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Design and Construction of Prestressed Concrete Egg-Shaped Digestion Tanks

Projet et exécution de réservoirs ovoïdes en béton précontraint

Entwurf und Bau von eiförmigen Faulbehältern aus vorgespanntem Beton

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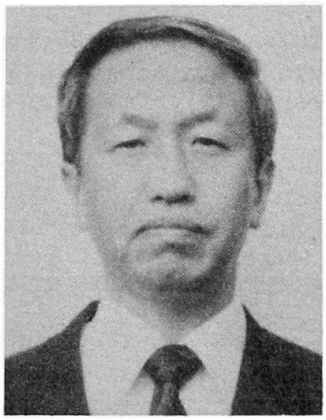

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SUMMARY

This report describes the design and construction of the first egg-shaped digestion tanks constructed in Japan, a country well-known for its earthquakes, especially from the aseismic viewpoint.

RÉSUMÉ

Le rapport décrit le projet et l'exécution des premiers réservoirs ovoïdes pour l'épuration des boues, réalisés au Japon. L'étude tient particulièrement compte des conditions sismiques régnant au Japon.

ZUSAMMENFASSUNG

Der Beitrag beschreibt den Entwurf und Bau der ersten eiförmigen Faulbehälter in Japan. Insbesondere wird der erdbebensichere Aspekt behandelt in einem Land, das für seine Erdbeben bekannt ist.

1. INTRODUCTION

Yokohama City is located about 30 km south of Tokyo and is the second largest city in Japan with a population of 3.16 million.

The city area of 43,000 ha is divided into nine sewage treatment districts. Sewage generated in the city is treated by 11 sewage treatment plants. To treat sludge from these plants efficiently, a plan is underway to convey the sludge to two sludge treatment centers, located in the coastal area for centralized treatment. In 1983 at the North Sludge Treatment Center, the construction of PC (prestressed concrete) egg-shaped digestion tanks was started. In 1987, 12 tanks (6,800 m^3 each) were completed (Fig. 1).

The PC egg-shaped digestion tanks feature a shell structure. Many such tanks have been constructed in Europe, primarily West Germany, because of the highly efficient sewage sludge digestion and ease of maintenance. However, earthquakes seldom occur in these regions.

This report describes the first design and construction of PC egg-shaped digestion tanks in Japan, a country well-known worldwide for its earthquakes, especially from the aseismic viewpoint.

