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FOUNDATION PERFORMANCE OF LARGE DIAMETER TANKS

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ABSTRACT

The paper presents a detailed case history of foundation performance of six 60-m diameter, 15-m high, floating roof fuel oil tanks and six 96.8-m diameter, 20-m high, fixed roof process water tanks built for a large power plant. Tank walls were supported by concrete ringwall footings. General subsurface conditions at the site are discussed, along with proposed site grading and the rationale for tank foundation selection. Because vibro-replacement improvement of site soils had been used beneath settlement-sensitive structures, there was skepticism regarding the decision to support the tanks on unimproved soils. To allay doubts about the adequacy of tank foundation performance, a staged hydrotesting procedure and an extensive settlement monitoring program were developed and implemented. The excellent tank hydrotesting results demonstrated that ground improvement was not needed due to the more settlement-tolerant nature of the tanks.

KEYWORDS

Tanks, settlement, hydrotesting, floating roof, fixed roof

INTRODUCTION

Twelve large-diameter tanks (six floating roof fuel oil tanks and six fixed roof process water tanks) were erected in connection with a five-unit, oil-fired power plant being built next to an existing power plant of similar size and layout. Vibro-replacement improvement of soils had been used for support of the adjacent existing plant and tanks and was also needed for the new plant structures. Thus, vibro-replacement improvement of the soils beneath these 12 new tanks was perceived to be required as well. However, careful characterization of subsurface conditions beneath the tanks and settlement analyses indicated that the tanks could be built without ground improvement. Available experience with tank hydrotesting further supported this conclusion. A compromise was reached that allowed the tanks to be supported on unimproved ground, provided a comprehensive staged hydrotesting program with extensive settlement monitoring was developed and implemented. The tanks were then erected and hydrotested and excellent settlement performance was observed. It was confirmed that vibro-replacement ground improvement was not needed, due to careful characterization of subsurface conditions, extensive analysis, and the more settlement-tolerant nature of these tanks.

The following sections provide summary descriptions of the tanks, site, and subsurface conditions; the tank foundation selection strategy; development of the hydrotesting/settlement monitoring program; and the results of tank hydrotesting.

TANKS AND TANK FARM LAYOUT

The six floating roof fuel oil tanks are 60 m in diameter and 15 m high and are located immediately south of the existing power plant. The six fixed roof process water tanks are 96.8 m in diameter and 20 m high and are located east of the new power plant, several hundred meters north of the fuel oil tanks and immediately north of the existing power plant. The layouts of these two tank farms are shown on Fig. 1, which also includes information to be referenced in subsequent sections. (It should be noted that Fig. 1 shows the layout of the two tank farms together to save space in this paper. The tank farms are actually several hundred meters apart, as indicated above.)

