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Observation and Analysis of Settlements of Oil Tanks on High Compressive Saturated Soft Clay

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SYNOPSIS This paper summarizes the experiences obtained in the design and construction of oil tank foundations on untreated high compressive saturated soft clay. Through the study and analysis of the various data collected from long-term observation, the author has proposed a number of suggestions on the designing of the foundation of oil tanks, the calculation of the deformation of tank floors, allowable differential settlement and the spacing of tanks. In addition, the paper also gives an account of the behaviour of the site and the deformation of tanks resulting from the Tangshan Earthquake.

INTRODUCTION

Thirty-three oil tanks were successively built on high compressive saturated soft clay in the fifties in the coastal regions of North China. While the allowable bearing capacity of the foundation was only 5-6 T/m^2, the load of oil tanks was set at 11-15 T/m^2. Therefore, methods such as preloading by water-filling at different stages were used for the purpose of consolidating the soft clay. As a supplementary measure, sand-bedding of different thicknesses was also used in the practice. Consequently, the requirements of the design were finally met. All these tanks have been functioning well up to this moment.

SOIL CONDITIONS AND FOUNDATION DESIGNING

The soil of the site could be divided into six layers. The thickness of each layer and its characteristics are shown in Figure 1.

The foundation of the oil tanks was made by steamrolling the clayey soil one layer after another and over the steamrolled clayey soil were spread a layer of coarse sand with variable thickness (with a thickness of 20 cm at the shell of the tanks and 40 cm in the center) and a layer of sand asphalt with a thickness of 5 cm, as shown in Figure 2. In view of the large settlement as well as the differential settlement resulting from the loading of the tank, measures such as pre-raising the elevation of the foundation and making the elevation of the center of the foundation higher than that at the periphery of the tank were adopted on the basis of estimated settlements.

THE PRELOADING OF TANKS BY WATER-FILLING

Upon the completion of the construction of

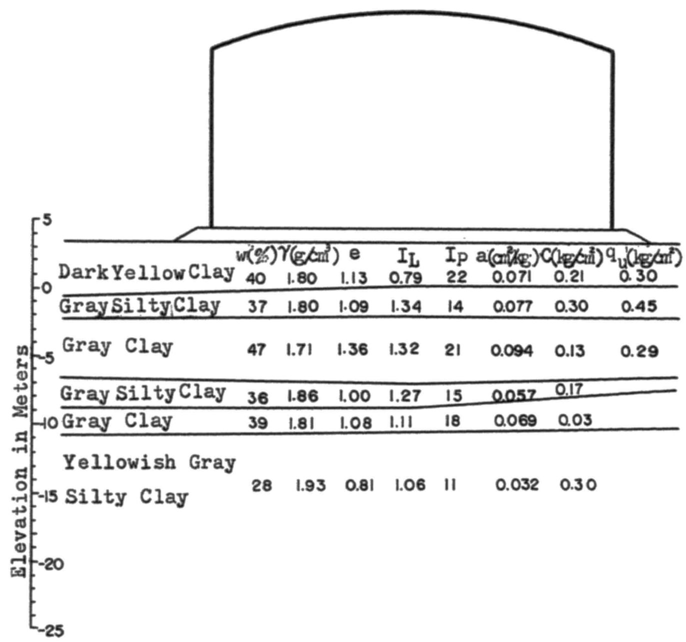

Fig. 1. Section of Soil Layers and Characteristics of Each Layer

tanks, preloading by means of water-filling was generally done in three stages. During the period of preloading, soft connectors were used for the connection of the pipes with the tanks. The period of preloading of the tanks by means of water-filling was 15-271 days, see Table I. It is obvious that the shorter the time of water-filling, the larger the total settlement of the tanks. This might be the result of the large lateral deformation of the sub-soil because of too quick water-filling. Slow water-filling would delay the use of the tanks. What is more, as is shown in Table I, there was no decrease in the total settlement of the oil tanks even if the period of water-filling

