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TANK SETTLEMENT DUE TO HIGHLY PLASTIC CLAYS

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ABSTRACT

Settlement during hydro-testing of two 30-m diameter oil tanks was generated mostly by a layer of highly plastic clay at about 10 m depth. Based on about 5 months of readings on one of the tanks, the total predicted settlement at the tank perimeter was about 300 mm (with little differential movement) and at the center was closer to 550 mm. The settlement of a 7-m diameter water tank located close to the oil tanks followed quite a different pattern during hydro-testing. Within about 6 days, the tank had settled about 130 mm on one side, but only about 20 mm on the other. The water tank was only about half the height of the oil tank, and the diameter was less than one quarter, resulting in loading at the depth of the plastic clay layer of less than 15% of that of the oil tank. Yet, settlement rates were much faster than those of the oil tank, and differential settlement was not anticipated based on the depth of the clay layer. This paper describes the settlement measurements and computations made for the oil tanks and describes the efforts made to determine the reasons for the unanticipated settlement of the water tank and the actions taken to remedy the situation.

INTRODUCTION

A layer of very highly plastic clay with some organic content exists beneath a power plant site located on the Damietta Branch of the River Nile in Egypt. The layer is typically about 10 m below ground surface and generally ranges in thickness from 2 to 4 m. Because of this layer, the major power plant structures were founded on piles driven to a sand bearing stratum at about 27 m depth. However, tanks for the project were not pile supported, and the estimated amount of settlement beneath the larger tanks was significant.

Settlement during hydro-testing of two 30-m diameter oil tanks was measured regularly. After about 5 months of readings, the recorded settlement on the perimeter of one of the tanks ranged from about 190 mm to 230 mm. It was apparent that most of this settlement resulted from consolidation of the highly plastic clay layer.

The performance of a 7-m diameter filtered water tank located about 150 m from the oil tanks was very different during hydro-testing. Within about 6 days, the tank had settled about 130 mm on one side, but only about 20 mm on the other.

This paper describes the settlement measurements and computations made for the oil tanks during hydro-testing and the anticipated settlement expected when filled with oil. The paper also describes the efforts made to determine the reasons for the unanticipated settlement of the water tank and the actions taken to remedy the situation.

SITE CONDITIONS

The site lies on the Damietta Branch of the River Nile and is relatively flat, gradually dropping from about El. +8 m (MSL) at the edge of the Nile to about El. 5.5 m at the oil tanks, which are 550 m from the river. The oil tanks are approximately 15 m apart. The filtered water tank has a ground elevation of about 5.9 m and is 150 m from the oil tanks and 400 m from the river. Final site grade is El. +6 m.

SUBSURFACE CONDITIONS

In the area of the filtered water and oil tanks, subsurface Layer I has an average thickness of about 1.5 m and is uncontrolled fill consisting of sand, gravel, clay, and concrete debris. This fill was removed from under all of the tanks.

Layer II has an average thickness of about 7 m and is interbedded sand and clay, with about 80% of the material being clay. The clay has high plasticity (CH), with an average liquid limit (LL) of 76 and a plasticity index (PI) of 43. It is stiff, with an estimated undrained shear strength (c_u) of 90 kPa. The sand is medium dense with an estimated angle of internal friction (φ) of 36 degrees. The average high strain elastic modulus (E) of the sand and clay is estimated to be about 45 MPa.

Layer III is the layer of most interest in this paper. Beneath Oil Tank 1, the boring log indicates medium to stiff silty clay from 7 to 10.2 m depth. Pocket penetrometer readings range from 60 to 130 kPa. Beneath Oil Tank 2, the boring log shows peat from 8.25 to 9.75 m and soft silty clay from 9.95 to 11 m depth. Pocket penetrometer readings range from 40 to 140 kPa. Based on laboratory testing of samples of this layer, the soil has an average LL of 83, a PI of 48 (CH material), a natural moisture content of 62%, a c_u of 45 kPa, and a compression ratio (CR) and recompression ratio (RR) of 0.34 and 0.033, respectively. However, tests made from additional borings performed beneath the filtered water tank indicate that Layer III can have more extreme properties, as discussed later in the paper.