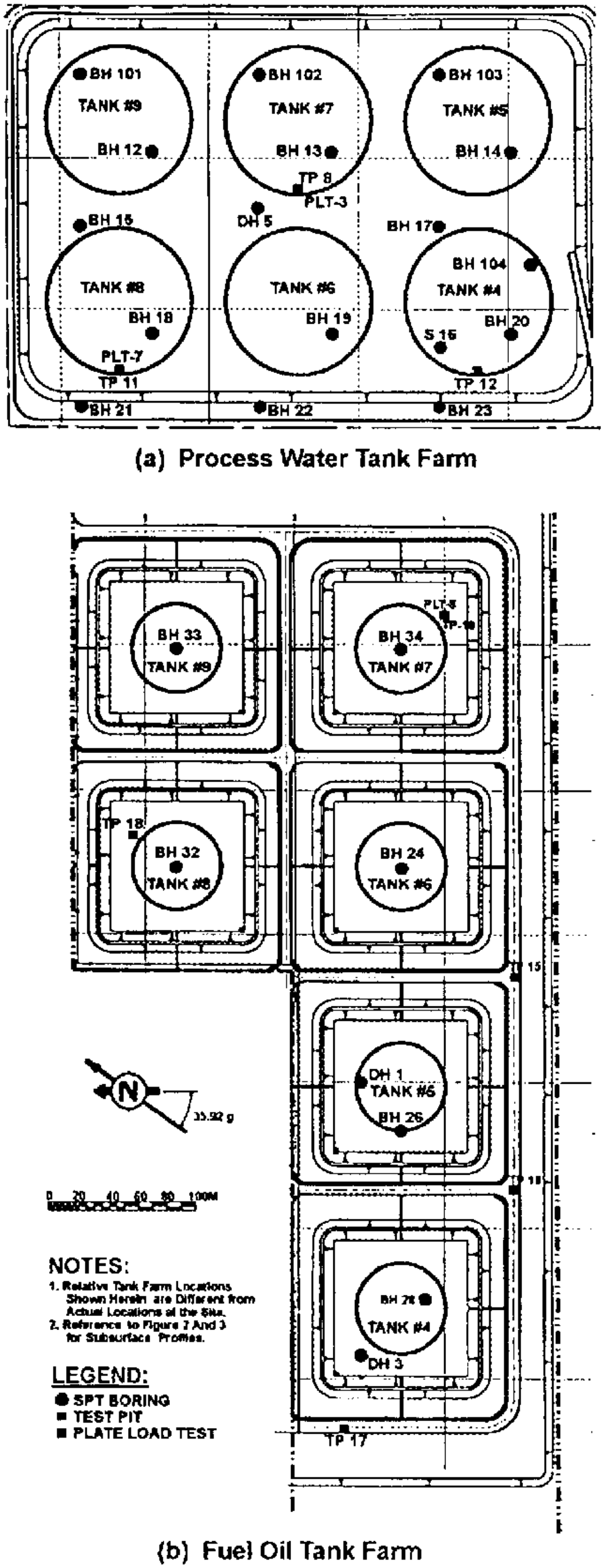

Fig. 1 Process water and fuel oil tank farms

SITE AND SUBSURFACE CONDITIONS

The site is located on a coastline where the topography is generally flat and virtually no vegetation is present. The existing grade is about El. -2 m with respect to plant datum (-2 m PD) at both the process water and fuel oil tank farm areas. About 4.4 m of structural fill was placed in the process water tank farm area to reach final grade at El. +2.4 m PD. Minor grading was required in the fuel oil tank farm area to reach final grade at El -1.8 m PD.

Subsurface conditions disclosed by SPT borings drilled at the fuel oil tank farm area are illustrated by the typical subsurface profile shown on Fig. 2. Also included on Fig. 2 are typical fuel oil tanks and final grade information. The stratigraphy includes a 2-m thick upper layer of generally loose to medium dense, fine, silty sand underlain by about 2 m of generally soft to medium stiff silts/clays. Another 4 m of silty sands are encountered beneath the clay layer on the western portion of the fuel oil tank farm. Intermittent ledges of coralline limestone are encountered in a generally dense sand matrix beneath the silty sand (8 m depth) and silts/clays (4 m depth.) This sand layer with coralline limestone is identified as the coral layer on Fig. 2. SPT refusal was often encountered in the coralline limestone, which was then cored. Ground water was encountered at a depth of about 2 m below existing grade at the time of drilling. Laboratory consolidation tests on representative, undisturbed samples of the silt/clay layer disclosed the following typical values: OCR = 2.3, CR = 0.21, RR = 0.03 and $c_v = 4.2\ m^2/yr$.

Subsurface conditions disclosed by SPT borings drilled at the process water tank farm area are illustrated by the typical subsurface profile shown on Fig. 3. Also included on Fig. 3 are typical process water tanks and final grade information. The stratigraphy is similar to that encountered by the SPT borings drilled at the fuel oil tank farm area, except that the coral layer is consistently encountered at a depth of about 8 m below grade. Ground water was encountered at a depth of about 2 m below existing grade at the time of drilling. Laboratory consolidation tests on representative, undisturbed samples of the silt/clay layer disclosed results similar to those at the fuel oil tank farm area.

TANK FOUNDATION SELECTION

When the existing plant and tanks were built, the soils beneath all plant structures and tanks were improved with stone columns installed to the top of the coral layer. A similar ground improvement program was developed for the new plant structures, but ground improvement beneath the new tanks generally was not deemed necessary. The case for not using ground improvement beneath the more settlement-tolerant tanks was made based on the careful characterization of subsurface conditions (summarized above), settlement calculations, available tank settlement criteria, experience with

