

BEHAVIOUR OF CYLINDRICAL WELDED STEEL TANKS SUPPORTED ON PAD FOUNDATION OVER RECLAIMED LAND

by
S. K. Kong and D. Q. Yang

*Reprinted from
Proceedings of 5th International Symposium on
Field Measurements in Geomechanics
December 1~3, 1999, Singapore, pp.169-175*

Behaviour of cylindrical welded steel tanks supported on pad foundation over reclaimed land

S.K.Kong & D.Q.Yang

Moh and Associates (S) Pte Limited, Singapore

ABSTRACT: Development of tank farm over reclaimed land requires advanced geotechnical knowledge, good engineering judgement as well as suitable instrumentation system for achieving practical and economical design of tank foundation system and timely completion of project. This paper describes the methodology of geotechnical study and engineering analysis for constructing large scale steel tanks on reclaimed land underlain by poor soils at the southern island of Singapore using pad foundation. Discussion on the design method/criteria, engineering consideration and hydrotests of these cylindrical welded steel tanks is presented in this paper. The behavior of foundation soil monitored by using settlement profilers, inclinometers, piezometer, settlement points and heave markers during hydro-testing period is also described.

1 INTRODUCTION

Construction of large scale steel tanks over weak soil such as reclaimed land underlain by poor soils is usually costly if pile systems are required. This paper describes the methodology of geotechnical study and engineering analysis for constructing three (3)-nos. of 44.9m diameter x 20m high BFO Tanks and one (1) no. of 22.5m diameter x 16.95m high Fuel Oil Cutterstock Tank (Figure 1) on reclaimed land consisting of hydraulic filled sand, coral & marine clay and Old Alluvium at the southern island of Singapore using pad foundation. This paper focuses on the approach in soil investigation, tank layout evaluation, foundation analysis, construction control and field observation for achieving practical and economical design of tank foundation under the critical geotechnical and geological conditions of this tank site.

2 GROUND CONDITIONS

The ground conditions of the tank site were investigated by borehole exploration works. According to the geological map (PWD, 1976), the basic geological formation at the site appears to be predominantly the Jong Facies (Ji) of Jurong Formation overlying with the Reef Member (K_r) of Kallang Formation and the hydraulic sand fill. As indicated in Figures 2 & 3, the subsoil condition at the site is erratic and consists of five (5) layers, namely i) Sand Fill, ii) Marine Deposits consisting of interbedded corals, marine clay and silty fine sand, iii) stiff to very stiff Clayey Silt with Clayey Sand, iv) hard Sandy Clayey Silt and v) very hard Sandy Silty Clay with varied thickness. Mackintosh Probe Tests were carried out to further investigate the possible extent of soft marine clay/silty clay encountered in Borehole Nos. BH-1, BH-2, BH-3, BH-7 and BH-16 (Figure 4).