Layer IV extends below Layer III at all locations, down to the maximum 60 m depth drilled. It consists of interbedded sand and clay layers with about 75% of the material being sand. The sand is dense (average SPT N-value of about 40) with an estimated φ of 37 degrees. The clay is highly plastic (CH) with an average LL of 71 and a PI of 35. It is very stiff, with an estimated c_u of 120 kPa. The average high strain E of the sand and clay is estimated to be about 60 MPa.

Design groundwater level at the tank locations is at El. +4.0 m, or about 2 m below final grade.

PERFORMANCE OF 30-M DIAMETER OIL TANKS

Each of the oil tanks performed in a relatively similar manner during hydro-testing. However, the 100% test load was sustained on Tank 2 for about twice as long as on Tank 1; thus, this paper focuses on Tank 2.

Measured Settlement

Figure 1 shows the locations of the settlement monitoring points on the perimeter of the 30-m diameter tank. The settlement of each of these points during hydro-testing of the tank is plotted against a natural time scale in Fig. 2. The percentage of hydro-test load applied is also shown in Fig. 2. Maximum (100%) hydro-test load was estimated as 127.5 kPa at foundation level. It took approximately 40 days to fill the tank with water, and the tank remained full for about 4 months. At that point, the total amount of settlement around the tank perimeter ranged from 190 to 230 mm, with an average of 210 mm. Figure 3 shows the detailed loading and unloading schedule for the hydro-testing.

The settlement of the four monitoring points plotted against log time during the 4 months at 100% hydro-test load is shown in Fig. 4. Since the layer causing most of the settlement (Layer III) was assumed to be normally consolidated or close to that state, the relatively linear relationship between settlement and log time was anticipated. During the second 2 months at maximum loading, the plots of Point 1 and, to a lesser extent, Point 2 indicate a decrease in the log rate of settlement. This is not the case for the other two settlement points.

The plots in Fig. 4 can be used to obtain an approximate estimate of the total settlement of the tank. (Assume here that 95% settlement is a reasonable approximation of total settlement.) Although there is not a great deal of differential settlement across the tank compared with total settlement, Point 3 consistently shows the most settlement. Based on the slope of the settlement-versus-log-time line for Point 3, it would take an estimated 1.4 years to reach 300 mm settlement. For Point 1, which consistently shows the least settlement, the time to reach 300 mm settlement would be 2.75 years, based on the slope of the settlement-versus-log-time line over the first 2 months. Based on the reduced slope for the second 2 months, this time increases to almost 10 years. Although only an approximation, it seems reasonable to adopt 300 mm as the average total settlement (95% consolidation) around the perimeter of the tank. Although the curves in Fig. 2 provide only a picture of the early stages of settlement, an average value of 300 mm extrapolated from these curves appears reasonable and possibly conservative.

Note that the total rebound shown in Fig. 2 after 2 months of draining the tank and then another month of sitting unloaded is about 35 mm for all four settlement points.

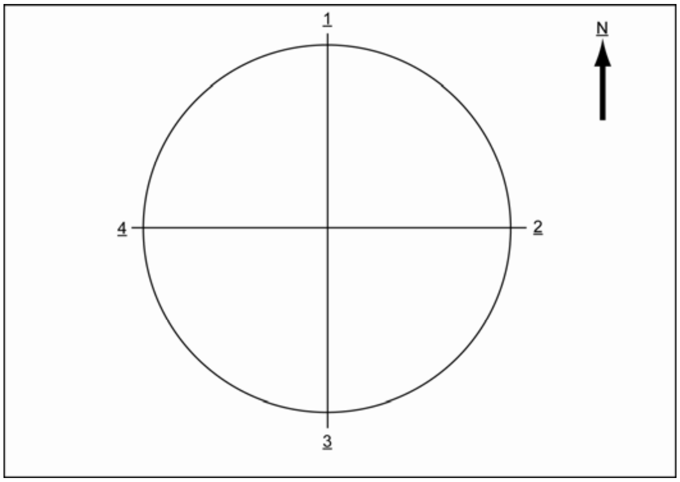

Fig. 1 Locations of settlement monitoring points on 30-m diameter tank.