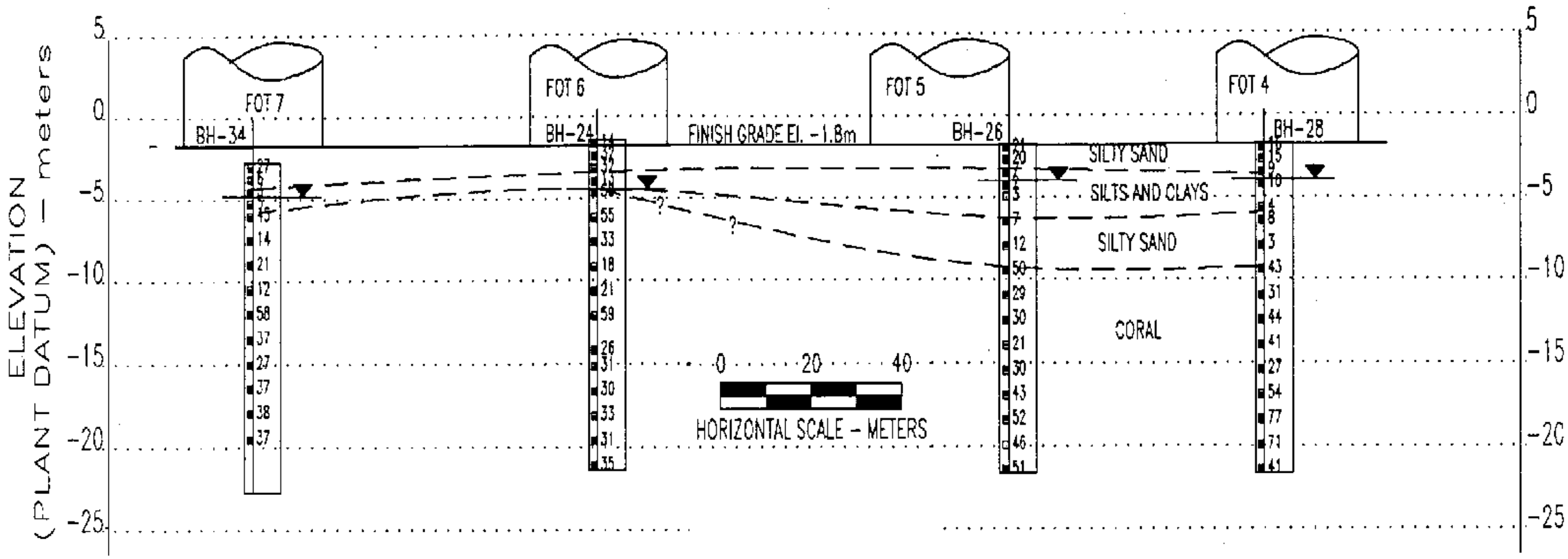

Fig. 2 FOT area subsurface profile

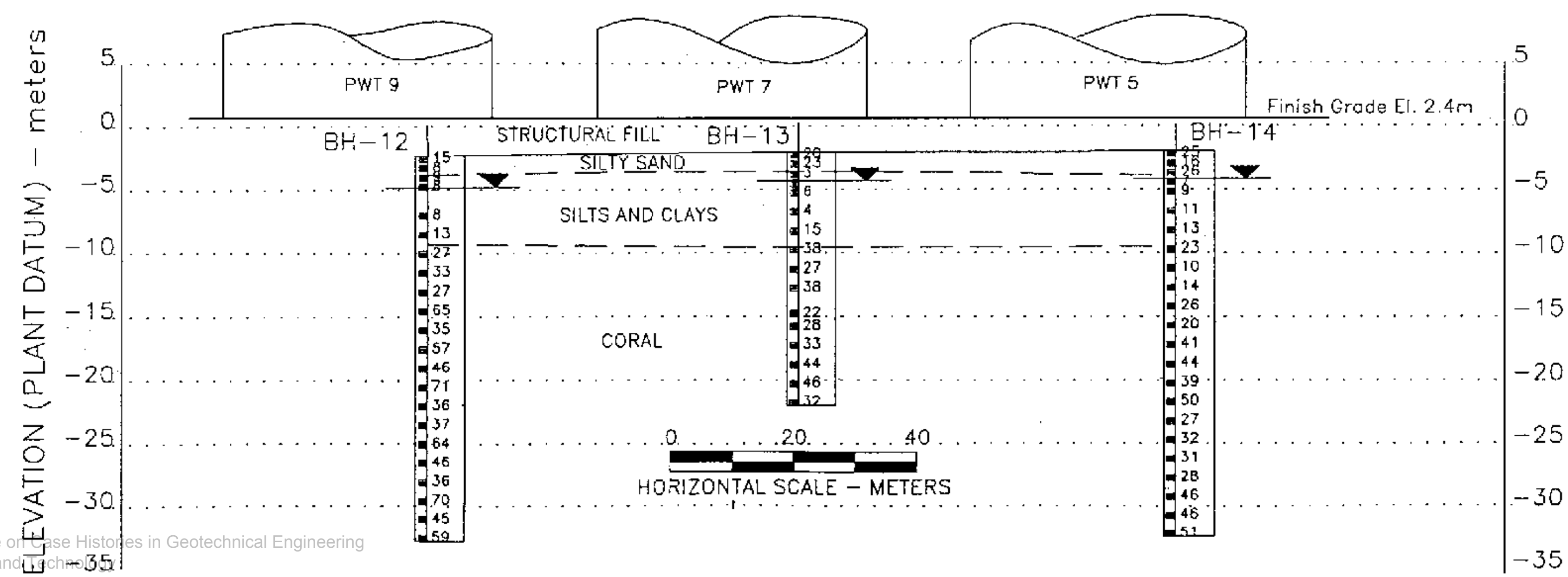

Fig. 3 PWT area subsurface profile

erecting and hydrotesting tanks, and the development of a comprehensive staged hydrotesting program with extensive settlement monitoring.

Tank Settlement Criteria

The following tolerable settlement criteria were adopted as a basis for evaluating tank performance during hydrotesting. These criteria are based on published literature (Rosenberg and Journeaux 1982) and have been used extensively for tank settlement performance evaluation.

Shell Settlement. *Uniform settlement* of the concrete ringwall footing is generally not used as a tolerable settlement criterion, because uniform settlements do not cause detrimental effects to either the tank shell or bottom. Uniform settlement of the concrete ringwall footing can generally be accommodated by providing flexible tank/pipe connections.