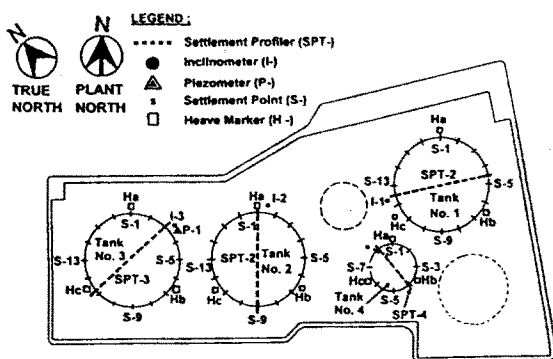


FIG. 1 Layout of Tanks and Instruments

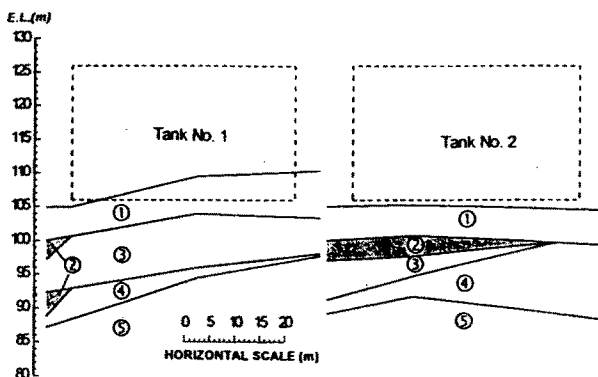


FIG. 2 Subsoil Condition at Tank Nos. 1 & 2

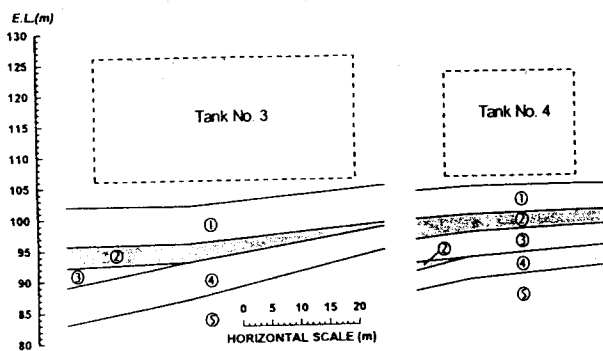


FIG. 3 Subsoil Condition at Tank Nos. 3 & 4

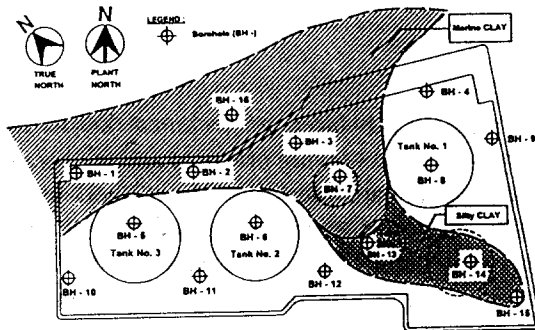


FIG. 4 Extent of Soft Marine Clay/Silty Clay

3 TANK FOUNDATION

3.1 Design Consideration

Generally speaking, foundation should be designed to provide an economical means of transmitting loadings from structures to the underlying soil stratum without causing soil failure or excessive settlement. For the present case, the feasibility of flexible foundation scheme was evaluated by detailed geotechnical analysis for economical design. Flexible foundation commonly adopted in tank design consists of a granular overburden layer or a compacted soil pad, or a combination of both. Tank load is spread through granular overburden layer to the underlying soil. For poor soils consisting of loose sand and marine clay as in the present case, instability and settlement of pad foundation are of major concern.

3.2 Bearing Capacity and Stability Analysis

Two modes of tank foundation failure have been observed in practice, namely, base shear and edge shear failures. Base shear involves failure of the entire tank acting as a unit, where edge shear involves local failure of a part of the tank perimeter and a contiguous portion of the base. Since the subsoil conditions of the site deviates greatly from the ideal uniform condition assumed in conventional bearing capacity theories, a more refined method proposed by Duncan & D'Orazio (1984) which takes into account the effects of the granular pad, the fill layer, the undrained shear strength variation with depth and the effect of

surcharge to the shear strength of granular fill was used in the bearing capacity analysis. Bishop's simplified method for circular failure mode was adopted in the checking of edge shear failure of tanks. The results of bearing capacity analysis of pad foundation scheme (Table 1) indicated that all 4 tanks possessed adequacy factor of safety against base shear failure except for possible edge failure within the localized soft clay zone found at Tank Nos. 2, 3 & 4 where slightly lower factor of safety values of 1.33 to 1.44 were obtained.