TABLE I. Date of the Settlement of Tanks

Tank No.	Roof[1] Type	Diameter (m)	Height (m)	Water-Filling Duration (days)	Max. Shell Settlement (mm)	Shell Settlement (mm)	Relative[2] Tilt δ/D (%)	Differential Settlement[3] Δρ/ℓ (%)		
								Before Earthquake	After Earthquake	Final
101	D	30	13	15	1049	1009	0.15	0.28	0.27	0.50
102	D	18	13	15	1083	943	1.37	-	-	1.02
103	D	12	13	15	785	740	0.80	-	-	0.81
104	D	18	13	15	927	866	0.44	-	-	0.65
105	D	12	13	15	789	757	0.40	-	-	0.43
106	D	18	13	15	1007	998	0.10	0.24	0.28	0.09
107	D	18	13	15	1122	1044	0.75	0.46	0.47	0.48
108	D	14	10	173	761	756	0.24	0.58	0.60	0.93
109	D	14	10	60	794	728	0.74	0.16	0.61	1.27
110	D	20	9	60	788	734	0.56	0.54	0.54	0.36
111	D	20	9	60	721	691	0.22	0.55	0.31	0.22
112	C	12	9	85	841	725	1.84	-	-	1.17
113	C	12	9	35	851	799	0.83	0.48	0.48	0.53
114	C	12	9	28	934	791	2.38	1.30	1.40	1.51
115	C	12	9	42	756	738	0.51	-	-	0.20
116	C	12	9	42	937	824	1.90	1.07	1.16	1.21
117	C	12	9	45	919	846	1.23	0.75	0.75	0.78
118	C	12	9	39	706	673	0.63	0.39	0.39	0.40
119	C	12	9	41	718	693	0.41	-	-	0.35
120	C	12	9	171	740	696	0.74	0.38	0.37	0.47
121	C	12	9	68	775	727	0.79	0.48	0.45	0.50
122	C	12	9	27	766	734	0.55	0.29	0.33	0.35
123	C	12	9	29	942	888	0.85	0.29	0.47	0.54
124	C	12	9	47	755	736	0.32	0.31	0.24	0.20
125	C	12	9	271	737	732	0.09	0.03	0.17	0.06
126	C	12	9	26	896	835	1.02	0.62	0.63	0.65
127	C	12	9	30	927	845	1.38	0.75	0.80	0.88
128	C	12	9	49	670	609	1.03	-	-	0.66
129	C	12	9	48	803	756	0.78	0.50	0.45	0.50
130	C	12	9	27	847	805	0.72	0.44	0.50	0.46
131	C	12	9	28	876	803	1.34	1.02	1.10	0.85
132	C	12	9	102	745	648	1.58	-	-	1.00
133	C	12	9	220	785	716	1.15	-	-	0.73

Notes: 1) D = dome roof
C = cone roof

2) δ = difference in settlement between diametrical points
D = diameter of the tank

3) Δρ = difference in measured settlement between two points
ℓ = circumferential distance between measuring points on shell

was prolonged. With this type of site, 45 to 60 days of water-filling by stages would serve the purpose.

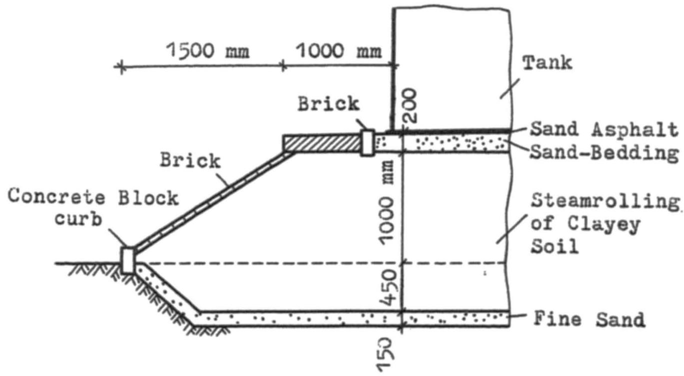

Fig. 2. Structure of Tank Foundation

SETTLEMENT AND DIFFERENTIAL SETTLEMENT OF THE TANKS

Systematic observation of the settlement was carried out during the construction of the tanks and such observation is still going right now. A precision level was used as the observation apparatus. Benchmark No. 1 was placed at the depth of 221 meters from the surface of the site, and Benchmark No. 4 was placed at the depth of 2 meters. Using Benchmark No. 1 as a measuring standard, the subsidence of Benchmark No. 4 is shown in Figure 3. The figure shows that there was practically no subsidence of the benchmark after its placement in 1960, but beginning from the seventies the subsidence became quite evident. This was due to large-area subsidence of ground in this region. Such subsidence apparently caused no harm to the tanks. The actual settlement of the tanks (after deducting the large subsidence of the ground) is listed in Table I. It is clear from the table that although the average settlement of the shells of most tanks ranged from 0.7 to 1.0 meter, the tanks operated normally. The settlement-time curve of a number of typical tanks is given in Figure 4. This figure shows that it took roughly 15 to 20 years for the tanks to be stabilized. Over 80 per cent of the settlement took place within 2 to 4 years and 90 per cent of the settlement in 5 to 8 years.