Planar tilt is defined as the difference in measured settlement between two diametrically opposed points on the tank shell divided by the diameter of the tank, i.e.,

$$\textit{Planar tilt} = (S_1 - S_2)/D = \Delta S_D/D \qquad (1)$$

where: S_1, S_2 = settlement of two diametrically opposed points of the tank shell, in mm
D = tank diameter, in mm
ΔS_D = difference between S_1 and S_2 = differential settlement between two diametrically opposed points of the tank shell, in mm

The maximum tolerable *planar tilt* is 1/200, or 0.5 percent. For a 96.8-m (96,800-mm) diameter tank, such as the process water tanks, the maximum tolerable value of differential settlement (ΔS_D) is 484 mm, and for a 60-m (60,000-mm) diameter tank, such as the fuel oil tanks, the maximum tolerable value of differential settlement (ΔS_D) is 300 mm. When a perfect planar tilt occurs, all points along the concrete ringwall footing remain on a plane with a slight tilt from the horizontal.

Out-of-plane distortion is illustrated in Fig. 4 (Rosenberg and Journeaux 1982). If a perfect planar tilt of the tank occurs, a plot of the settlements along the perimeter of the tank would result in the cosine-shaped curve shown in Fig. 4. When the tilt is not perfect, points of the concrete ringwall footing move away from the slightly tilted plane described in the previous paragraph. The result is that when settlements along the perimeter of the tank are plotted, they do not fall on the cosine-shaped curve shown in Fig. 4. An out-of-plane differential movement (u) described in Fig. 4 develops, and the *out-of-plane distortion* is defined as:

$$\textit{Out-of-plane distortion} = [u_i - (u_{i-1}/2 + u_{i+1}/2)]/L = \Delta S_{op}/L \qquad (2)$$

where: u_i , u_{i-1}, u_{i+1} = out-of-plane differential movement, in mm, for three neighboring, equally spaced tank shell points
L = distance, in mm, between equally spaced points i, i-1, i+1

The maximum tolerable *out-of-plane distortion* is 1/450, or 0.22 percent. For a 96.8-m (96,800-mm) diameter tank and eight equally-spaced settlement markers, such as the process water tanks, the maximum tolerable value of ΔS_{OP} is 84 mm, and for a 60-m (60,000-mm) diameter tank and eight equally-spaced settlement markers, such as the fuel oil tanks, the maximum tolerable value of ΔS_{OP} is 52 mm.

Bottom Plate Settlement. *Edge-to-center distortion* is defined as the maximum difference in measured settlement between the center of the tank bottom over the radius of the tank, i.e.,

$$\textit{Edge-to-center distortion} = (S_C - S_E)/R = \Delta S_{EC}/R \qquad (3)$$

where: S_E = settlement under the edge of the tank, in mm
S_C = settlement under the center of the tank, in mm
R = tank radius, in mm
ΔS_{EC} = difference between S_C and S_E = differential settlement between the edge and center of the tank, in mm

The maximum tolerable *edge-to-center distortion* is 1/50, or 2 percent. For a 48.4-m (48,400-mm) radius tank, such as the process water tanks, the maximum tolerable value of differential settlement (ΔS_{EC}) is 968 mm, and for a 30-m (30,000-mm) radius tank, such as the fuel oil tanks, the maximum tolerable value of differential settlement (ΔS_{EC}) is 600 mm.

Settlement Analyses

Settlement analyses were performed using the typical consolidation parameters previously described for the silt/clay layer, and elastic parameters for the granular soils (including structural fill to be placed in the process water tank area). Based on the SPT N-values, an elastic modulus of 17,500 kPa was selected for the natural granular soils in the process water tank area, and a value of 13,500 kPa was selected in the fuel oil storage area. The elastic modulus of granular structural fill was selected to be 22,500 kPa, based on previous experience.

Consolidation settlement analysis of the silt/clay layer was performed using the TCON Version 4.99 software package (TAGA 1993) that allows the simulation of load application with time.

