements. The site was preloaded with 10- to 13-m surcharge until the compressible soils reached about 90% consolidation. Wick drains were used to reduce the time required to achieve 90% consolidation. Settlements under each tank during surcharge and hydrotest programs were monitored. Settlements of 0.6 m to 1.73 m were measured during the surcharge program in 120 to 450 days. The post-surcharge hydrotest program involved measurement of settlements of tanks full of water during a 90- to 150-day period. Maximum settlements of up to 90 mm were measured during the hydrotest program. Heave of up to 44 mm was recorded after emptying the tanks.

A slide failure occurred at the location of the surcharge for Tanks 305 and 307. The reasons for the slide and remedial measures employed are discussed.

2. Subsurface Conditions

The subsurface conditions in the tank farm were investigated by performing four rotary wash standard penetration test (SPT) borings with depth ranging from 21.3 to 40.4 m, and sixteen piezocone penetration tests (PCPT) with depths ranging from 13.34 to 29.25 meters. After a slide in the surcharge fill occurred near Tanks 305 and 307, six SPT soil borings and 14 post-surcharge CPTs were performed. A cross section (A-A') through the site is shown in Figure 2.

The subsurface conditions consist of about 3 to 4 m of loose to medium dense silty fine to medium sands, which are partly fill and partly natural soil. Below the sandy soils are native, very soft to soft, compressible silty clay and clayey silt deposits. The thickness of very soft clayey soils at the site varies from about 3 to 8 meters. Thicker soft soil is present in the northwest portion of the site. The thickness reduces towards east and south. The soft soils are underlain by medium dense sand, stiff to very stiff clay and clayey silt, and weathered siltstone. The elevation of siltstone bedrock ranges from about El. -10 m at the east end to about El. -19 m at the west end. Groundwater was encountered in all the borings at elevation ranging from El. +1.2 m to El. +2.6 meters.

The natural moisture content and plasticity data are shown in Figure 3. Undrained shear strengths of disturbed clayey soil samples were measured using hand vane, pocket penetrometer and unconfined compression test. The measured shear strengths of the soft clayey soils ranged from about 4.5 to 25 kN with an average of 15 kN. Undrained shear strength was also estimated by Skempton's 1957correlation with plasticity index [4], and from CPT tip resistance and a cone factor of 15. These results are summarized in Figure 4. The measured S_u values are generally lower than the estimated S_u based on Skempton's formula which is expected because the measured values are obtained from disturbed soil samples. Undrained shear strength from PCPT soundings is in good agreement with shear strengths computed from Skempton's formula.

The compression index ratio, $C_c/(1 + e_0)$ ranged between 0.22 and 0.38, and coefficient of consolidation, C_v, from 2 to 15 cm/sec^2. The recompression index ratio, $C_r/(1 + e_0)$ ranged between 0.025 and 0.06.

3. Surcharge Program

Prior to the surcharge program, we performed analysis to estimate the time required to complete 90% consolidation with and without the use of wick drains. The results indicate that it would take about 20 to 140 months for a 3 to 8 m thick clay layer to achieve 90% consolidation. With wick drains at a triangular spacing of 1.0 to 1.5 m, the time required to reach 90% consolidation can be reduced to about 2 to 7 months, respectively. Wick drains were installed in most tank areas at a triangular spacing of 1.25 m. The surcharge program in the tank farm was divided into several phases. In most areas, surcharge was placed over a period of about 30 days and kept for about 3 to 4 months. The maximum surcharge heights were 11 m to 14 m. Settlement plates, piezometers, and inclinometers were installed to monitor the ground settlements, porewater pressures, and lateral ground displacements during surcharge.

3.1 Settlements During Surcharge

A summary of measured settlements during surcharge is shown in Table 1. The measured settlements and surcharge heights with time for two tanks are shown in Figure 5. Time settlement data from 15 tanks is shown in Figure 6. The measured total settlement at the center of each tank ranged from 579 to 1726 mm. Prior to surcharge, we made estimates of settlements due to surcharge loads for 90% consolidation which ranged from 840 to 1470 mm.

Our analysis of the data also shows that 90% consolidation was achieved within 3 to 4 months after completion of the surcharge fill. This agrees fairly well with our initial estimate of 2 to 7 months for wick drain spacing between 1.0 and 1.5 meters.

3.2 Porewater Pressure Response

Ten piezometers were installed at selected locations to measure the response of porewater pressure in the soft clay layer during surcharge. The initial water elevation ranged from 2.1 to 2.5 meters. Maximum water height ranged from El. 4.4 m to El. 9.2 m under surcharge. This indicates maximum pore pressure increase of 14 to 33% of the surcharge loading.

3.3 Lateral Ground Displacements

To monitor the lateral movement of the ground due to surcharge, two inclinometer stations were installed at a distance of about 34 m to the north of the centerline of Tanks 305 and 307, respectively. A maximum lateral displacement from 180 to 190 mm to the north was recorded. The maximum lateral movement occurred at about 5.0 to 5.5 m below the ground surface where the soft clay layer is located.