Theoretical Settlement

It is important to note that the settlement readings outlined above are on the perimeter of the tank. The corresponding settlement beneath the center of the tank will be significantly higher. Also, although most of the settlement recorded is due to the consolidation of Layer III, a component of the settlement is due to the compression of Layers II and IV.

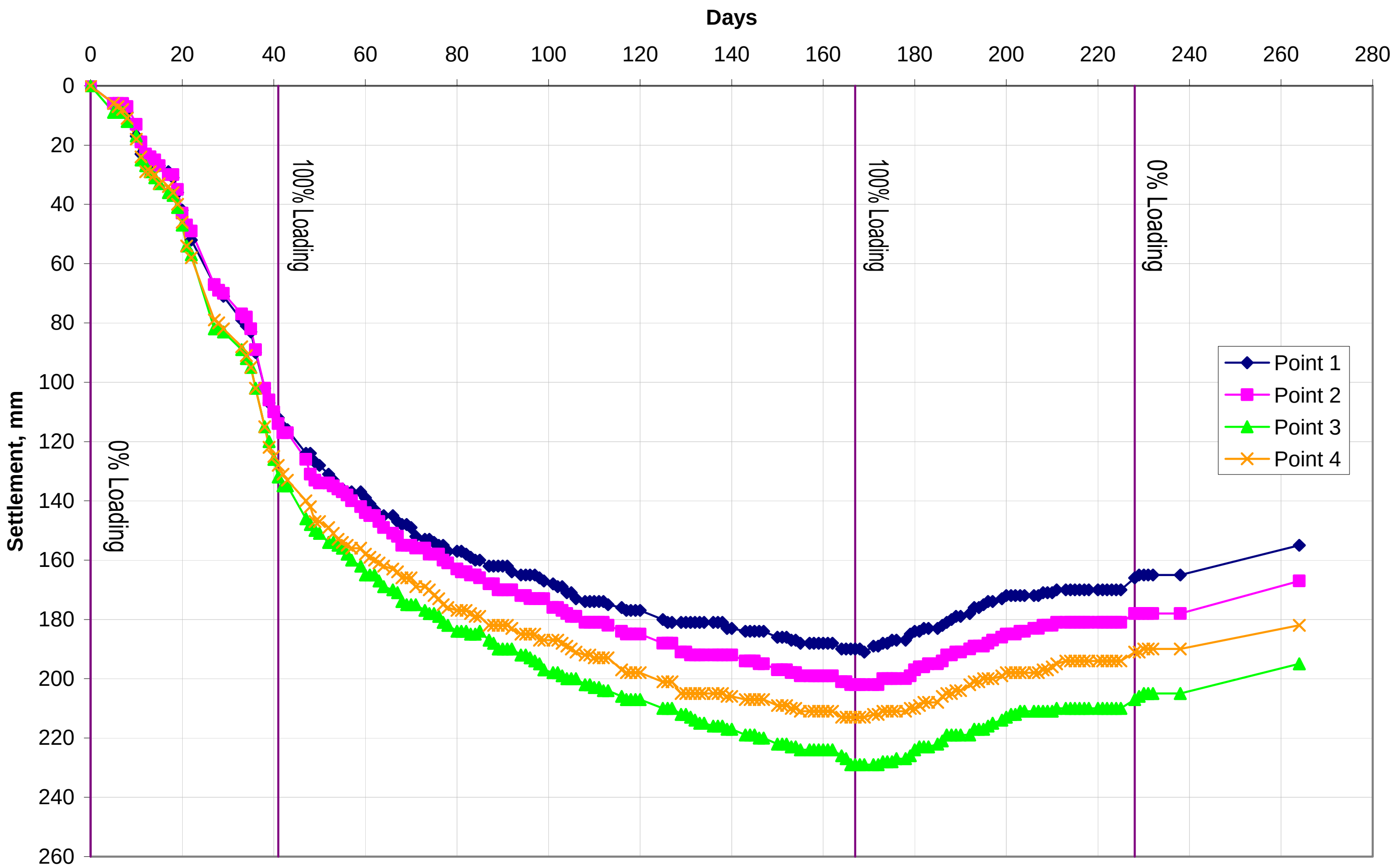

Fig 2. Settlement of monitoring points vs. time.