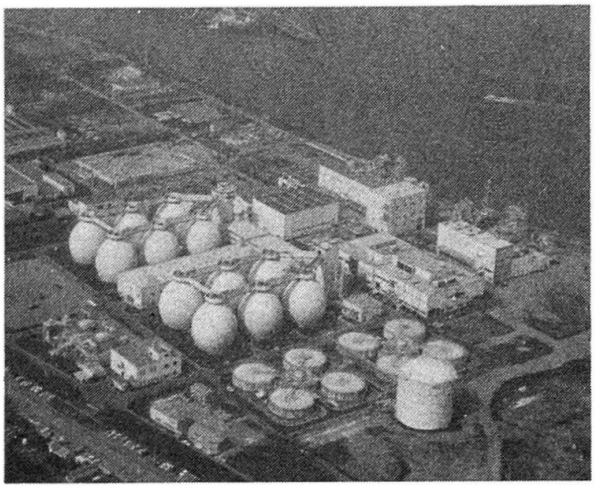


Photo 1 General View of North Sludge Treatment Center

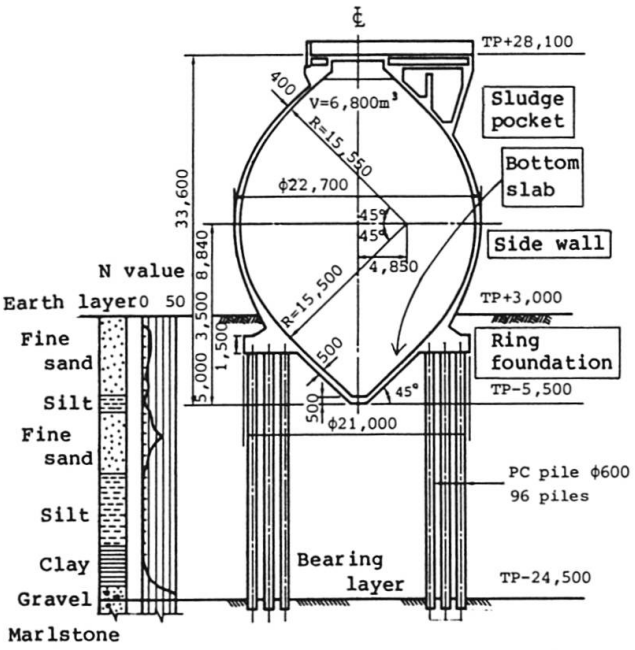


Fig. 1 Tank Structure and Ground Condition (Unit: mm)

2. OUTLINE OF THE STRUCTURAL DESIGN

2.1 Basic Structure

Steel, RC (reinforced concrete), and PC are suitable for structural members of egg-shaped digestion tanks. PC is used for the 12 tanks of North Sludge Treatment Center by the reason of resistance to corrosion, watertightness, airtightness, and maintenance, etc.

A spread foundation which merely buries the lower part of the tank is usually the most effective since it does not lose the excellent features of the shell structure. However, in an earthquake country like Japan, it is necessary to ensure tank stability during earthquakes. Moreover, since the construction site is reclaimed land along the Tokyo Bay, so the foundation ground is weak

and the bearing layer is 27.5 m below the ground surface. A pile foundation system which supports the tanks by PC piles made of high-strength concrete through the ring foundation was therefore selected.

2.2 Design Procedure

The allowable stress design method was used for the designing these tanks. The structural analysis of these tanks was performed using the finite element method in order to analyze the tank's side wall and bottom slab and the massive ring foundation. The tank was designed by the seismic coefficient method and checked by dynamic analysis. Ambient vibration was also measured after completion of the tank to confirm the dynamic analysis results.

The design flow is shown in Fig. 2.

