Improved Design Philosophy for the Structural System of Oil Storage Tanks

Un concept pour améliorer la structure porteuse des réservoirs à essence

Über verbesserte Entwurfsgrundlagen für das Tragsystem von Oeltanks

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1. Introduction

In December 1974, a large oil storage tank in a tank farm located in Western Japan collapsed due to cracks developed at the corner bottom plate. The collapse caused large amount of oil to flood into the sea, thereby giving serious damage to its biological environment. The accident urged re-examination of the safety of similar tanks. Under such circumstances, the authors' firm was asked to study and analyze the structural safety of large cylindrical tanks constructed on a deep reclaimed site in Yokohama City.

The investigation was aimed at: firstly, recommending measures to improve structural safety of tanks on the basis of fundamental considerations on them (Fig. 1) and comprehensive evaluation of the data obtained through the authors' observation of 18 emptied tanks which have sunk at a considerable degree; and secondly, analyzing static and dynamic behaviours of cylindrical oil tank constructed on deep, heterogeneous, loose soil easily subject to consolidation settlement, and establishing certain design criteria to be used as guidelines by the municipal authorities.

The present paper deals with comparative analyses of essential matters involved in "flexible-flexible" structures (Fig. 2) on a basis of the test findings and design improvement proposal derived from a series of analysis.

Fig. 1 Comparison of Present Modelling with Real Structure

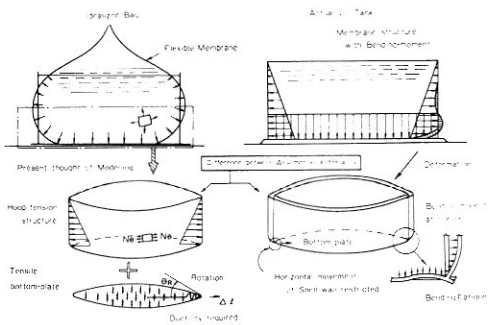
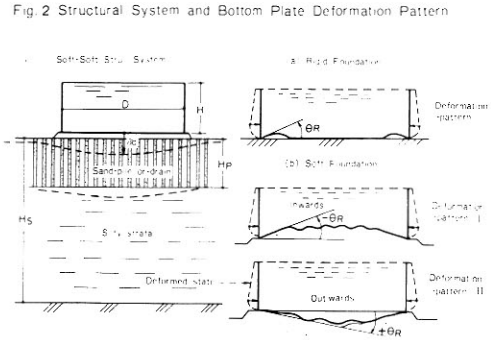


Fig. 2 Structural System and Bottom Plate Deformation Pattern



2. Behaviours of 18 Emptied Tanks

The tested tanks are grouped into three types, namely, 10,000 kℓ tanks (25 to 42 m diam. and 12 to 21 m high); 30,000 kℓ tanks (48 to 55 m diam. and 15 m high); and 63,000 kℓ (64 m diam. and 22 m high).

The tanks are underlain by the loose soil stratum of which volume compressibility coefficients (m_{vc}) range from 0.5 to 2 x 10^{-2} cm^2/kg in a depth of 20 to 50 m below grade. The soil is, in a range down to 7 to 23 m, stabilized by sand-drain method using 40 to 50 cm diam. pipes.

As compared with the levels recorded upon the completion of tanks, overall absolute settlements of tanks were 30 to 195 cm at circumferential places of the tank and differential settlements were 10 to 80 cm between the center and the edge. In some instances, mean residual deformation angles, overall settlements and differential settlements were in considerable agreement with those obtained from FEM analyses of a monolithic tank-soil model as shown in Table 1. By this, authors could have the confidence to proceed to detailed theoretical analysis.

The utmost emphasis in the checking was given to the corner at which shell and bottom plates are joined by fillet welding. As shown with statistical curves in Fig. 3 gained from processing measured data aquired at places of 2 m pitch along circumference of tanks, the plastic residual deformation angles of bottom plates at the corner due to the forced bending moment arising from filled or empty state of tank on plastically deformed supporting soil were found to be about two or three degrees on an average, though each measured value varied depending on the construction conditions. At some points where the underlying soil was very loose, an angle of as much as eight degrees was found.