3.4 Settlement During Hydrotest

After 90% consolidation was achieved, the surcharge was removed and the tanks were constructed. Controlled water tests were performed by gradually filling the tanks with water to heights of 25%, 50%, 75%, and 100% of full water height. Eight settlement monitors were installed around each tank to measure the edge settlement of the tanks during water test. Water was kept at full height in each tank for about 1- to 3-month period.

A summary of observed tank edge settlements during water test is presented in Table 1. Typical observed tank edge settlements and water level variation with time for Tank 304 are shown in Figure 7. Time-settlement data for 15 tanks is shown in Figure 8. The observed minimum and maximum tank edge settlements ranged from 37 to 89 mm.

3.5 Rebound

At the end of the water test, the tank was emptied and the amount of "rebound" was measured. Rebound is a measure of the amount of elastic (recoverable) settlement of the subsurface soil. Measured rebound ranged from about 9 mm to 44 mm.

4. Slide Failure

A slide failure occurred in the surcharge fill at the location of Tanks 305 and 307. The surcharge in the area of these tanks was raised from about El. +2 m to El. +14.88 m during a period of about one month. After a heavy rainfall, the surcharge moved laterally to the north by about 3 m and disrupted the existing ditch located about 50 m to the north of Tank 305. An approximate cross section of the as-built surcharge in the area of Tanks 305 and 307 and the condition after the slide are shown in Figure 9.

4.1 Stability Analyses

Stability analyses of the slide were performed using the computer program STABL/G [5]. We evaluated two types of potential failure surfaces, namely, 1) a deep-seated circular failure through the base of the soft clay, and 2) a sliding block wedge-type failure along a plane near the top of the soft clay/sand interface between El. -0.5 m and El. -1.5 meters.

The analyses under the pre-failure surcharge loading indicated that both a wedge-type failure, and a deep-seated failure through the base of the soft clay, are probable failure mechanisms. Soil shear strengths were back-calculated for both the wedge-type failure and the deep-seated failure conditions. The results indicate that the average shear strength at the surface of the soft clay for the wedge failure was 19 kPa and for the entire clay layer for deep circular failure was 26 kPa. These values are higher than some of the measured or interpreted values of the shear strength of the clay shown in Figure 4.

The factor of safety for the full surcharge height of 14.88 m was calculated to be less than 1.0 for a slide plane along the top of the soft clay layer. The rapid placement of the fill did not provide adequate time for the consolidation of the clay and resulting strength increase. In addition, the presence of the ditch to El. -0.5 m provided a shorter failure path along the top of the soft clay, thus further reducing the factor of safety.

4.2 Remedial Measures

After the slide, various options including use of piles and re-routing of the ditch were considered for remedial measures to support Tanks 305 and 307. The option selected included:

- Removing surcharge in the area and installing new wick drains,
- Resurcharging area of Tanks 305 and 307 in stages,
- Installing inclinometers and additional settlement monuments to measure settlement and lateral ground movement during surcharging,
- Surcharging area of roadway north of Tanks 305 and 307 to increase shear strength,
- Making drainage modifications to prevent ponding of water,

- Developing a monitoring program to assess the settlements, pore pressures, and lateral ground movements, and
- Verifying the shear strength increase by performing cone penetration tests.

4.3 Verification of Shear Strength Increase

A total of 14 CPTs were performed to verify the increase in shear strength in the soft clay layer in and around the area of Tanks 305 and 307. A review of these data shows that:

- The top of the soft clay has been pushed down from about El. - 1 m to El. -3.8 m in the area of Tank 305 due to settlement and intermixing of the clay with the overlying sand.

- The undrained shear strength of the soft clay soils in the areas of Tank 305 has improved significantly compared with the pre-surcharge values. The CPT data indicate that the undrained shear strength of the soft clay soils in the areas of Tanks 305 and 307 increased from about 15 to 19 kPa before the surcharge to about 48 to 58 kPa after the surcharge.

5. Evaluation of Post-Construction Settlements

Post-construction tank settlement can be subdivided into the following components: elastic rebound/recompression which occurs due to surcharge removal and subsequent loading from the tank during water test, remaining primary consolidation which was not completed during the surcharge program, and long-term secondary consolidation.

Upon removal of the surcharge fill, a certain amount of elastic rebound of the ground surface occurred. When the tanks were constructed and filled with water, elastic recompression occurred in a relatively short time. Our estimated rebound ranged from 16 to 98 mm. Actual rebounds ranging from 9 to 44 mm were measured during discharge of water at the end of water tests (see Table 1). We assumed that about the same amount of rebound occurred after the removal of surcharge.

About half of the remaining primary consolidation settlement was estimated to occur during the one-month water test, and the remainder would occur after the tanks were put into service. Secondary compression was computed to vary from 17 to 99 mm using a secondary consolidation coefficient, $C\alpha$, of 0.15 obtained from a correlation with in situ moisture content after NAVFAC [6].