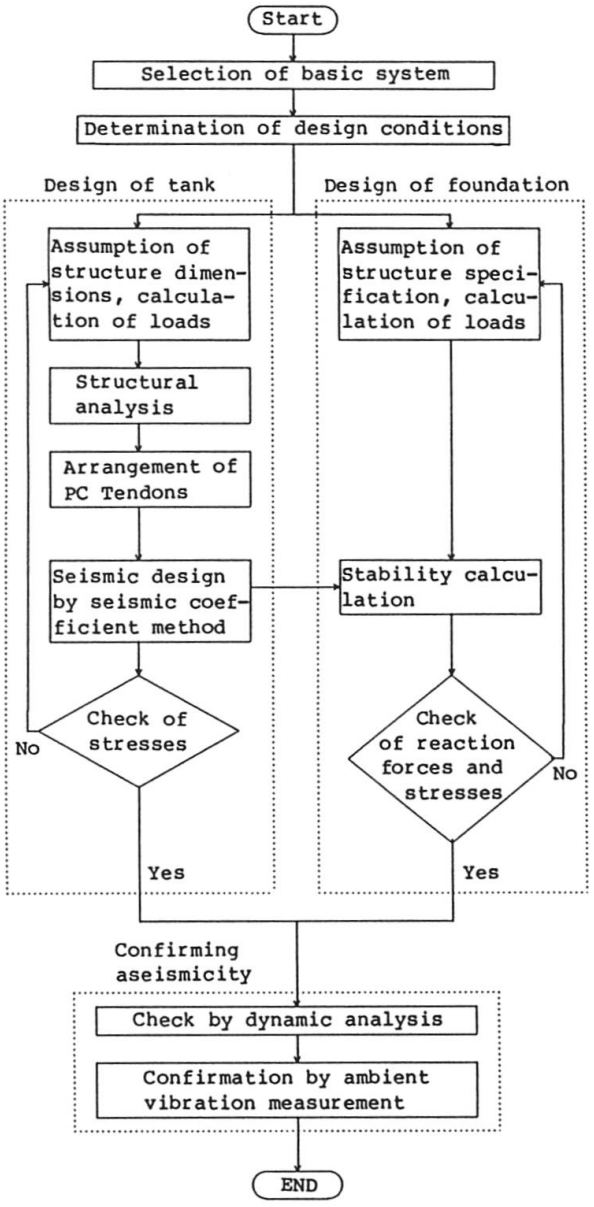


Fig. 2 Design Flow of PC egg-shaped digestion Tank

2.3 Material Properties and Design Loads

The specifications for materials used for these tanks are shown in Table 1. Loads, combinations of loads, and allowable stress increasing factors considered in design are shown in Table 2. Since sludge in the tank is constantly maintained at 35 degrees centigrade, the difference of temperature between tank and atmosphire is considered to be the principal load.

The horizontal seismic coefficient Kh used for the seismic coefficient method is 0.2. It was determined from the area and ground where tanks are located, the importance of structures, and past earthquakes.

2.4 Structural Analysis

The structural analysis of the side wall and bottom slab is based on the finite element analysis program for axisymmetric shells. The massive ring foundation was modeled by solid elements and analyzed together with shell elements. Fig. 3 shows the analysis model used. Piles are evaluated as springs bearing the bottom of the ring foundation. The vertical bearing force of the ground is not included in the analysis model since it is extremely small and can be neglected. The whole section of concrete is considered to be effective for evaluating the rigidity of members. Young's modulus Ec is 3.5×10^5 kgf/cm^2, and Poisson's ratio ν is 1/6.

Using the analysis model above, all loads except prestress were analyzed as shown in Table 2. The analyzed results corresponding to the loads included in a load combination were summed up to estimate the sectional forces. The arrangement and introduced force of PC tendons were determined based on the result above.

An example of the sectional forces when the tanks are filled with liquid is shown in Fig. 4. It can be seen that the side wall and bottom slab are under axial compression stress in both circumferential and meridian directions.

2.5 Arrangement of PC Tendons

The forces introduced by PC tendons in the side wall and bottom slab are calculated so that they are subject to the overall sectional compression stress under the full liquid condition. The resultant PC tendon arrangement is shown in Fig. 5.

Table 1 Material Specifications

Material	Specification
Concrete	$\sigma ck = 400\ kgf/cm^2$ *
PC tendon	Prestressing strand SWPR7B 9- ϕ 15.2 mm (Cable comprising 9 PC strands ϕ 15.2 mm, specified tensile strength 19 kgf/mm^2)
	Prestressing bar SBPR 95/120 ϕ 32 mm (Yield strength 95 kgf/mm^2, specified tensile strength 120 kgf/mm^2)
Reinforcing bar	Deformed bar SD35 (yield strength 35 kgf/mm^2)

*: Specified strength based on the 28-day strength of cylindrical test piece; ϕ = 100 mm; h = 200 mm

Table 2 Loads, Combination of Loads, and Allowable Stress Increasing Factors

Load condition / Kind of load		Operation			Earthquake			Remarks
		Full liquid		Empty	Full liquid		Empty	
		Winter	Summer		Winter	Summer		
Dead load		o	o	o	o	o	o	Including top accessories, insulation material, and inner equipment
Hydraulic pressure		o	o		o	o		
Digester gas pressure		o	o		o	o		0.4 tf/m^2
Prestress		o	o	o	o	o	o	
Temperature	Winter	o			o			External temperature 0°C
	Summer		o			o		External temperature 30°C
Buoyancy		o	o	o	o	o	o	
Influence of earthquake					o	o	o	Kh = 0.2 Kv = 0
Allowable stress increasing factors		1.0	1.0	1.0	1.5	1.5	1.5	

Notes . Influence of wind is excluded because it is smaller than that of earthquake.

. Influence of temperature is determined using the temperature difference considering the effect of insulation material around the outer face of tank body.