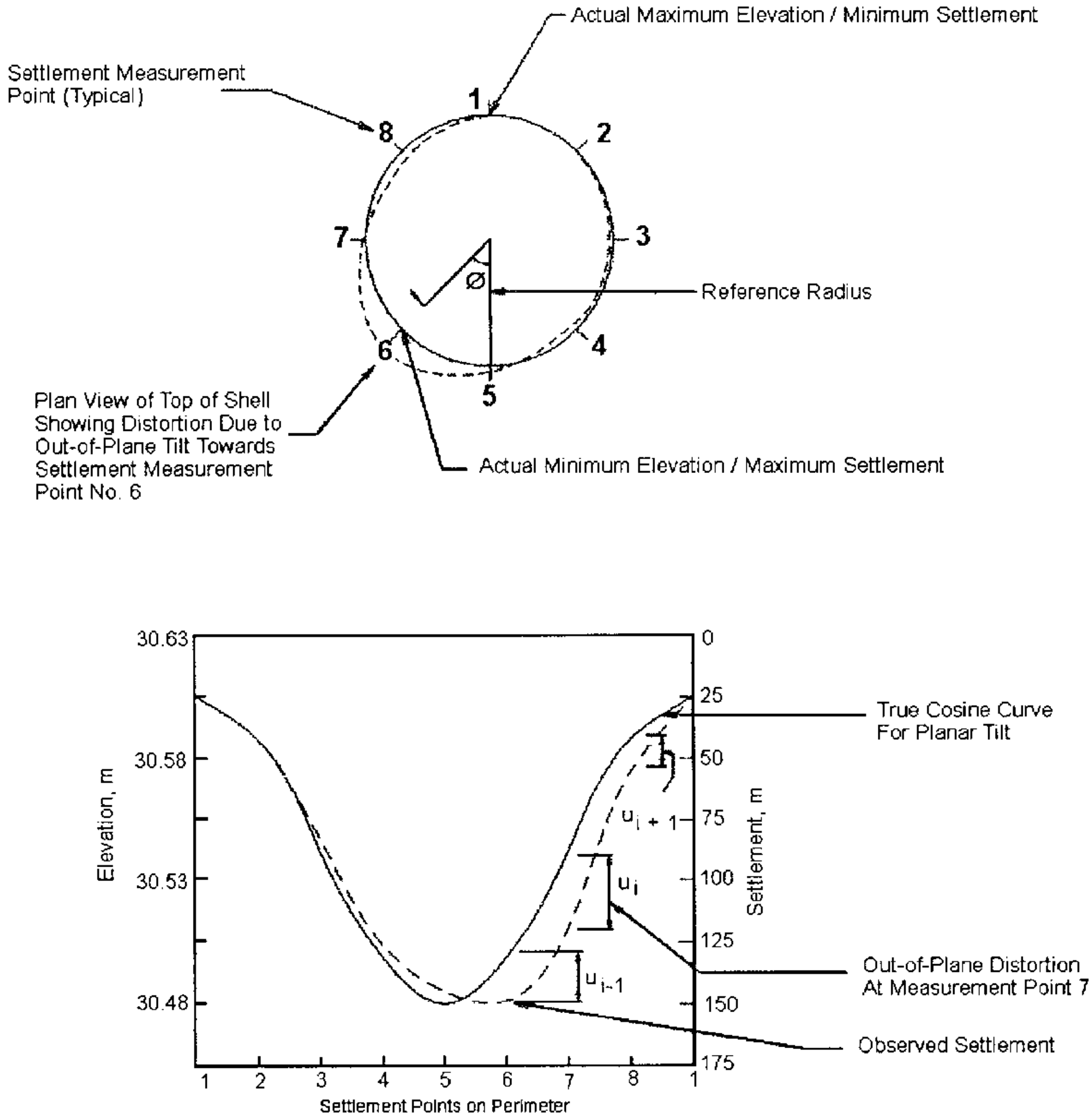

Fig. 4 Planar & out-of-plant tilt evaluation (Rosenberg & Journeaux 1982)

Analysis results indicated settlements of 55 mm at the edge and 100 mm at the center of the fuel oil storage tanks at the end of hydrotesting. Calculated settlements were 140 mm at the edge and 260 mm at the center of the process water tanks at the end of hydrotesting. The TCON analyses also indicated that the settlements in the silt/clay layer would stabilize within a short period of time (weeks rather than months).

The calculated settlements would result in edge-to-center distortions much smaller than the maximum tolerable values previously described. The calculated settlement values were also within the range of tolerable limits included in the authors' database of tank settlement measurements during hydrotesting (Senapathy *et al.* 1994).

<u>Staged Hydrotesting Program</u>

The following staged hydrotesting procedure was developed and implemented:

Step 1 - Install settlement monitoring markers at eight equally spaced locations along the perimeter of the tanks.

Step 2 - Obtain the "zero-loading" reading of each of the settlement monitoring markers.

Step 3 - Fill tank to 50 percent capacity. Obtain one set of readings immediately before filling the tank, one set of readings twice a week during filling, and one set of readings immediately after filling the tank to 50 percent.

Step 4 - Hold the 50 percent load and monitor settlement daily. The duration of hold was to be determined based on the settlement performance of the tank. It was estimated that the 50 percent load would have to be held for about 1 week.

Steps 5 and 6 - Similar to Steps 3 and 4, but for 75 percent load.

Step 7 - Similar to Step 3, but for 100 percent load (full tank.)

Step 8 - Hold the full load and monitor settlement daily for 2 weeks and then twice a week thereafter. The duration of hold was to be determined based on the settlement performance of the tank. It was estimated that the load would have to be held for about 6 weeks.

Settlement measurements were also made under the center of the first fuel oil tank (FOT #4) and the first process water tank (PWT #4) to be hydrotested.

SETTLEMENT MONITORING RESULTS

Detailed settlement monitoring results are presented for FOT #4 and POT #4, i.e., the first fuel oil tank and the first process water tank to be hydrotested. Changes to the hydrotesting procedure based on the settlement behavior of FOT #4 and PWT #4 are discussed. Remarks are offered regarding the settlement behavior of the remaining tanks.

Fuel Oil Tanks

The time vs. settlement curves for the eight settlement markers located along the sides and at the center of FOT #4 are shown in Fig. 5.