We considered these three components and used them to estimate the settlement during a one-month water test of the tanks, as well as the long-term, post-water test settlement. The post-water test settlement was computed as the other half of the remaining primary consolidation plus the long-term secondary consolidation. Our analysis indicated that the post-construction settlement in any of the tanks would not exceed 150 mm.

6. Evaluation of Bearing Capacity and Stability of Proposed Tank Foundations

The bearing capacity of a circular tank foundation resting on top of a thin sand stratum depends primarily on the bearing capacity of the underlying soft clay. For a clay stratum with thickness H, and a circular foundation with diameter D, the bearing capacity was estimated from the formula developed by Vesic' [7] as follows:

$$q_{ult} = q_{ult(clay)} \exp\{1.34 \,(H/D)\}$$

To evaluate $q_{ult\,(clay)}$, the following expression from Skempton [8] was used:

$$q_{ult\,(clay)} = 5\,c\,[1 + 0.2\,(B/L)] \approx 6\,c$$

where, c = cohesion or undrained shear strength of clay.

The maximum bearing pressure during tank operation depends on the height of the fluid inside the tank. CPT soundings performed after the surcharge show an overall increase in shear strength of the soft clay layer below the tank areas by up to three times the original pre-surcharge values. Assuming that the soft clay layer increases in strength from 15 kPa before surcharge to 50 kPa (see Section 4.3) as a result of surcharge, the factor of safety increases from about 0.5 to greater than 1.5.

For Tanks 305, 307, 309, and 316, which are located near the existing ditch north of "N" Street, the failure mechanism involves a slope stability failure along a wedge, similar to the slide failure during the surcharge program. The stability analysis using the post-surcharge undrained shear strength for the clays indicate that the minimum factor of safety of 1.5 is present for such a failure.

This shows that the proposed tanks will have adequate stability during operation and acceptable level of post-construction settlement as a result of pre-loading program. The tanks have been in operation for about 1.5 years without any reported problems.

7. Conclusions

Based on the analysis of field data, the following conclusions are made:

1. The predicted vs. measured settlements under the surcharge showed good correlation.
2. Use of wick drains with a spacing of 1.0 to 1.25 m was helpful in reducing the settlement duration time from estimated 20 to 140 months to 3 to 6 months.
3. During a 3 to 6 month surcharge program, about 90 to 93% of the estimated settlement under tank loading was achieved.
4. During a 1 to 4 month hydrotest program, about 3 to 5% of the remaining consolidation settlement was achieved.
5. Estimated post-hydrotest consolidation settlements are about 1 to 3% of the estimated settlement under tank loading.
6. Estimated post-hydrotest settlements including secondary consolidation are expected to be less than 150 mm.
7. Rate of surcharge placement must be controlled so that adequate strength increase in soft soils is obtained to maintain stability. Fast surcharge loading to meet schedule can result in slope failures.

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Table 1. Summary of Measured Settlements During Surcharge and Water Tests

Tank No.	Surcharge Program			Water Test				
	Duration days (months)	Surcharge Height (m)	Maximum Settlement (mm)	Duration days (months)	Water Height (m)	Maximum Settlement Range (Average) (mm)	Permanent Settlement Range (Average) (mm)	Rebound Range (Average) (mm)
301	103 (3.4)	11.00	870	119 (4.0)	12.40	53-71 (63)	40-54 (48)	13-17 (15)
302	124 (4.1)	11.00	1075	119 (4.0)	12.40	53-66 (59)	32-44 (37)	21-22 (21.5)
303	100 (3.3)	11.00	709	119 (4.0)	15.90	40-84 (62)	21-61 (42)	22-23 (22.5)
304	166 (5.5)	13.10	1424	121 (4.0)	16.50	73-89 (82)	29-56 (45)	33-44 (38.5)
305	445 (14.8)	11.50	1726	119 (4.0)	16.50	54-88 (69)	-	-
306	167 (5.5)	12.60	923	94 (3.1)	16.50	53-61 (57)	22-33 (28)	28-31 (29.5)
307	445 (14.8)	11.25	1674	139 (4.6)	16.50	51-66 (62)	-	-
308	296 (9.9)	10.40	795	112 (3.7)	16.50	63-74 (68)	49-59 (55)	14-15 (14.5)
309	312 (10.4)	10.65	1195	102 (3.4)	16.50	46-61 (52)	26-37 (31)	20-24 (22)
310	191 (6.4)	11.00	629	85 (2.8)	14.70	41-50 (45)	26-36 (31)	14-15 (14.5)
311	185 (6.2)	11.00	579	100 (3.3)	16.50	37-55 (45)	19-40 (30)	15-18 (16.5)
312	137 (4.6)	11.00	662	84 (2.8)	15.80	54-59 (57)	36-40 (38)	18-19 (18.5)
313	202 (6.7)	11.00	679	82 (2.7)	15.80	44-57 (51)	30-42 (36)	14-15 (14.5)
315	225 (7.5)	10.25	717	91 (3.0)	16.50	51-65 (58)	34-48 (41)	17 (17)
316	312 (10.4)	10.40	1089	178 (5.9)	16.50	51-82 (76)	37-73 (54)	9-14 (11.5)