Table 1 Tank-dimensions Measured and Theoretical values

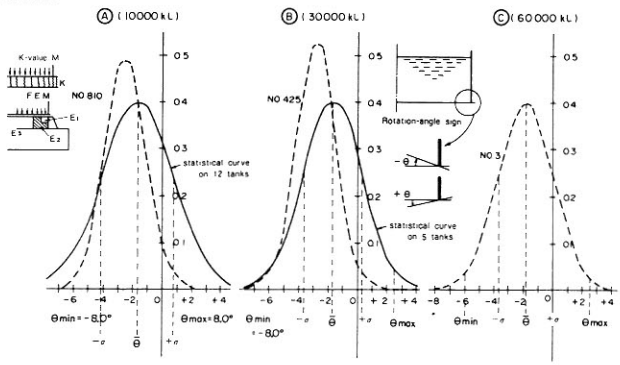
	D (m)	H (m)	Clay Depth (m)	Foundation	Fair Circum. Settlement (cm)	+θ (*)	Settlement (cm)
A 10,000kL	25.00 ~ 42.53	12.20 ~ 21.00	8 ~ 48	Sand-pile and drain	65 ~ 140	−1.74°	12
B 30,000kL	48.45 ~ 54.26	15.28	21 ~ 46	Pre-loading and Sand-drain	60 ~ 195	−1.73°	5
C 63,900kL	63.90	21.90	40	Vibro flotation	180	−1.86°	1

* : from measured values

(Theory —corner rotation angle)

Soil condition Method	By FEM			By K – value Method		
	CASE 1	CASE 2	CASE 3	K0 kg/cm³	K10 kg/cm³	K1 kg/cm³
A (NO 24)	0.39°	1.00°	1.49°	0.85°	0.97°	1.02°
C (NO 3)	2.04°	2.50°	2.85°	2.11°	2.37°	2.53°

Fig. 3 Statistical Distribution of Rotated Angle



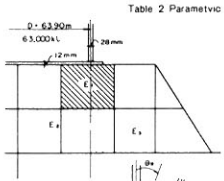
3. Theoretical Analyses of Tanks Constructed on Loose Soil

The tanks now under consideration are a kind of membrane structures subject to bending constraints at the shell-to-bottom joint. In addition, the tanks stand on loose soil whose properties remain unclarified by a quantitative analysis. Thus, it is theoretically difficult to make an accurate model that can properly represent these structures. For the purpose of present study, however, an attempt was made which could enable FEM-parametric

studies to be applied, regarding the tank and the soil as single structural body. As an important step, equivalent Young's moduli of soil easily subject to consolidation settlement were determined on the basis of a presumption that δ-ϵ curve properties of them could be regarded as a pseudo-elastic body.

By applying FEM to the semi-infinite elastic solid constituted by thick layers of loose soil with circular pressure loaded upon the surface, displacement and pressure distribution in the soil, and particularly the range of concentrated stresses in the soil located directly below the tank shell were obtained. Then, based on the stress-concentrated area thus determined, elasto-plastic transitional range for the tank and soil was established in a number of stages, and a local area at the shell-bottom junction was taken out and given parametric studies to see the behaviours in the plastic range as a single structural body. Thus obtained are parametric chaning conditions of bending deformation and stresses in the bottom plate at the junction and in the soil as illustrated in Table 2.

Table 2 Parametvic Analysis Results by FEM with Corner Portion



Combination of Youngs Modulus of Soil unit (kg/cm²)

	E1	E2	E3
CASE 1	130	130	130
CASE 2	13	65	130
CASE 3	3	13	65

Mechanical State of Corner Botm Plate

	σ_R (t/cm²)	δ_V (mm)	P_R (kg/cm²)	θ_R (°)
CASE 1	5.75 (-4.46)	9.60	42.0	2.04
CASE 2	2.14 (-10.67)	11.5	13.2	2.50
CASE 3	1.00 (-13.26)	14.6	6.1	2.85

Thereafter, in order to assist in considerations about detail improvements and formulation of practical calculation method, chaning conditions of the bending moments and deformation of the junction were ascertained by giving parametric changes to tank-supporting soil spring while making reference to soil's subgrade reaction coefficients as found experimentally in the existing compacted soil foundation as shown in Table 3.