Table 1 Bearing Capacity of Shallow Tank Foundation

Tank No.	Tank Details		FOS (Duncan 1984)				
	D (m)	H (m)	Surcharge (kPa)		Base Shear Failure	Edge Shear Failure	
			Tank + Water	Pad		Major	Localized
1	44.9	20	200	16.5	3.25	1.66	-
2	44.9	20	200	16.5	2.95	1.67	1.33
3	44.9	20	200	16.5	2.64	1.66	1.44
4	22.5	16.9	169	16.5	2.45	1.78	1.38

Notes : D - tank diameter, H - tank height, FOS - factor of safety

3.3 Settlement Analysis

Steel storage tank is a type of flexible structure, which generally can withstand larger magnitudes of total and differential settlement than those acceptable for other types of structures. However, the following detrimental effects, which may be induced by the differential settlement of tank, shall be considered in the design.

- Differential settlement between opposite sides of the shell which may cause the shell to deform elliptically, therefore setting up excessive stresses in the shell.
- Differential settlement between two closely spaced points along the shell which may cause the shell to buckle.
- Large differential settlement between the shell and the tank bottom may cause the bottom to tear away from the shell.

Table 2 summarizes the results of settlement analysis for the 4 tanks resting on pad foundation.

It should be noted that the predicted settlement is

Table 2 Predicted Soil Settlement underneath Tank Pad

Tank No. & Location	Si, mm	Sc, mm	St, mm	ΔS, mm	Tolerable ΔS, mm (NAVFAC DM-7)	
Tank No. 1	C	63	55	118	49	180
	E	39	30	69		
Tank No. 2	C	136	72	208	90	180
	E	52	66	118		
Tank No. 3	C	83	75	158	72	180
	E	52	34	86		
Tank No. 4	C	161	119	280	124	90
	E	100	56	156		

Si : elastic settlement, Sc : consolidation settlement, St : total settlement, ΔS : differential settlement between edge (E) & centre (C),

Table 3 Types and Quantities of Instruments

Instrument Type	Tank No.			
	1	2	3	4
Inclinometer	1	1	1	1
Settlement Profiler	1	1	1	1
Piezometer	0	0	1	0
Settlement Point	16	16	16	8
Heave Points	9	9	9	9

Table 4 Deformation Indices specified by Tank Designer

Indices	Limits
Planar Tilt	1 : 200
Dish Type Settlement	1 : 90
Localized settlement	1 : 90
Out-of-Plan Settlement of Tank Perimeter	< 0.55%
Out-of-Plan Settlement of Tank Base	< 0.22%

based on average ground conditions and does not include deformation of the tank pad and lateral soil movement.

4 FOUNDATION IMPROVEMENT

In order to improve the performance of steel tanks against uneven settlement and edge shear failure, the following improvement measures were adopted.

- i) Slight shifting of the tank farm boundaries and tank positions to minimize detrimental effect attributed to the localized soft clay,
- ii) Recomposition of upper loose sand between EL102m and EL105m A.C.D.

5 HYDRO-TESTS AND MONITORING

5.1 General

In order to verify the foundation adequacy of the 4 steel tanks constructed on granular pad and to minimize the post construction settlement of tank to an acceptable limit, hydro-test was conducted on all the 4 tanks. The tank behavior was monitored by the installed instruments (Table 3) during the hydro-testing period in accordance with criteria given by the tank designer (Table 4).

5.2 Test Procedures and Control

- i) Water filling was carried out at the rate of 1m per day for Tank No. 3 and 2m per day for Tank Nos. 1, 2 & 4.
- ii) Water filling was terminated and held for 24 hrs for further observation under the following conditions :
 - Ground movements exceed 10mm per day
 - Differential settlement/distortion reaches 80% of allowable limits

- Obvious change in load-settlement profile
- If continuous increase in settlement were observed, the water surcharge shall be released by 1.5m and hold for 24 hrs for further observation.

5.3 Frequency of Monitoring

Instrument monitoring was carried out at the following frequency.

- i) Prior to commencement of test
- ii) At 25%, 50%, 75% & 100% water filling
- iii) At 50% & 100% water discharging

6 OBSERVED FOUNDATION BEHAVIOR

6.1 General Settlement and Base Deformation

Table 5 indicates the general performance of the 4 tanks during loading and unloading cycles of the hydro-testing. No significant ground heave was observed during the hydro-tests.