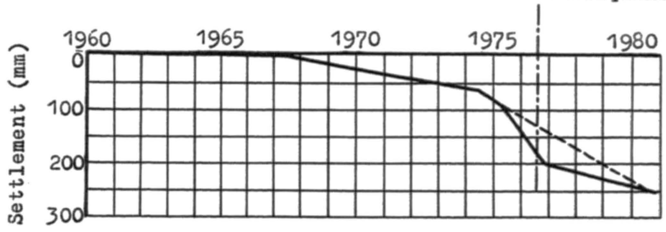

Fig. 3. Settlement —— Time Curve of Benchmark No. 4

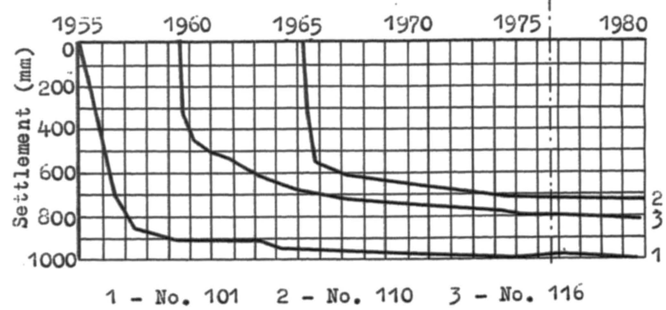

Fig. 4. Settlement —— Time Curve of Tank No. 101, No. 110 and No. 116

The differential settlement and relative tilt of the tanks is shown in Table I. All the tanks are still operating normally and there has been no relevelling. There are differences in the amount of allowable differential settlement specified by different countries (Marr, Ramos and Lambe, 1982). On the basis of the analysis of the data collected from the author's long-term observation, 0.5% would be recommended for the allowable differential settlement and 0.8% for the allowable relative tilt in the case of dome-type and cone-type tanks.

When the severe earthquake registering 7.8 on the Richter Scale hit Tangshan on July 28, 1976, the earthquake intensity of the area where the tanks are located was 8. The tanks stood the test of this most severe earthquake and this is demonstrated by the fact that no accident occurred due to any trouble developed over the foundation. It can be surmised from Figure 3 that aside from the large-area subsidence of the earthquake subsidence of the ground in that particular region was about 5 cm at the time of the Tangshan Earthquake. This is primarily because the sedimentary deposit up to a depth of 221 meters from the ground surface was made denser by the earthquake. As is shown in the settlement-time curve in Figure 4, the tanks did not experience obvious additional settlement during the earthquake. It can also be seen from the comparison shown in Table I between the differential settlements observed before and after the earthquake that the differential settlement of most tanks did not increase. This proves once again that the design of the foundation of the tanks was sound.

DEFORMATION OF THE TANK FLOOR AND DEFORMATION OF THE SOIL AROUND THE TANKS

The size of the deformation of the tank floor is of great importance to the normal operation of the tanks. The rupture of a storage tank in Mizushima, Japan was caused by separation of welds in the tank floor (Bell and Iwakiri, 1980). To study the behaviour of the deformation in the tank floor, measurements were taken on the deformation of the tank floor and the deformation of the soil around the tanks. The solid lines in Figure 5 show the results of such measurements of oil tank No. 133. According to the theory on elastic-homogeneous halfspace, the vertical uniform circular load gives rise to the calculated vertical displacement of the surface of the ground as shown by the broken lines in Figure 5. For the sake of comparison the edge of the bottom plate of the tank is taken as a meeting point between the curve calculated and the curve actually measured. As is shown in Figure 5, the measured curve of the bottom plate is quite close to the calculated curve. Therefore, while designing the oil tanks, the differential settlement between the center of the bottom plate and the edge can be estimated by using the value obtained through the use of the theory on the elastic-homogeneous halfspace.

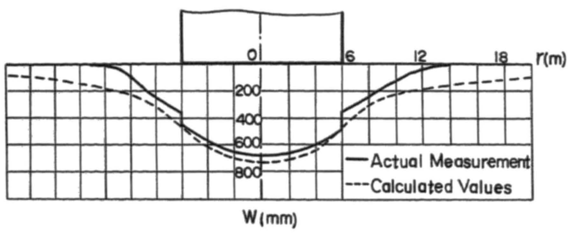

Fig. 5. Deformation of the Tank Floor and Deformation of the Soil Around the Tank

Figure 5 also shows that the deformation in the soil on the edge of the tanks actually observed has undergone some abrupt changes and that the deformation of soil around the tanks actually measured was much smaller than that determined by theoretical calculation. This was the result of the shearing failure of the soil under the edge of the bottom plate. Besides, it can be seen from the measured deformation curve of the ground surface that its deformation decreased rapidly and that at the place 0.75 D close to the edge of the tank (D being the diameter of the tank) the deformation actually measured was very small. In the project, the smallest spacing between the tanks was 0.75 D. Judging from the measured settlement and the operation of the tanks, no trouble developed as a result of this small spacing. Therefore, in areas of soft clay, the net spacing between one tank and another may be set at 0.75 D to D.