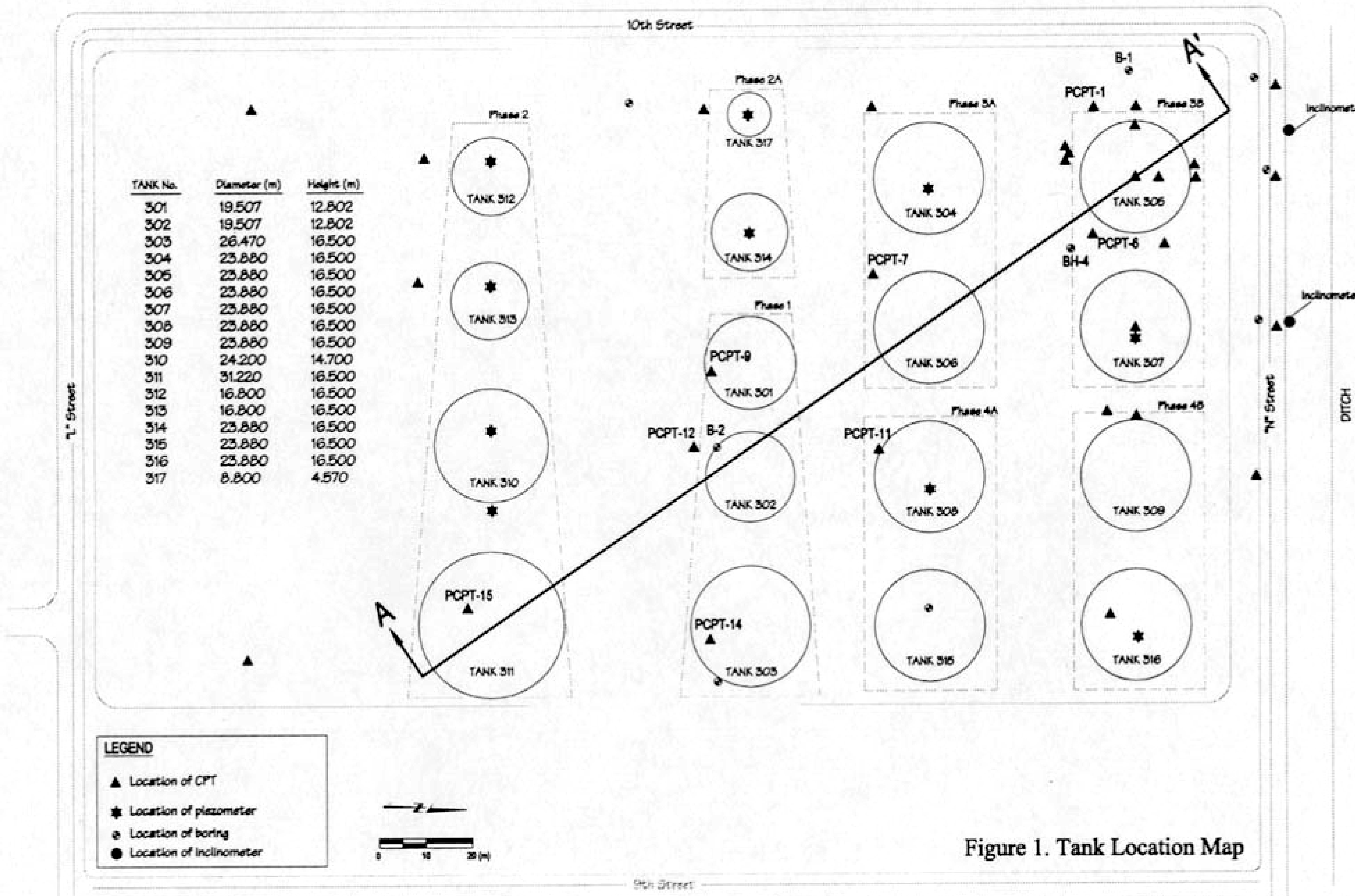

Figure 1. Tank Location Map

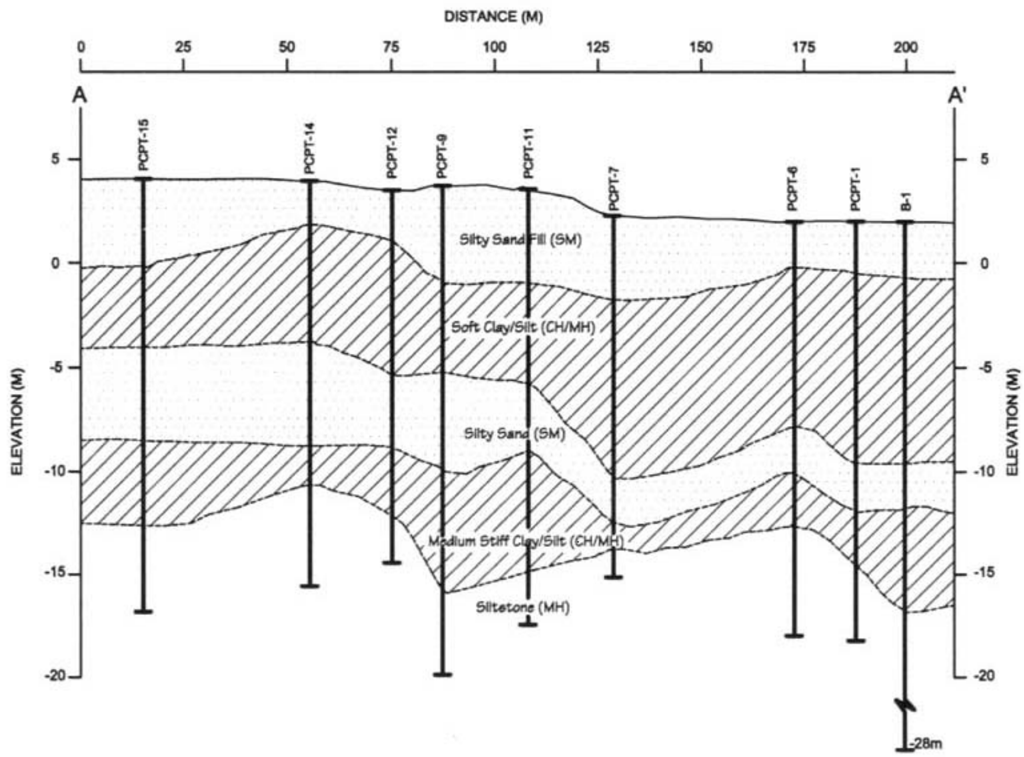

Figure 2. Cross Section A-A'