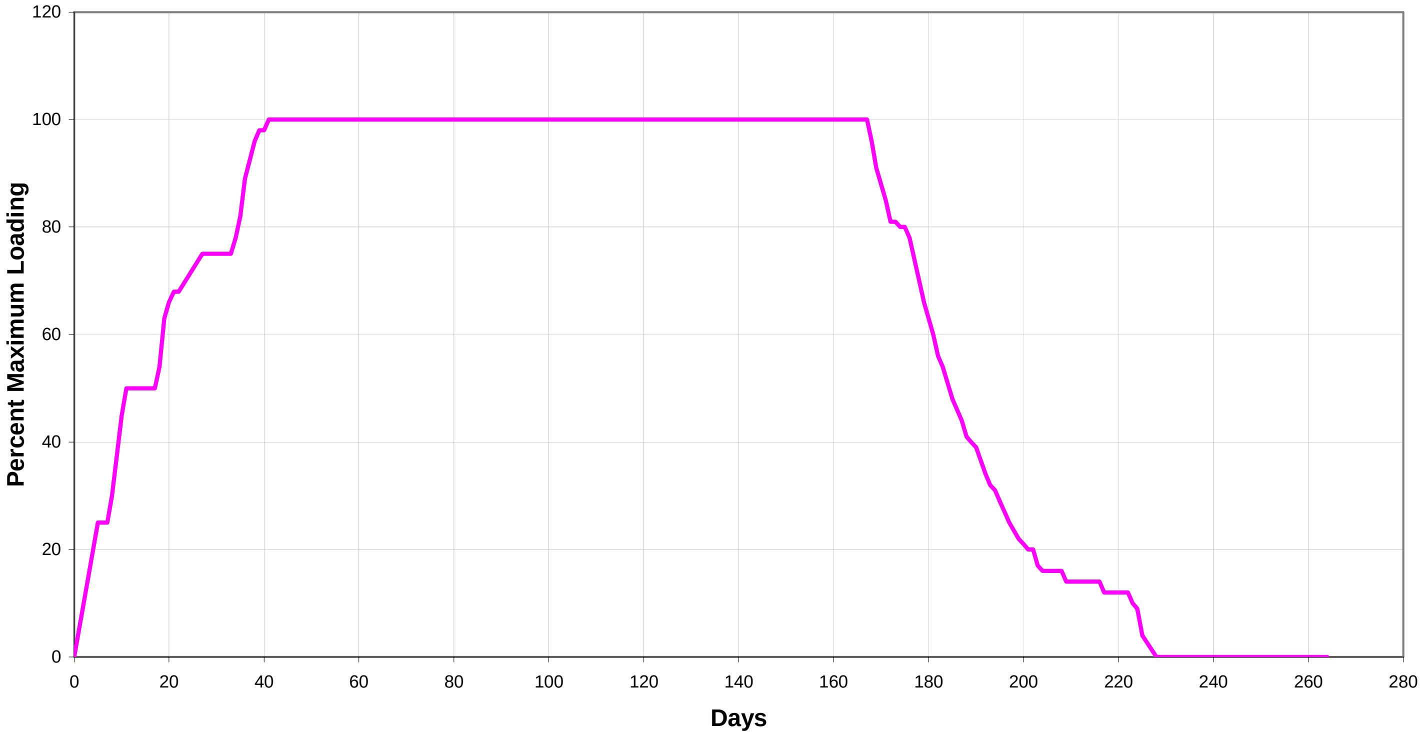

Fig. 3. Percentage loading of tank vs. time.