Table 5 General Performance of Tanks under Hydro-test

Test Load Water Level, m	Settlement recorded along Settlement Profiler, mm			Max. Lateral Displacement, mm	Change in Pore-water Pressure kPa	
	Edge Point B	Centre	Edge Point A			
Tank No. 1	5	**28 (5*)	28	21 (6)	1.4 @ 5m	N.A.
	10	33 (22)	35	22.5 (39)	4.6 @ 6m	
	15	33.5 (28)	44	33 (51)	12.4 @ 7.5m	
	20	50.5 (34)	69	63 (98)	37.1 @ 7m	
	10	52 (28)	72	66 (97)	41.5 @ 7m	
	0	49.5 (20)	70	60 (83)	38.5 @ 7m	
Tank No. 2	5	21 (8)	21	20 (41)	12.2 @ 5.5m	N.A.
	10	9 (10)	9	8 (73)	26.9 @ 5.5m	
	15	51.5 (20)	70	74.5 (110)	43.8 @ 5.5m	
	20	77 (27)	103	112 (159)	61.4 @ 6m	
	10	78 (28)	110	117 (167)	63.1 @ 6m	
	0	80.5 (10)	110	115 (148)	59.8 @ 6m	
Tank No. 3	5	36.5 (14)	28	31 (25)	10.9 @ 5.5m	19.6
	10	54.5 (32)	49	64.5 (85)	36.1 @ 6m	20.1
	15	63.5 (50)	82	108 (139)	62.2 @ 6m	12.2
	20	84.5 (72)	112	139.5 (188)	81.3 @ 6m	6.9
	10	87 (74)	115	141.5 (186)	82.0 @ 6m	-
	0	85 (67)	116	141.5 (182)	78.8 @ 6m	3.4
Tank No. 4	5	18 (36)	26	24 (33)	6.2 @ 4.5m	N.A.
	10	48 (77)	62	51 (68)	20.4 @ 4.5m	
	16.9	131.5 (166)	127	93 (138)	64.8 @ 4.5m	
	8	137.5 (174)	130	95 (135)	67.1 @ 4.5m	
	0	140 (172)	133	92.5 (134)	63.4 @ 4.5m	

Notes : * settlement point readings (i.e. shell settlement) including tank pad deformation,
 ** settlement profiler readings excluding tank pad deformation,
 Points A & B : tank shell positions right above settlement profiler as shown in Figure 5.