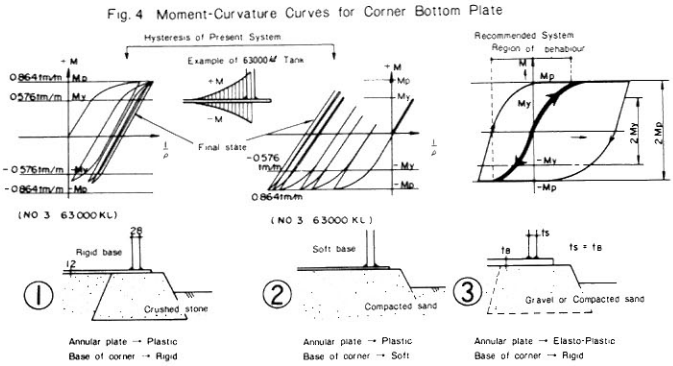
Table 3 Mechanical State Values on Improved Corner Details

		K = 1000 kg/cm³	K = 100	K = 10	K = 1
Improved 1	δ_V (mm)	0.435 (0.755)	1.75 (1.95)	5.7 (5.71)	27.3 (30.4)
	P_R (kg/cm²)	43.50 (75.50)	17.50 (19.50)	5.70 (5.71)	2.73 (3.04)
	M_R (t·m/m)	3.25 (2.06)	3.51 (1.30)	3.09 (0.80)	2.93 (0.48)
	σ_R (t/cm²)	2.53 (8.66)	2.74 (5.50)	2.40 (3.40)	2.28 (2.07)
Improved 2	δ_V (mm)	0.62	2.10	7.51	44.7
	P_R (kg/cm²)	62.40	21.00	7.51	4.47
	M_R (t·m/m)	3.75	3.22	2.62	1.82
	σ_R (t/cm²)	2.91	2.48	1.71	0.97

Tank Scale 63,000 kL D = 63.90 m H = 21.90 m

Inferred from these analytical results, three types of hysteresis loop on bending moment to curvature corresponding to the kind of combination of the mechanical state of corner bottom plate with the degree of deformation characteristics of its foundation are thought to exist as illustrated in Fig. 4.

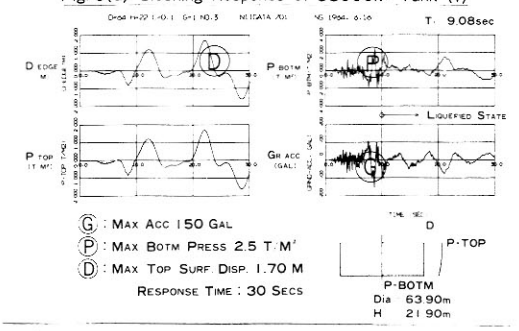
Fig. 4 Moment-Curvature Curves for Corner Bottom Plate



From various considerations on them the type ③ may be said much more better and safer even for bending fatigue in reference to fracture mechanics.

In order to see dynamic behaviours of the assumed tank-soil structure during earthquakes, response analyses of liquid contained in a rigid cylinder were made using ground surface waves in which long natural components are predominant as measured for reclaimed loose land and a few kinds of other ordinary strong waves. Fig. 5(a) shows a typical liquid response to the Niigata Earthquake-wave in 1964 which has the characteristic of transfer to long period of wave from usual earthquake pattern after occurrence of soil liquefaction, representing the overflow type due to large liquid-surface displacement with the value of 1.7 m shown by sign (D). Fig. 5(b) shows a typical response to the severe Kwanto Earthquake-wave on Sept. 1, 1923 restored by Prof. N. Nasu which has the maximum acceleration of 390 gals in the usual strong earthquake pattern, making characteristic of occurrence of very high pressure to shell-wall and bottom plate with the value of 0.8 Kg/cm^2 shown by sign (P) which forms an important condition for check against the fracture of corner bottom plate at any strong earthquake. With these response analyses the conditions of liquid agitation, the acting pressure distribution on tanks and the deformation of liquid were obtained.