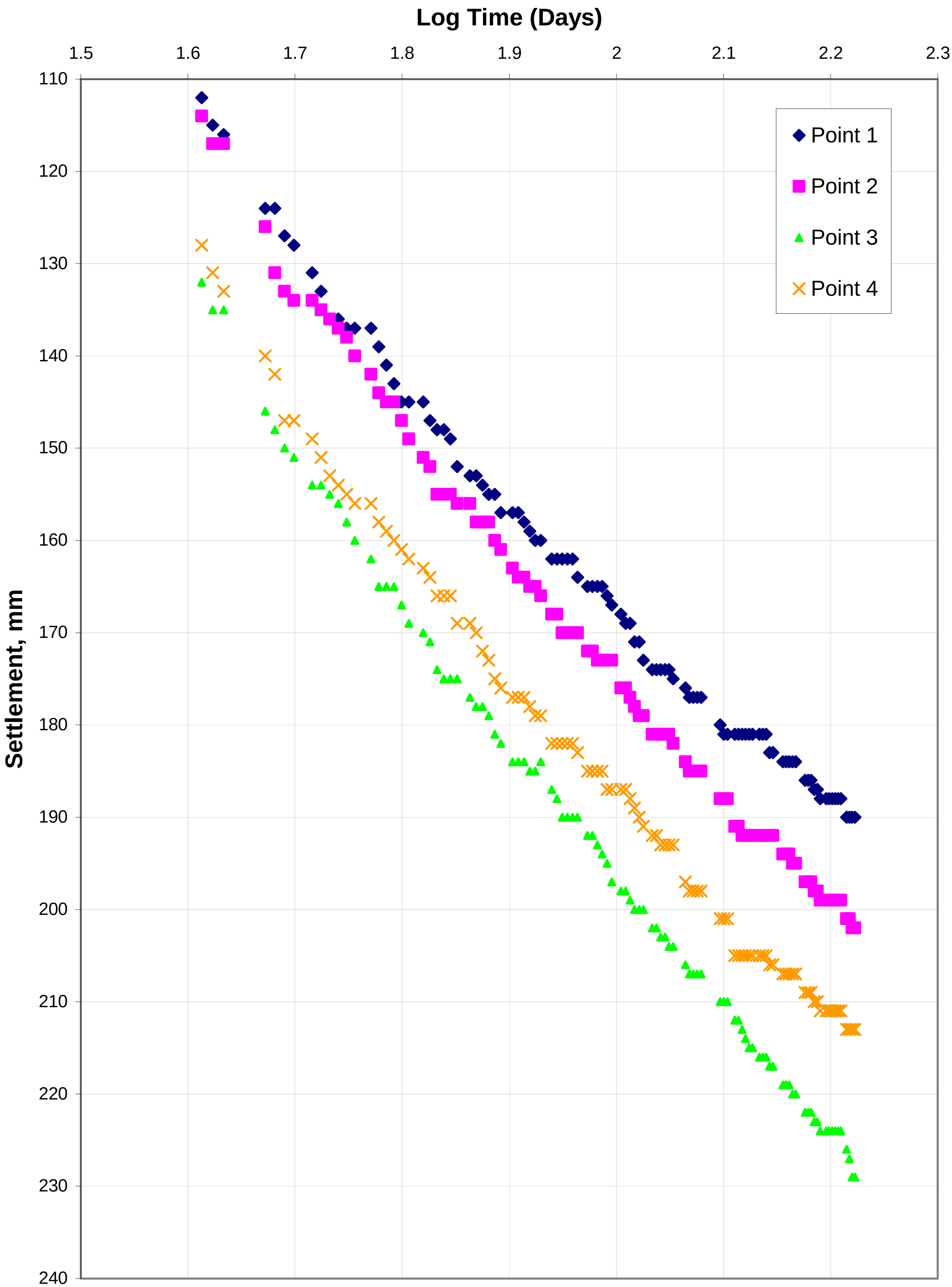

Fig. 4. Settlement vs. log time at 100% loading.

Using a pseudo-elastic approach with a Boussinesq-type stress distribution below the tank, the compression of Layers II and IV due to the full hydro-test load is computed as about 33 mm at the perimeter and 60 mm at the center. Thus, the consolidation settlement at the perimeter due to Layer III is 300 mm – 33 mm = 267 mm.