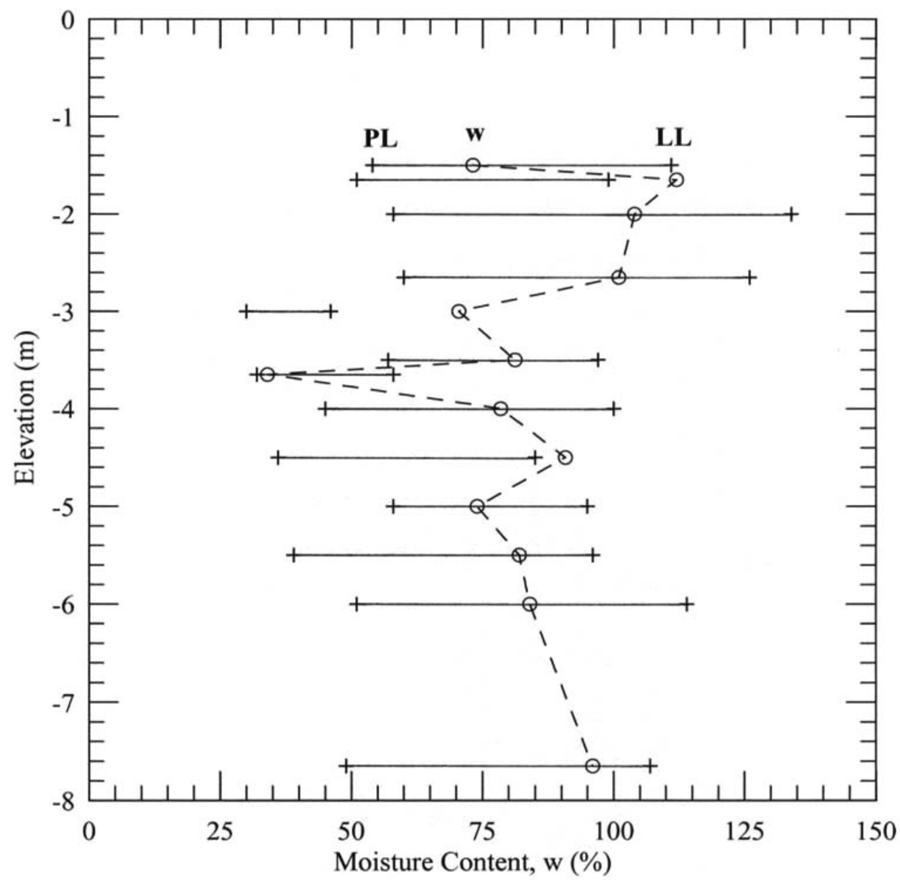

Figure 3. Distribution of Moisture Content (w), Liquid Limit (LL), and Plastic Limit (PL)