DEFORMATION OF SOIL AT DIFFERENT DEPTHS AT THE SITES OF THE OIL TANKS

The deformation distribution curve of the soil layer is shown in Figure 6 in accordance with the results of the actual measurement of the deformation of soil at different depths of the tank site. Figure 7 gives the percentage of deformation of each layer. It can be seen that the deformation of the soil layer with a thickness of D/3 in the upper part accounted for 42% to 50% of the total deformation, deformation of the soil layer with a thickness of D/2 roughly for 52% to 64% and deformation of the soil layer with a thickness of D for 79% to 95% (D being the diameter of the tank). Therefore, differential settlement and tank tilting can be reduced by selecting a site with a relatively uniform supporting soils of the foundation and by ensuring the uniformity of sand-bedding at the tank sites. By comparing the deformation distribution curve of the 4-month operation of the tanks with that of the 169-month operation of the tanks, one can see that with the increase of time, the deformation of the soil layer started from the upper part and gradually expanded into the lower part. Namely, the proportion of the upper soil layers in the deformation decreased somewhat while that of the lower soil layers in the deformation increased a little. The increase was biggest for the soil layer with a depth of D. What is more, it can also be seen from Figure 6 that the depth of the effective compression layer of the foundation has a tendency to increase gradually with time. Assuming that the soil layer accounting for 95% of the total settlement is the lower limit of the depth of the effective compression layer, the thickness of the effective compression layer is 13 meters when t equals 4 months and about 22 meters when t equals 169 months. This deserves attention when we determine the depth of the effective compression layer of the foundation.

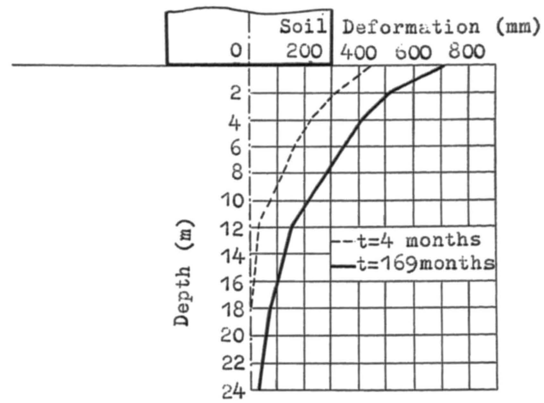

Fig. 6. Deformation of Soil at Different Depth

CONCLUSIONS

As borne out by the experience of the project, in the construction of oil tanks on high compressive saturated soft clay, the method of preloading by means of water-filling in stages for the purpose of consolidating the soft clay proves to be successful, and economical. The fact that there was no increase in the settlement of the tanks and in the differential shell settlement during Tangshan Earthquake proves that the design of the foundation was sound and reliable.

The deformation of the tank floor of the tank is quite close to the curve defined by theoretical calculation. Therefore, the differential

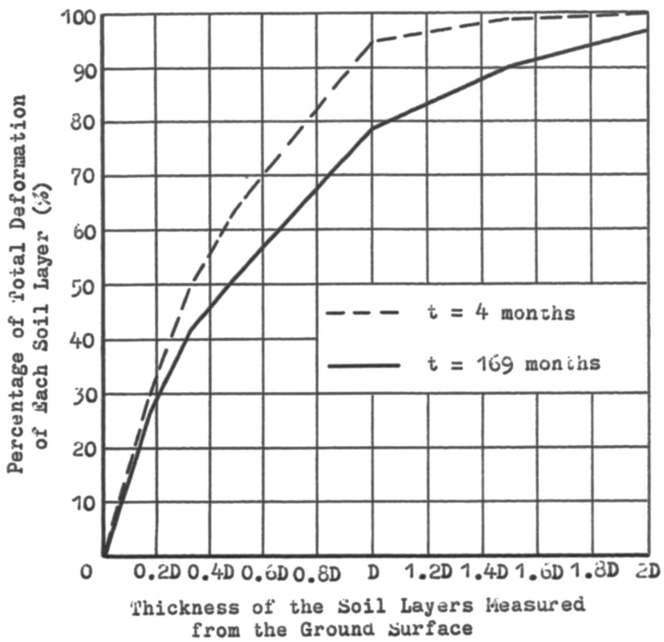

Fig. 7. Percentage of Total Deformation of Each Soil Layer

settlement between the center of the bottom plate and the edge can be estimated by using the value obtained through theoretical calculation.

To avert any possible damage from too small a spacing between one tank and another in areas of soft clay, the net spacing between two tanks may be 0.75 D to D.

As the soil layers of the upper part account for a large percentage of the total deformation, the differential shell settlement and tank tilting can be reduced by selecting a site with a relatively uniform supporting soil and by ensuring the uniformity of sand-bedding at the tank sites.

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