The data in Fig. 5 indicate that the maximum settlement at the edge of FOT #4 was 111 mm and the minimum settlement was 38 mm. The average settlement along the edge of the tank was about 71 mm, which is larger than the predicted 55 mm but well within tolerable limits. The data in Fig. 5 also show how quickly the settlements stabilized after loading stages were reached. Based on these results, the hydrotesting procedure was changed to allow holding the 100 percent load for a period of no more than 2 weeks for the remaining fuel oil tanks.

Figure 6 shows a plot of settlements for equally spaced markers located along the perimeter of FOT #4 and PWT #4 at the end of hydrotesting under 100 percent load. The figure includes a continuous cosine-shaped curve that would represent a perfect tilt of the tank and actual settlement measurements that are represented by hollow squares. The vertical distances between the hollow squares and the continuous curve represent out-of-plane differential settlements at the settlement marker locations.

The data in Fig. 6 indicate that the maximum out-of-plane differential settlement for FOT #4 was about 23 mm. The maximum out-of-plane distortion was about 1/2,100, or 0.047 percent. This value is about five times smaller than the 0.22 percent allowable.

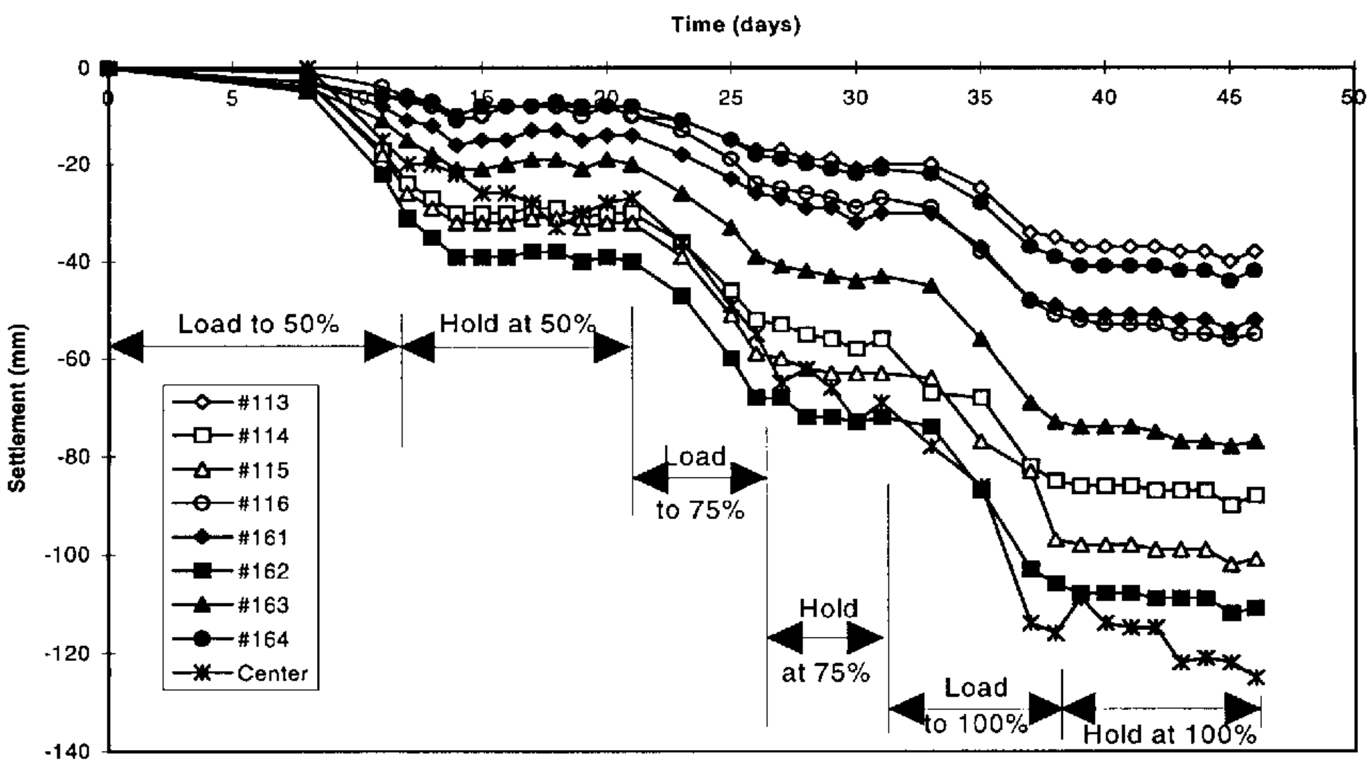

Fig. 5 Time vs. settlement curve for fuel oil tank No. 4

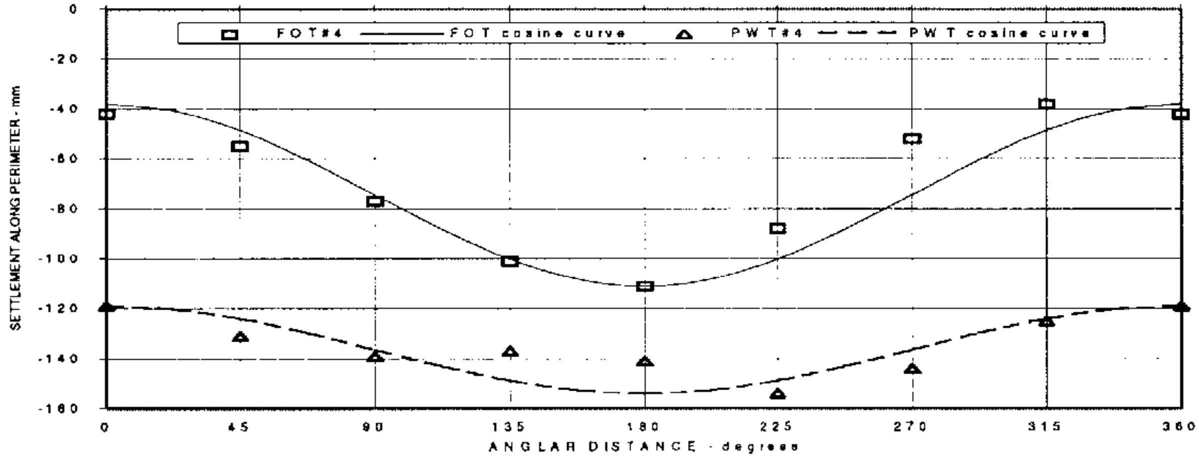

Fig. 6 Out-of-plane distortion

The maximum *planar tilt* for FOT #4 was 69 mm, which corresponds to about 1/870 or 0.12 percent. This value is more than 4 times smaller than the allowable.