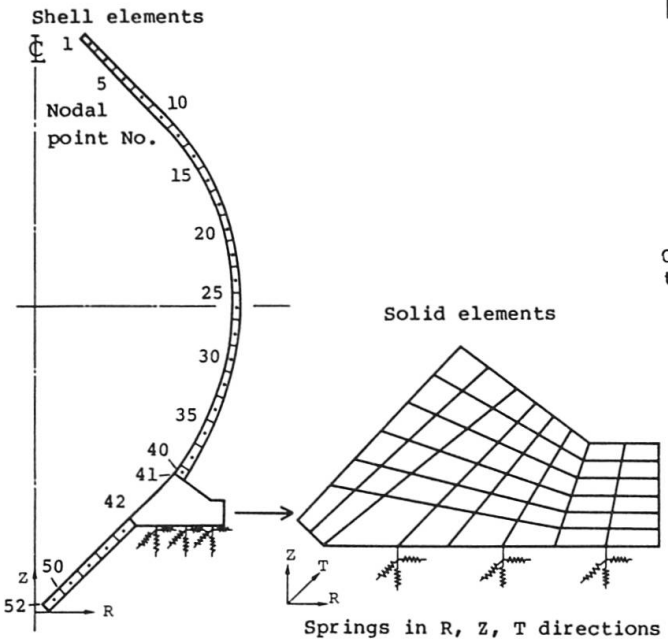


Fig. 3 Analysis Model

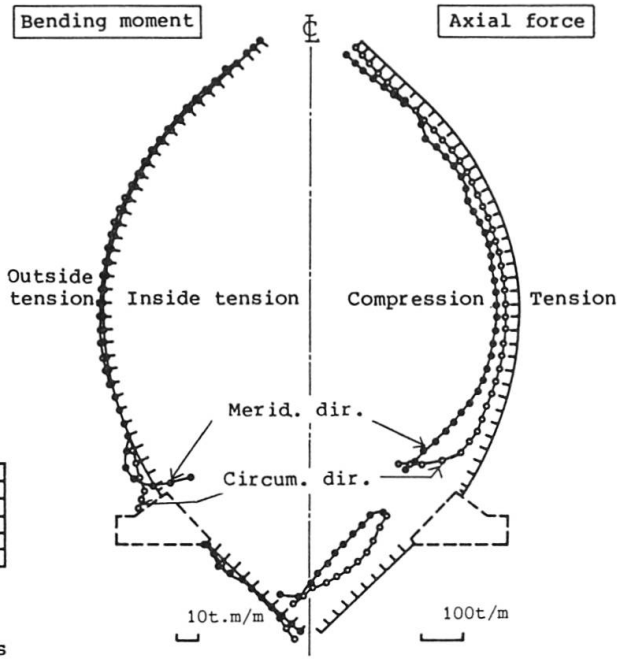


Fig. 4 Sectional Forces under Full Liquid Condition (Winter)