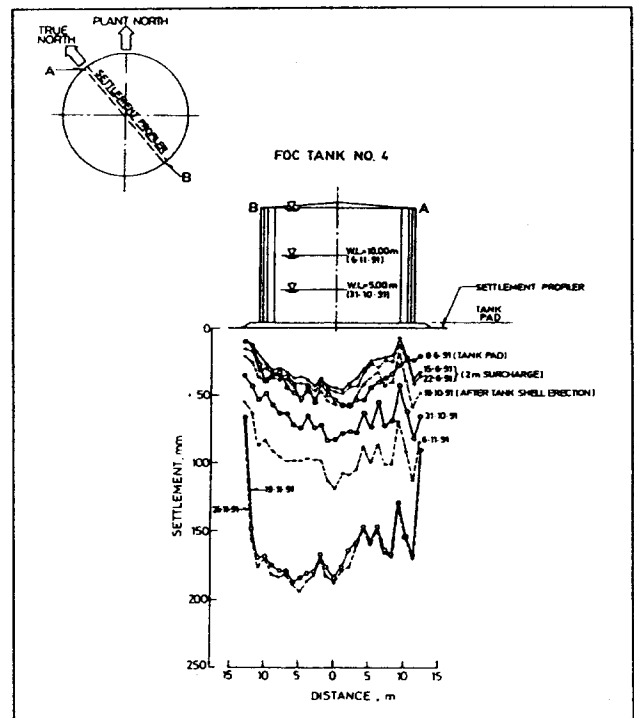
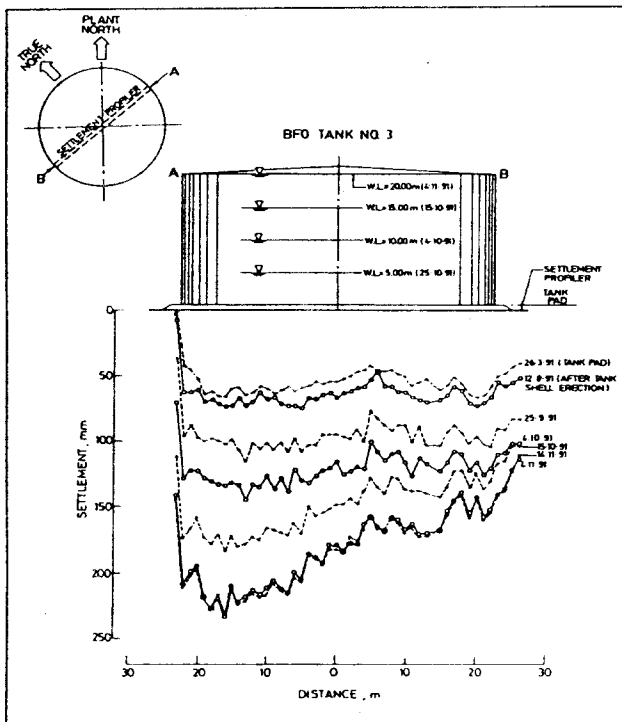
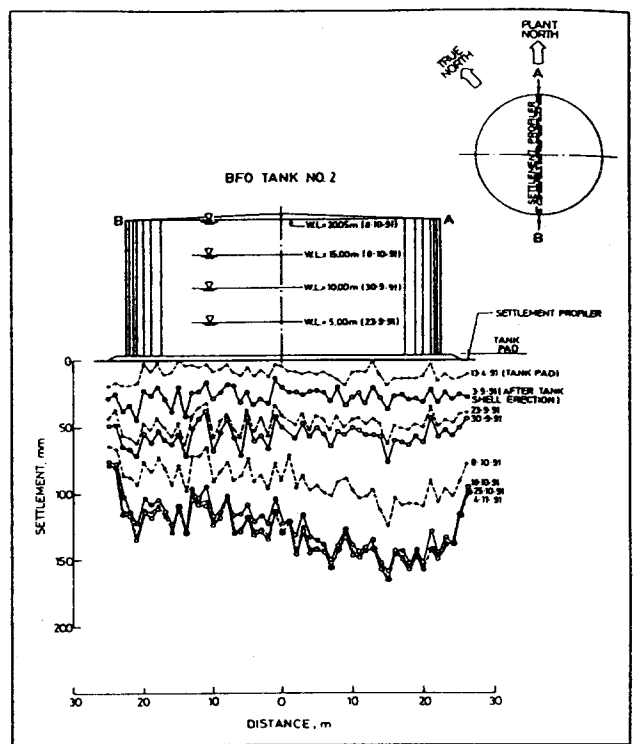
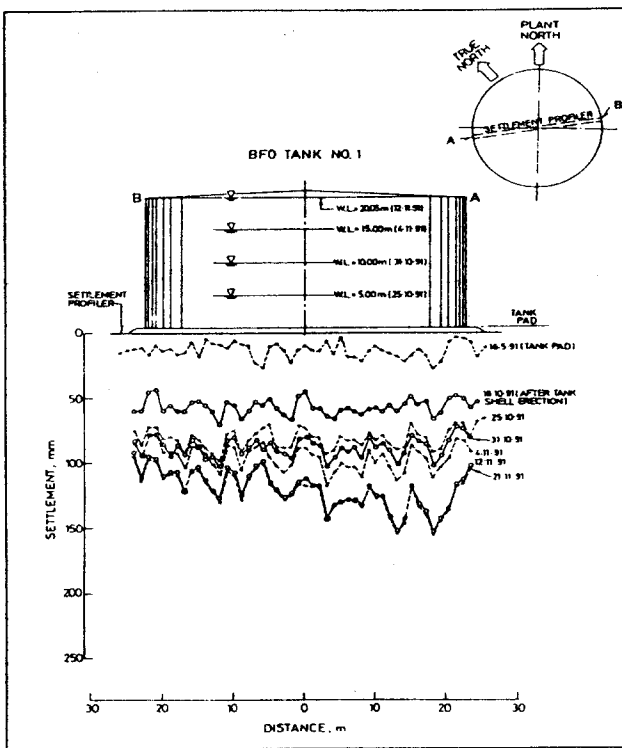