Using a conventional one-dimensional consolidation analysis for Layer III with a Boussinesq-type stress distribution below the tank, the CR required to produce a settlement of 267 mm beneath the perimeter of the tank is 0.63. The corresponding settlement under the center of the tank is about 485 mm. Adding the 60 mm settlement from Layers II and IV gives a total settlement under the center of the tank of about 545 mm. (Note that the CR of 0.65 is almost double the value of CR = 0.34 obtained from consolidation tests on samples from Layer III. Given the extreme values of PI measured in this layer under the filtered water tank (see below; as high as PI = 330), a value of CR = 0.63 is hardly surprising.)

PERFORMANCE OF 7-M DIAMETER WATER TANK

The 7-m diameter filtered water tank settled rapidly and unevenly during hydro-testing. Settlement on one side of the tank was around 130 mm, while settlement on the other side was only about 20 mm. There appeared to be two potential sources for the settlement. The first was compression of Layer III. The second was possibly poor compaction of the upper 1.0–1.5 m of fill that replaced Layer I immediately beneath the tank before construction. The rapid settlement of the tank (mainly within 6 days of loading) and the fact that this settlement was so uneven strongly suggested that the fill was to blame. The full load of the tank (estimated at around 90 kPa at foundation level) was bearing directly on the fill, and a poorly compacted zone would account for the differential settlement.

The backfill was tested by conducting two plate load tests on the in-place backfill near the 130 mm and 20 mm settlement locations. In addition, two soil borings were drilled adjacent to these points.

The results of these investigations did not lead to any definite conclusions regarding the cause of the settlement. The plate load tests indicated the fill tested was in a dense condition, i.e., no loose zones were encountered at the test locations.

The borings each encountered layers of what the boring logs described as peat at around 10 m depth. However, tests showed a maximum of only 6% organic content. Nevertheless, the layer was very highly plastic, with measured LL values ranging from 154 to 414 and corresponding PI values from 115 to 330. The layer was somewhat thicker beneath the 130 mm settlement side (3 m versus 2.2 m), but the difference in thickness alone does not explain the differential settlement. No undisturbed samples of the layer could be obtained in these borings, and so no consolidation or strength tests could be run.

It was noted that the layer overlying the boring where 130 mm of settlement was measured was more granular than in the other boring, which would have resulted in better drainage of the peaty layer and more rapid settlement. If this was the cause of the 110 mm of differential settlement, then this argument also suggests that if the tank had remained full, the settlement would have increased from 20 mm to closer to 130 mm over time, i.e., the differential settlement would have been substantially reduced. However, the tank was not reloaded out of concern that any further settlement might cause some permanent damage to the tank and foundation system.

DISCUSSION AND CONCLUSIONS

There is no question that most of the settlement of the oil tanks during hydro-testing was due to the highly plastic and compressible Layer III soils. Since the unit weight of oil is only about 80% of that of water, the long-term settlement of the tanks filled with oil was estimated as about 245 mm at the perimeter and 460 mm at the center, using the CR value of 0.63 back-calculated from the hydro-testing results. These settlements also include the estimated compression of the Layer II and IV soils. Note that these perimeter settlements are only about 35 mm more than the average perimeter settlement from the 5 months of hydro-testing. After hydro-testing, separation of the center support of the tank from the tank base was observed (this support was attached to the roof).

The reasons for the settlement of the filtered water tank are inconclusive. The height of the water tank was only about one-half that of the oil tank, and the diameter was less than one-quarter, resulting in an estimated loading at the depth of Layer III of less than 15% of that of the oil tank. Yet, settlement rates were much faster than those of the oil tank. The obvious cause of the very rapid differential settlement was an unevenly compacted surface fill layer, although limited testing did not reveal this. Normally, such extreme settlement in such a short time could not be attributed to a layer as deep as Layer III. However, as has been demonstrated, Layer III is no ordinary layer and seems capable of producing abnormal results. In the end, the filtered water tank was removed in one piece from its ringwall, the ringwall was demolished, and the ground was improved using unreinforced concrete drilled piles extending below Layer III to within about 1 m of the bottom of the tank subgrade. The tank was reloaded and experienced minimal settlement.