Fig. 5(a) Sloshing Response of 63000kℓ Tank (1)



Taking into considerations of the above sloshing effects and using the distribution pattern of active pressure calculated by the seismic coefficient of 0.3 prescribed simply in Japan, asymmetrical aspects of horizontal force acting on the assumed tank-soil structure were elucidated by FEM. From these results, it was found that compressive force, bending moment and special deformation at the tank lower end would possibly cause buckling of the shell plate as shown in Fig. 6.

Fig. 5(b) Sloshing Response of 63000kℓ Tank (2)

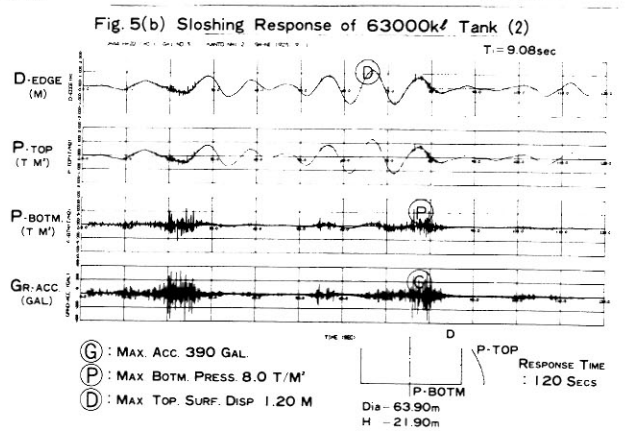
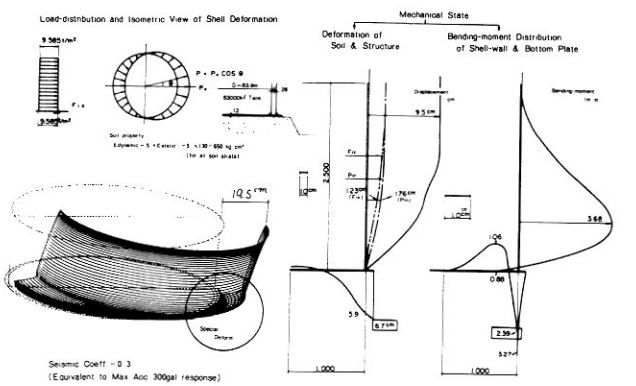


Fig. 6 FEM Analysis on Shell-Soil Str. System for Horizontal Pressure



On the other hand, basic dynamic analyses by both frequency-analysis-method and earthquake response of tanks were conducted on the rocking and sway motions, regarding the tank as a rigid body supported by vertical and horizontal springs, and sinking of the shell into the foundation in various cases was measured as shown in Fig. 7. The results calculated on the

level of response to earthquake acceleration of 300 gals show that such sinking generally resembles one caused by asymmetrical horizontal force; therefore, large sinking thus caused was considered to lead to large deformation and in some worse cases failure or fracture of the bottom plate.

4. Improvement in Design

From the foregoing analyses, the following were considered a prime consideration in improving the structural safety of large oil tanks constructed on reclaimed land consisting of deep, loose soil in view of preventing dreadful pollution or danger inevitably accompanying huge compensation.

(1) Compaction methods for loose silt layers should be improved to ensure more effective and economical compaction than is now available. In design practice, the initial consolidation settlement should be standardized and compiled with at higher values than are now commonly adopted as shown in Fig. 8.

(2) As for the foundation, appropriate detail design should be adopted that will gradually change and decrease, in a number of stages, the equivalent Young's modulus especially for a certain depth and width of foundation located directly below the shell as illustrated in Fig. 9 and 10.