FIG. 5 Profiles of Soil Settlement beneath Tank Pad recorded by Settlement Profilers during Hydro-tests

6.2 Settlement and Base Deformation

Figure 5 shows the profiles of soil settlement beneath tank pad recorded by the settlement profilers during hydro-tests of Tank Nos. 1 to 4.

Figure 6 shows the plot of tank edge settlement versus time for Tank No. 3 during the hydro-test. The safety of the tank structures were closely monitored

and analyzed during hydro-testing and the deformation indices of all the 4 tanks as summarized in Table 6 were found within the permissible limits given by the Tank Designer. Figures 7 shows the settlement contours of tank base plates recorded after hydro-test.

6.3 Lateral Soil Displacement

Lateral displacement of subsoil under tank edge was monitored by using inclinometers installed in the

Table 6 Deformation Indices recorded in Hydrotest

Tank No.	Max. Planar Tilt, % (Limit=0.5%)	Max. Out-of-Plan Settlement of Tank Perimeter, % (Limit=0.55%)	Max. Out-of-Plan Settlement of Tank Base, % (Limit=0.22%)
1	0.16 (10m)	0.27 (10m)	0.18 (0m)
2	0.32 (15m)	0.37 (10m)	0.14 (0m)
3	0.36 (20m)	0.42 (10m)	0.12 (0m)
4	0.31 (16.9m)	0.37 (16.9m)	0.13 (0m)