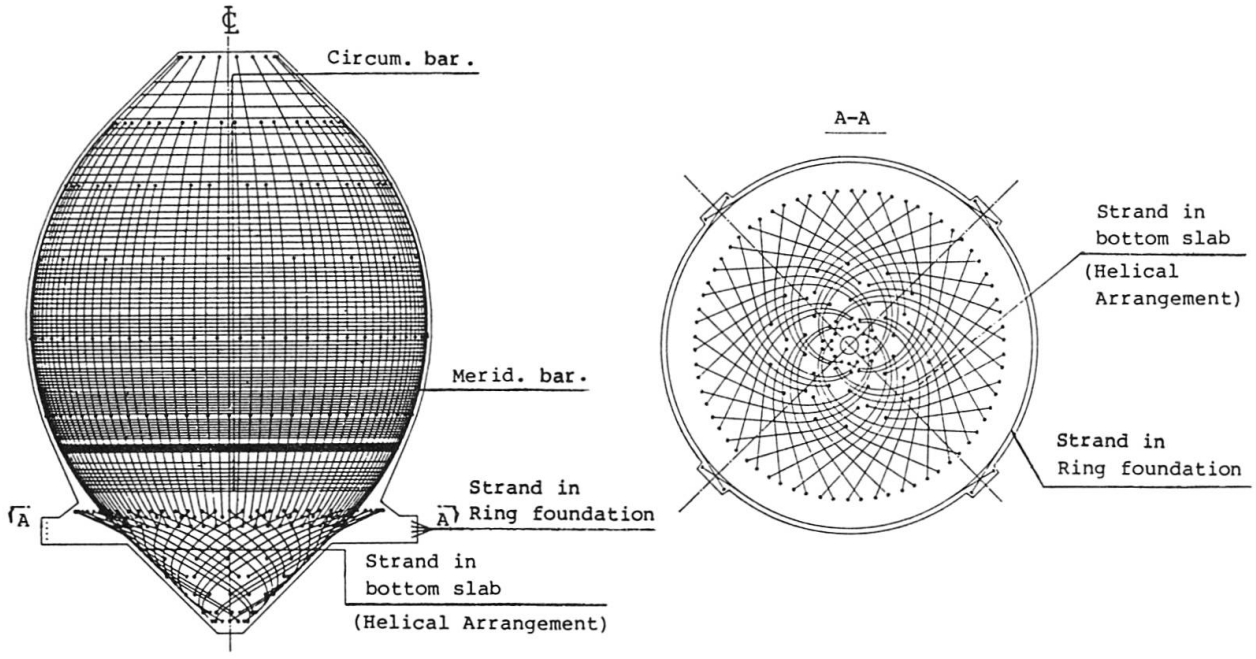


Fig. 5 PC Tendons Arrangement

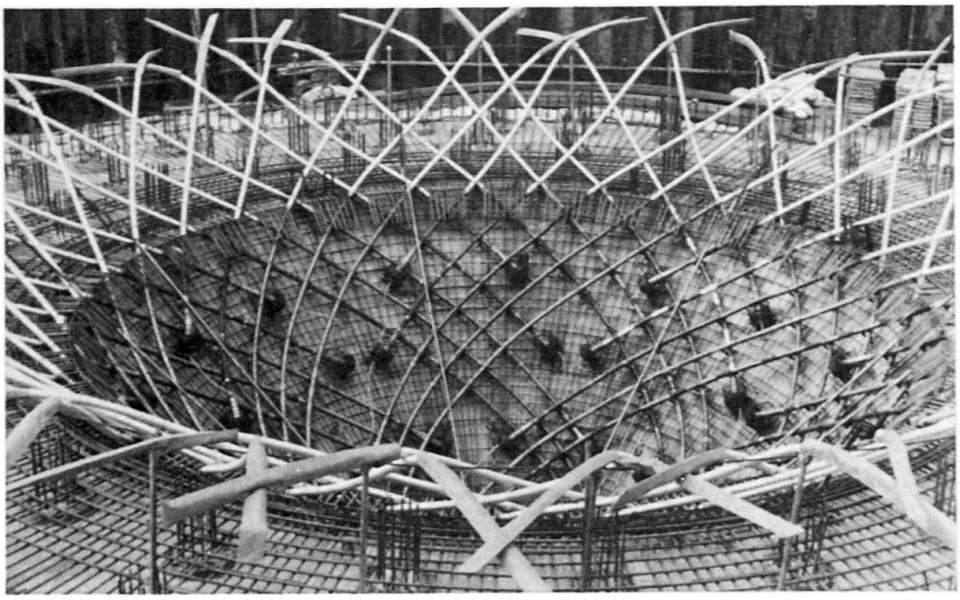


Photo 2 Bottom Slab PC Tendon Arrangement
(Helical arrangement)

2.5.1 Bottom Slab

The ground of the construction site is weak, so the bottom slab cone is designed as a PC member supported by a ring foundation, without expecting the bearing force. The hydraulic pressure causes tensile stresses in both circumferential and meridian directions in the bottom slab. Prestress must be introduced to cancel these tensile stresses. Since the slab portion is underground, it is difficult to position the anchorage of tendons outside the tank body as in the ordinary arrangement of circumferential PC tendons.

A helical arrangement of PC tendons was therefore developed for this design. This arrangement makes it possible to effectively introduce prestress simultaneously in both circumferential and meridian directions.

2.5.2 Ring Foundation

The ring foundation transmits loads from the tank body to piles and is designed as RC structure. However, prestress is introduced in the circumferential direction around the outer periphery of the ring foundation for the following reasons:

(1) The PC tendons anchorages of the bottom slab and the PC tendons anchorages in the meridian direction of the side wall are concentrated in the ring foundation. The ring foundation therefore requires strength.