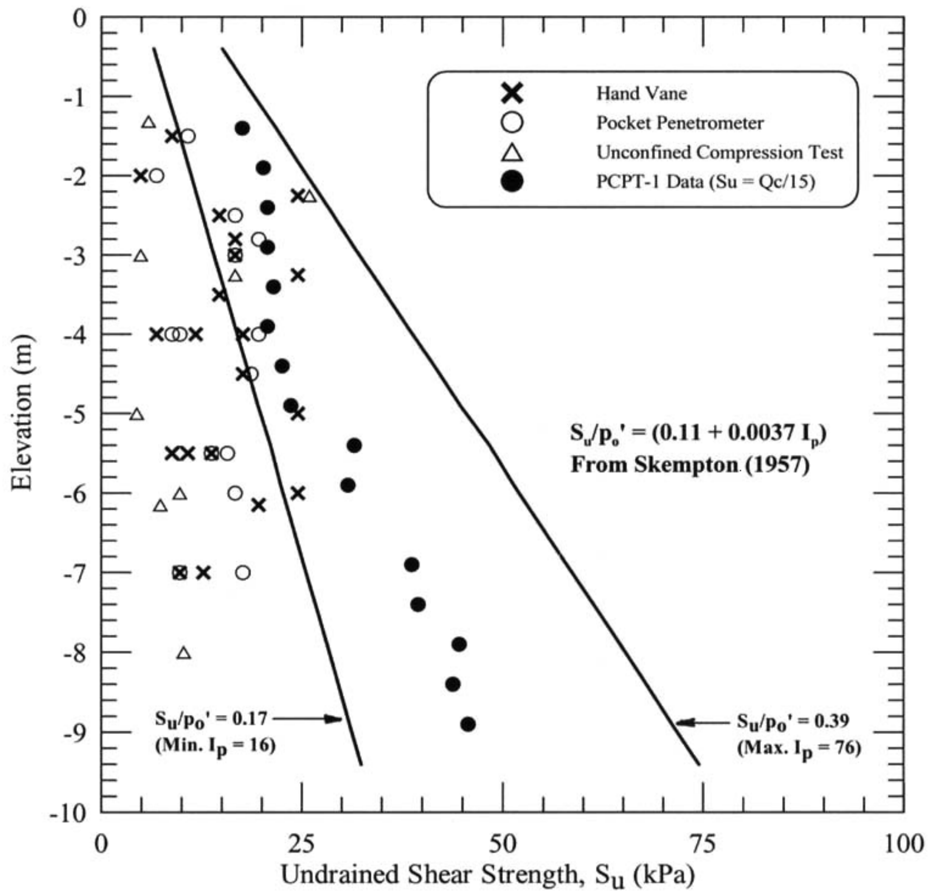

Figure 4. Shear Strength Distribution

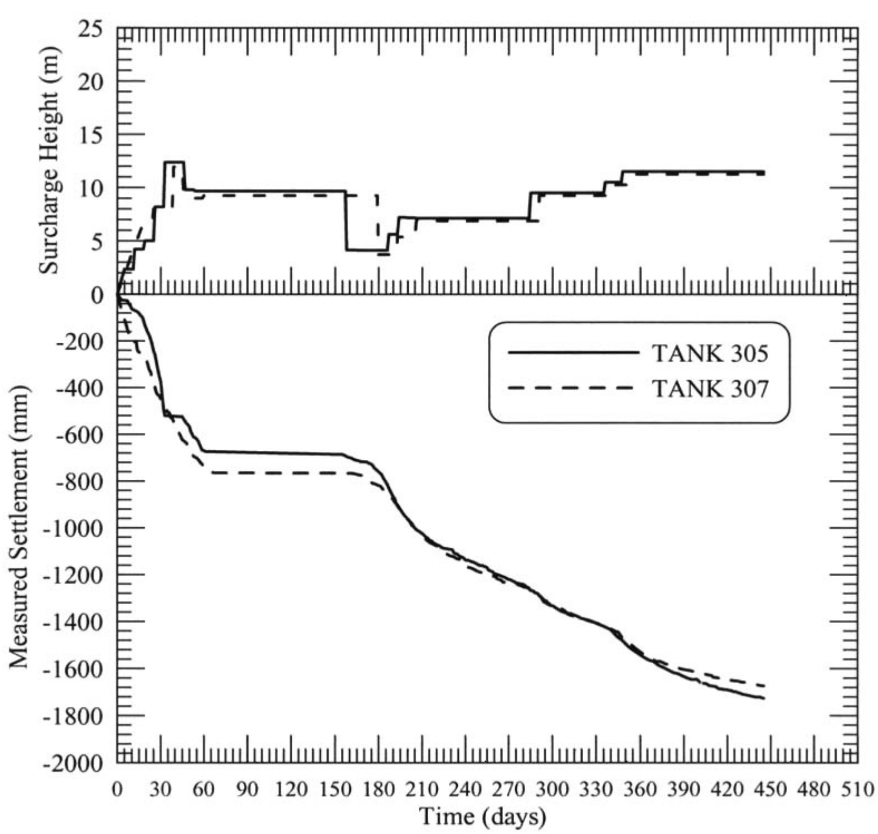

Figure 5. Settlement Data During Surcharge (Tanks 305 and 307)