Note : value shown in bracket denotes load water level

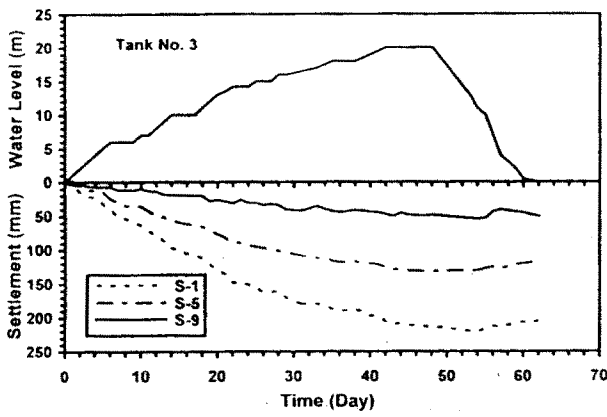


FIG. 6 Time-Settlement (Edge) Curves of Tank No. 3

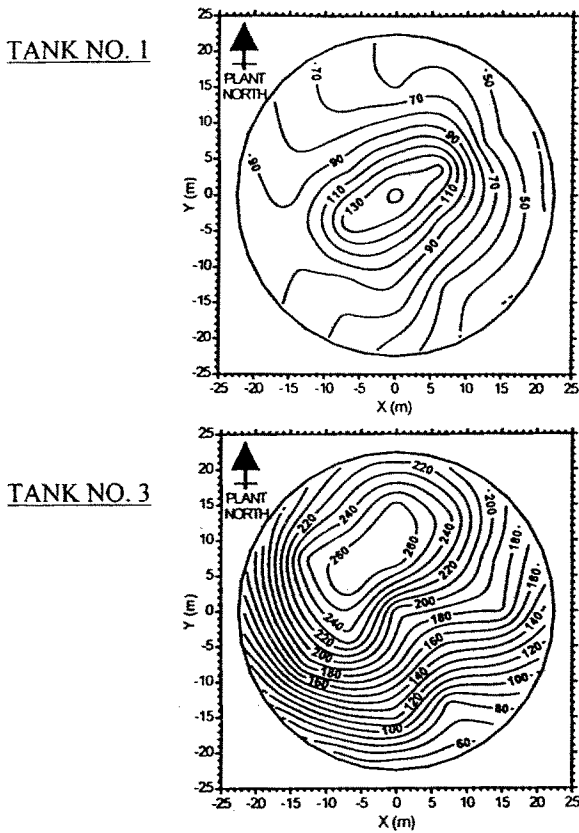


FIG. 7 Settlement Contours (in mm) of Tank Base Plate measured after Hydro-test

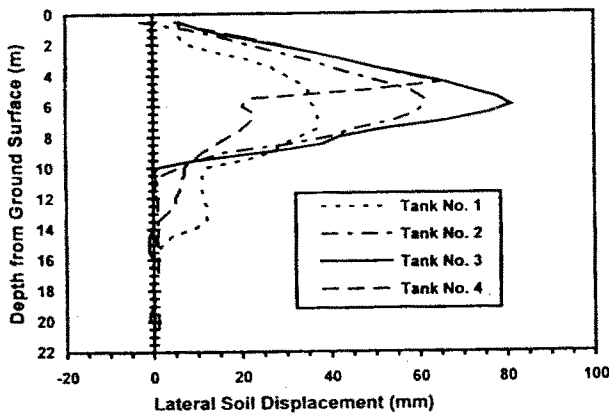


FIG. 8 Plots of Max. Lateral Soil Displacement Under Tank Edge

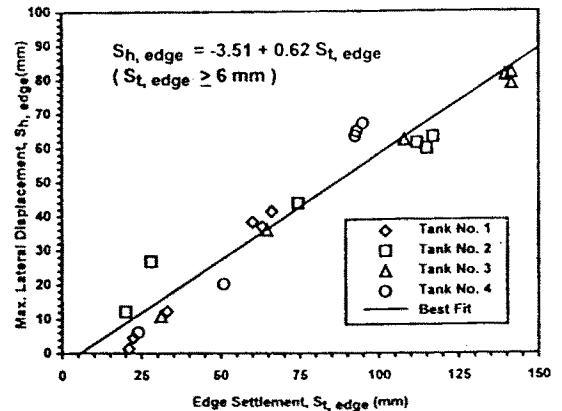


FIG. 9 Plot of Lateral Soil Displacement versus Tank Edge Settlement

soft clay zone during hydro-test as summarized in Table 5. Figure 8 shows the plots of maximum lateral displacement profiles of subsoil under edge of the 4 tanks recorded during hydro-test. Figure 9 shows the plot of lateral soil displacement versus soil settlement at tank edge. As indicated in Figure 9, the lateral displacement of subsoils at tank edge was found increasing linearly with increasing soil settlement recorded by the settlement profiler at position adjacent to the installed inclinometers.

7 FACTORS GOVERNING SETTLEMENT PROFILE SHAPE

As indicated in Figures 7 and 10, the classical dish-shaped settlement profile of flexible foundation over a deep compressible layer was not found for Tank Nos. 2 & 3 where existence of soft clay underneath tank pad and low factor of safety values against shear failure were found. The recorded shape of settlement profiles are found to be consistent with the study carried out by D'Orazio & Duncan (1987) that the shape of settlement profile becomes increasingly likely that the maximum settlement will occur off-centre, as the ratio of the effective tank diameter to the compressible layer (De/T) increases and the factor of safety decreases (Table 7).