(2) The side wall and bottom slab are rigidly connected to the ring foundation, and the hydraulic pressure causes local stresses. It is thus necessary to reduce such stresses by prestressing in the ring foundation.

2.5.3 Side Wall

The side wall is a shell structure having curved planes in two directions, so PC tendons are arranged in both circumferential and meridian directions to cancel the tensile force due to hydraulic pressure.

(1) PC tendons in circumferential direction

PC tendons are anchored in the circumferential direction by pilasters in ordinary cylindrical tanks. However, in the PC egg-shaped tanks, use of pilasters impairs the features of the thin-walled shell structure and is undesirable from the viewpoint of local stress, appearance, and installation of the insulator. Therefore, a method of anchoring PC tendons in small recesses of side wall members is adopted for this design, and prestressing bars are adopted as PC tendons to make such recesses small.

(2) PC tendons in meridian direction

Since the side wall is to be constructed by the ring segmental method, prestressing bars which can be freely coupled with little anchoring loss are adopted.

3. EXAMINATION OF RESISTANCE TO EARTHQUAKES

In Japan, seismic design of cylindrical PC tanks is generally performed by the seismic coefficient method.

Though the PC egg-shaped digestion tank has unique shape, it is basically a rigid tank made of PC. We thus assume that the seismic design can be considered similarly to the conventional cylindrical PC tank. Therefore, the seismic coefficient method is adopted for this tank, and the basic structure is studied and the members are designed accordingly. A seismic response analysis was performed by means of the finite element method, considering the interaction of the tank itself, contained liquid and the ground including piles. Ambient vibration measurement of the completed tank were also carried out. Resistance to earthquakes was thus examined by both analysis values and measured values. The flow of above examination is shown in Fig. 6.

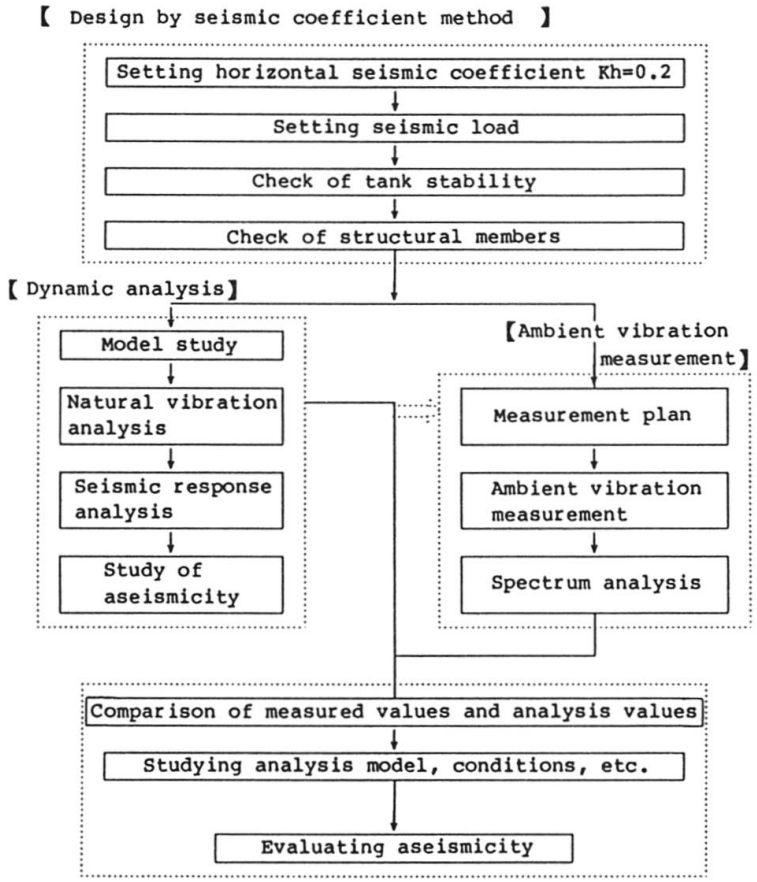


Fig. 6 The Flow of the Resistance to Earthquakes Examination

3.1 Design by Seismic Coefficient method

In the seismic coefficient method, seismic force is determined by multiplying the weight at each element of a structure by the seismic coefficient. The members are designed by applying the seismic force statically to the structure. In this case, earthquake loads shown in Table 2 are inertia force due to dead load and hydrodynamic pressure due to contained liquid.