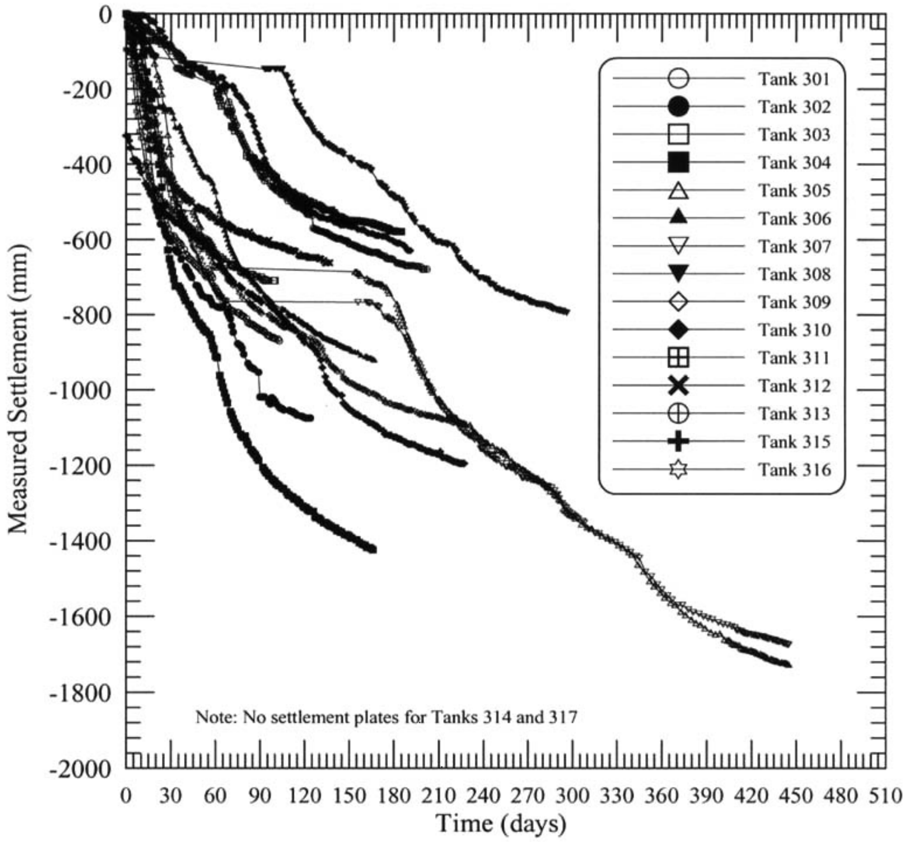

Figure 6. Settlement Data During Surcharge

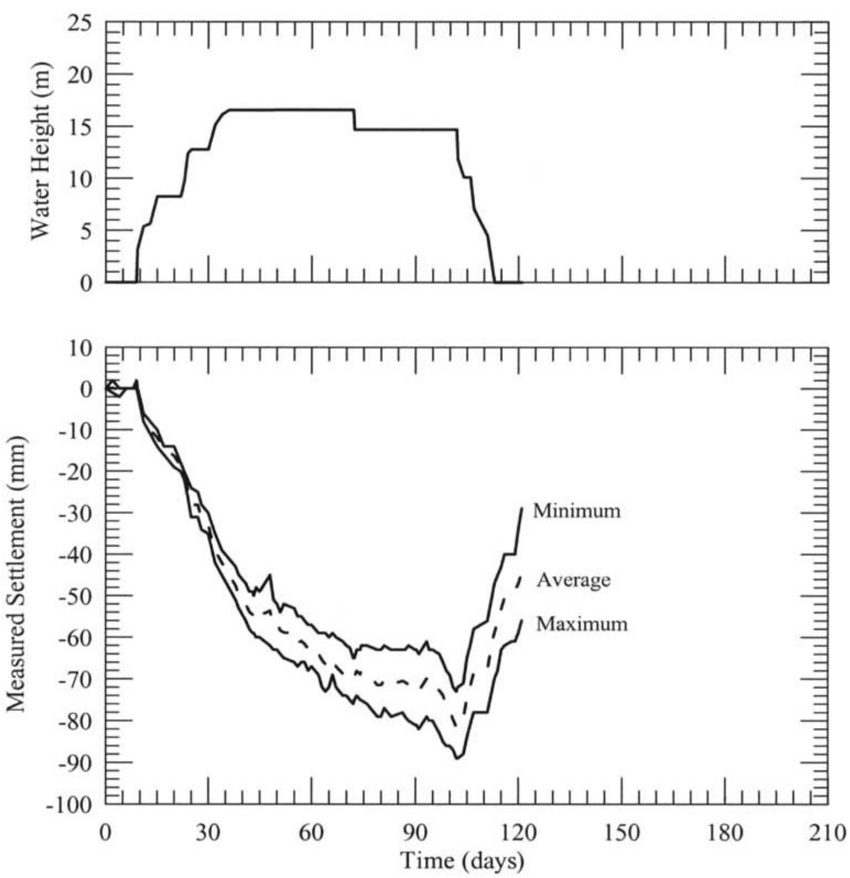

Figure 7. Settlement Data During Water Test (Tank 304)