(3) In combination with such foundation detail, appropriate detail design in shape and weld should be adopted that will ensure the mechanical safety of shell-to-bottom junction against repetitive stresses and fatigue failure as illustrated in Fig. 9 and 10.

(4) To prevent earthquake damage, appropriate countermeasures should be devised against the liquefaction failure of the ground and the failure of parts of foundation on which the shell-bottom junction is located as illustrated in Fig. 9 and 10.

Fig. 7 Diagram of Vertical Displacement of Corner Portion at Earthquake State

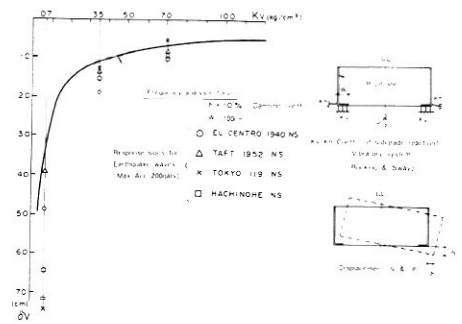


Fig. 8 Recommended Degree of Preliminary Consolidation

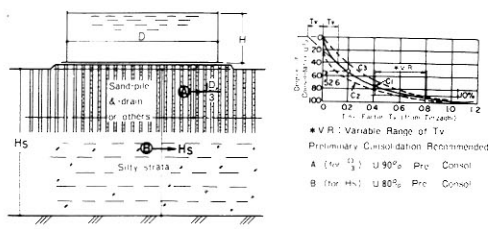


Fig. 9 Example of Improved Detail(1) around the Corner Portion

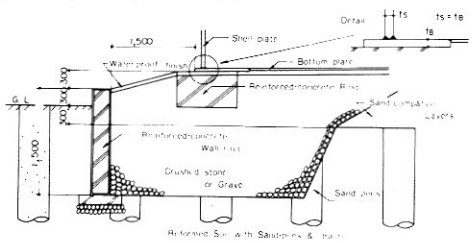
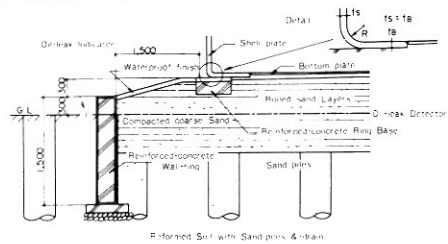


Fig. 10 Example of Improved Detail (2) around the Corner Portion



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SUMMARY

A large tank built on a deep and clayish soil should be a complete flexible-flexible structural system of a pure membrane structure and a soft soil. However, the tank designed by the current standards has unavoidable bending constraints at its corners. The authors have investigated eighteen large tanks, and have compared these with static and dynamic analyses of their flexible-flexible structural system. They propose a concept for improving the design of the tank-soil structural system.

RESUME

Un grand réservoir bâti sur un terrain argileux devrait être un système structural flexible composé d'une membrane et d'une terre molle. Cependant, les réservoirs construits selon les normes courantes présentent inévitablement des contraintes de flexion aux coins. Les auteurs ont fait des mesures sur dix-huit grands réservoirs et ont comparé celles-ci avec les calculs statiques et dynamiques de leur système structural flexible. Ils proposent un concept pour améliorer le projet du système structural réservoir-terre.

ZUSAMMENFASSUNG

Ein auf Tonboden gebauter Oeltank sollte ein flexibles Tragsystem aus einer Membrane und einem weichen Boden darstellen. Der nach den gewöhnlichen Normen gebaute Tank wird aber unvermeidlich Biegespannungen in den Ecken aufweisen. Von den Verfassern wurde die Nachprüfung von achtzehn Behältern durchgeführt, und mit statischen als auch dynamischen, numerischen Untersuchungen verglichen. Verbesserte Entwurfsgrundlagen werden für das Tragwerksystem Tank-Boden vorgeschlagen.