Figure 7 shows a plot of settlements of two points on the perimeter where maximum and minimum edge settlements were measured, as well as the center of tank settlement for FOT #4 and PWT #4. The data in Fig. 7 indicate that the maximum edge-to-center differential settlement for FOT #4 was 87 mm. The maximum edge-to-center distortion was about 1/870, or 0.29 percent. This value is more than 6 times smaller than the allowable.

The settlement behavior of the remaining fuel oil tanks was similar to that of FOT #4.

Process Water Tanks

The time vs. settlement curves for the eight settlement markers located along the sides and at the center of PWT #4 are shown in Fig. 8. It can be observed that the settlement marker placed at the center of the tank was damaged while filling the tank to 50 percent capacity. Also, the holding period at 50 percent loading did not fully stabilize before the tank was filled to 75 percent capacity.

The data in Fig. 8 indicate that the maximum settlement at the edge of PWT #4 was 154 mm and the minimum settlement was 119 mm. The average settlement along the edge of the tank was about 136 mm, which is almost identical to the predicted 140 mm and well within tolerable limits. The data in Fig. 8 also show how quickly the settlements stabilized after the 75 percent and 100 percent loading stages were reached. Based on these results, the hydrotesting procedure was changed to allow holding the 100 percent load for a period of no more than 2 weeks for the remaining process water tanks.

The data in Fig. 6 indicate that the maximum out-of-plane differential settlement for PWT #4 was 13 mm at the southern side of the concrete ringwall footing. The maximum out-of-plane distortion was about 1/400, or 0.025 percent. This value is more than 8 times smaller than the allowable.