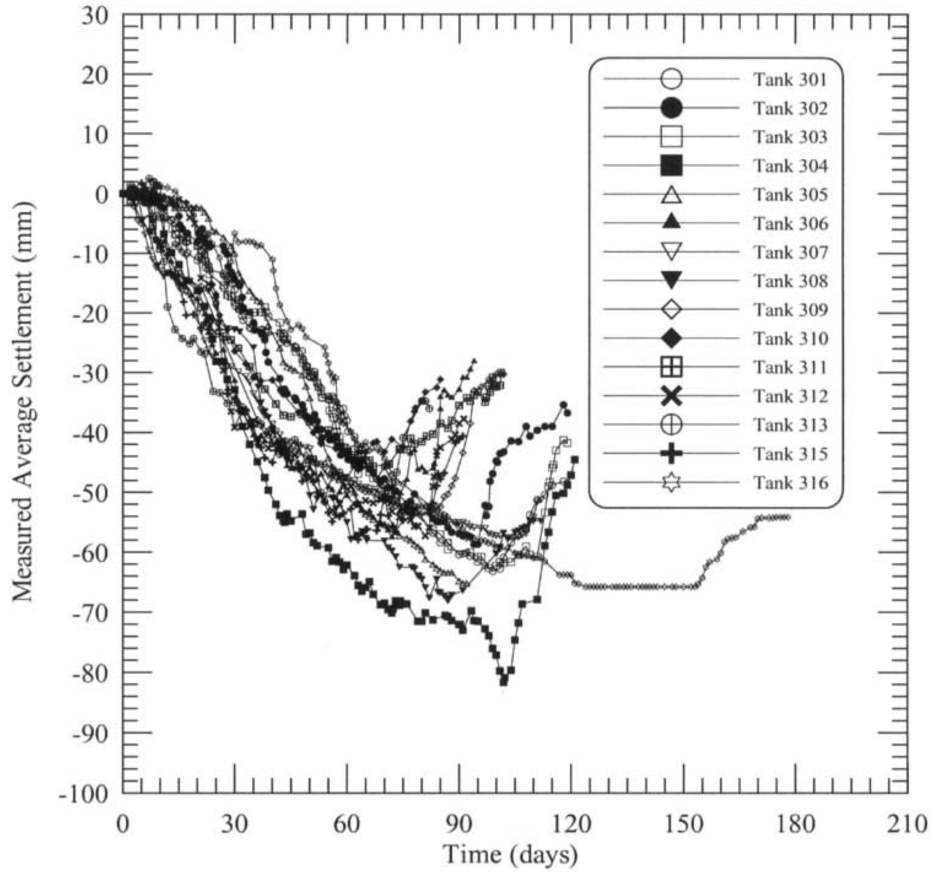

Figure 8. Settlement Data During Water Test

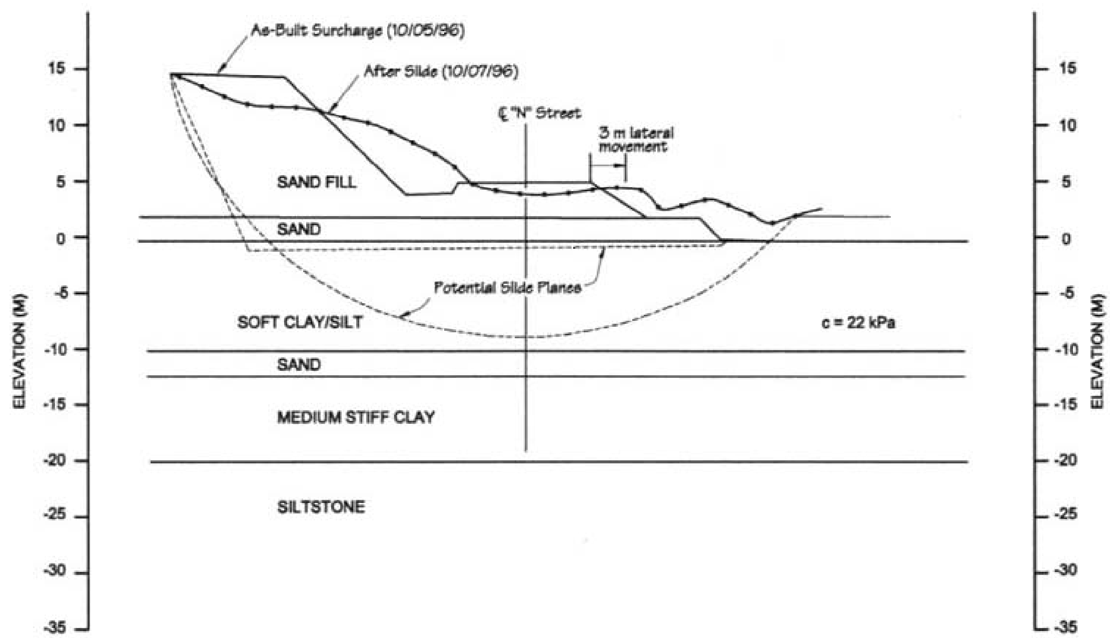

Figure 9. As-built surcharge and after-slide conditions for Tanks 305/307