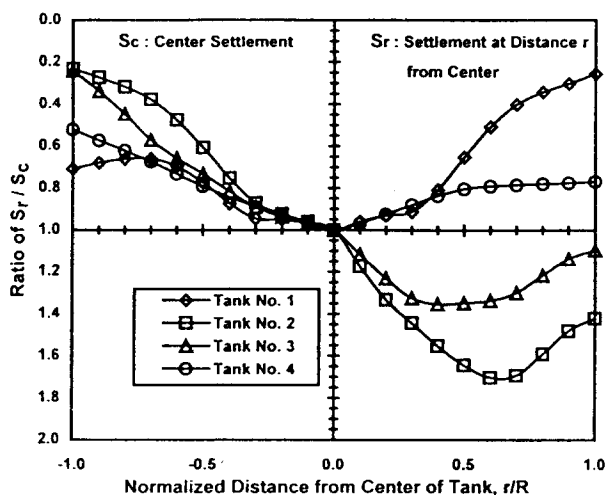


FIG. 10 Plots of Normalized Settlement Profiles of Tanks

Table 7 De/T and FOS Values of Tank Nos. 1 to 4

Tank No.	De/T	FOS
1	$T = 0$	1.66
2	18	1.33
3	16	1.44
4	10	1.38

8 CONCLUSIONS AND RECOMMENDATIONS

- 1) Construction of steel tank using pad foundation over complicated geological formation, such as reclaimed land underlying with erratic and weak subsoil as in the present case was found feasible under proper site investigation, detailed analysis, field construction control and monitoring of tank behavior during hydro-testing.
- 2) All the 4 steel tanks were successfully loaded to the full test load using water and the settlement rate, total settlement and deformation indices of tanks recorded during the hydro-test were found within the permissible limits.
- 3) Lateral displacement of subsoils at tank edge was found increasing linearly with increasing soil settlement recorded by the settlement profiler at position adjacent to the installed inclinometers. Further study is recommended to verify this observed behavior.
- 4) Analysis of settlement at tank edge should take into consideration of the effect of lateral soil displacement as observed in the present study.
- 5) Major components of vertical and lateral displacement of the subsoil under maximum test load remained unrecovered upon unloading. This behavior is presumed to be the result of densification of coral sand and consolidation and lateral deformation of soft clay.
- 6) The recorded shape of settlement profiles are found to be consistent with the study carried out by D'Orazio & Duncan (1987) that the shape of settlement profile becomes increasingly likely that the maximum settlement will occur off-centre, as the ratio of the effective tank diameter to the compressible layer (De/T) increases and the factor of safety decreases.
- 7) For the design of steel tank over complicated ground consisting of non-uniform soil layers, the effects of the granular pad, the fill layer, the undrained shear strength variation with depth and the effect of surcharge to the shear strength of granular fill (Duncan & D'Orazio 1984) should be considered in the bearing capacity analysis of tank foundation. Besides checking of soil bearing capacity against base and edge shear failures, the settlement of tank and the deformation of tank base should be carefully analyzed to avoid rupture failure of the tank structure.
- 8) The behavior of tank foundation during hydro-testing including the deformation indices of tanks should be closely monitored by suitable instrumentation system and properly analyzed during each stage of loading/unloading to ensure the structural safety of the cylindrical welded steel tank.

ACKNOWLEDGEMENT

The authors wish to thank Dr. Z. C. Moh for his review of the manuscript and valuable comments in the preparation of this paper.

REFERENCES

- Duncan J.M. & D'Orazio T.B. (1984). "Stability of steel oil storage tanks." *J. Geotech. Engrg. Div.*, ASCE, 110(9), 1219-1238.
- D'Orazio T.B. & Duncan J.M. (1987). "Differential settlements in steel tanks." *J. Geotech. Engrg. Div.*, ASCE, 113(9), 967-983.
- Public Works Department (1976), "Geology of the Republic of Singapore".