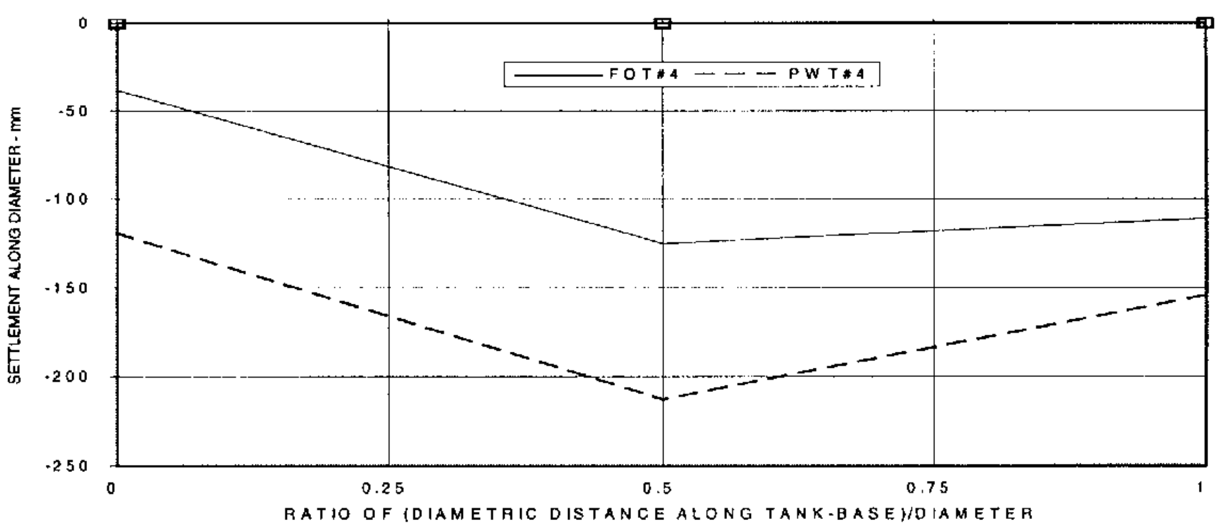

Fig. 7 Center-to-edge distortion

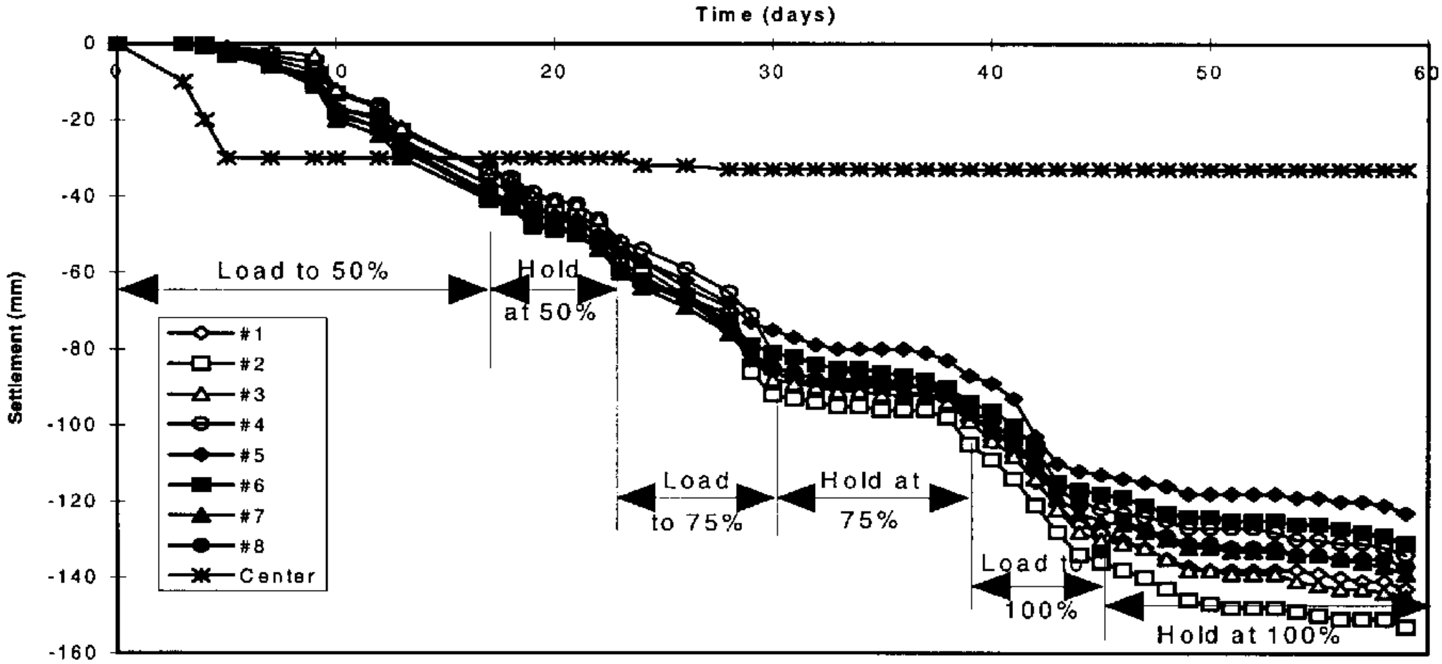

Fig. 8 Time vs. settlement curve for process water tank No. 4

The maximum *planar tilt* for PWT #4 was 23 mm, which corresponds to about 1/4,400 or 0.023 percent. This value is more than 22 times smaller than the allowable.

The center-of-bottom-plate settlement shown in Fig. 7 was calculated based on the settlement analysis results and edge settlements shown in Fig. 8 (the settlement marker at the center of the bottom plate was damaged, as shown by readings on Fig. 8). The data in Fig. 7 indicate that the maximum edge-to-center differential settlement for PWT #4 was 94 mm. The maximum edge-to-center distortion was about 1/515, or 0.19 percent. This value is more than 10 times smaller than the allowable.

The settlement behavior of the remaining process water tanks was similar to that of PWT #4, except that edge settlements of slightly more than 200 mm were observed for PWTs #7, #8 and #9. However, maximum planar tilts, out-of-plane differential settlements, and distortions remained well below tolerable limits.

CONCLUSIONS

Careful characterization of subsurface conditions, detailed settlement analyses, experience with tank hydrotesting, and the development of an acceptable staged hydrotesting procedure served as the basis for the foundation selection strategy for 12 large diameter tanks. The available data and rationale indicated that the tanks could be built without the then-perceived notion that ground improvement would be required. The tanks were erected and hydrotested without using ground improvement, and excellent settlement performance was observed. It was confirmed that vibro-replacement ground improvement was not needed, due to the more settlement-tolerant nature of these tanks.

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