3.1.1 Concept of Hydrodynamic pressure

As a equation for computing the design hydrodynamic pressure for the cylindrical tank, Housner's equation is generally used. But such a equation is not available for the egg-shaped tank.

To study the size and distribution of the hydrodynamic pressure, the seismic response analysis is performed using the axisymmetric finite element method, with the interaction between the tank body and the contained liquid considered. For this analysis, the contained liquid is assumed to behave in accordance with the velocity potential theory. The EL. CENTRO earthquake wave (NS, 1940) whose maximum acceleration was modified to 200 gal, was applied to the bottom of the ring foundation for 10 sec.

The distribution of the maximum hydrodynamic pressure was found to correspond favorable with the statically calculated distribution, assuming the contained liquid as fixed mass, shown in Fig. 7. The design should therefore be sufficiently accurate even when the hydrodynamic pressure is calculated statically as mentioned above.

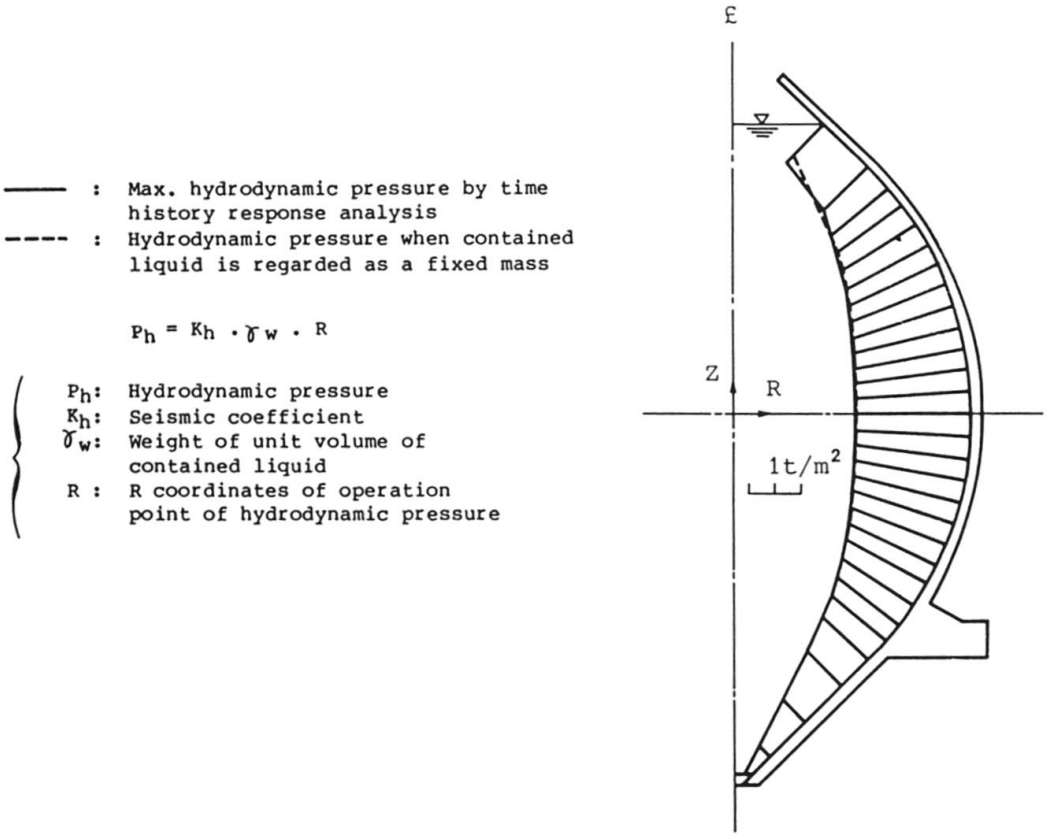


Fig. 7 Comparison of Hydrodynamic Pressure

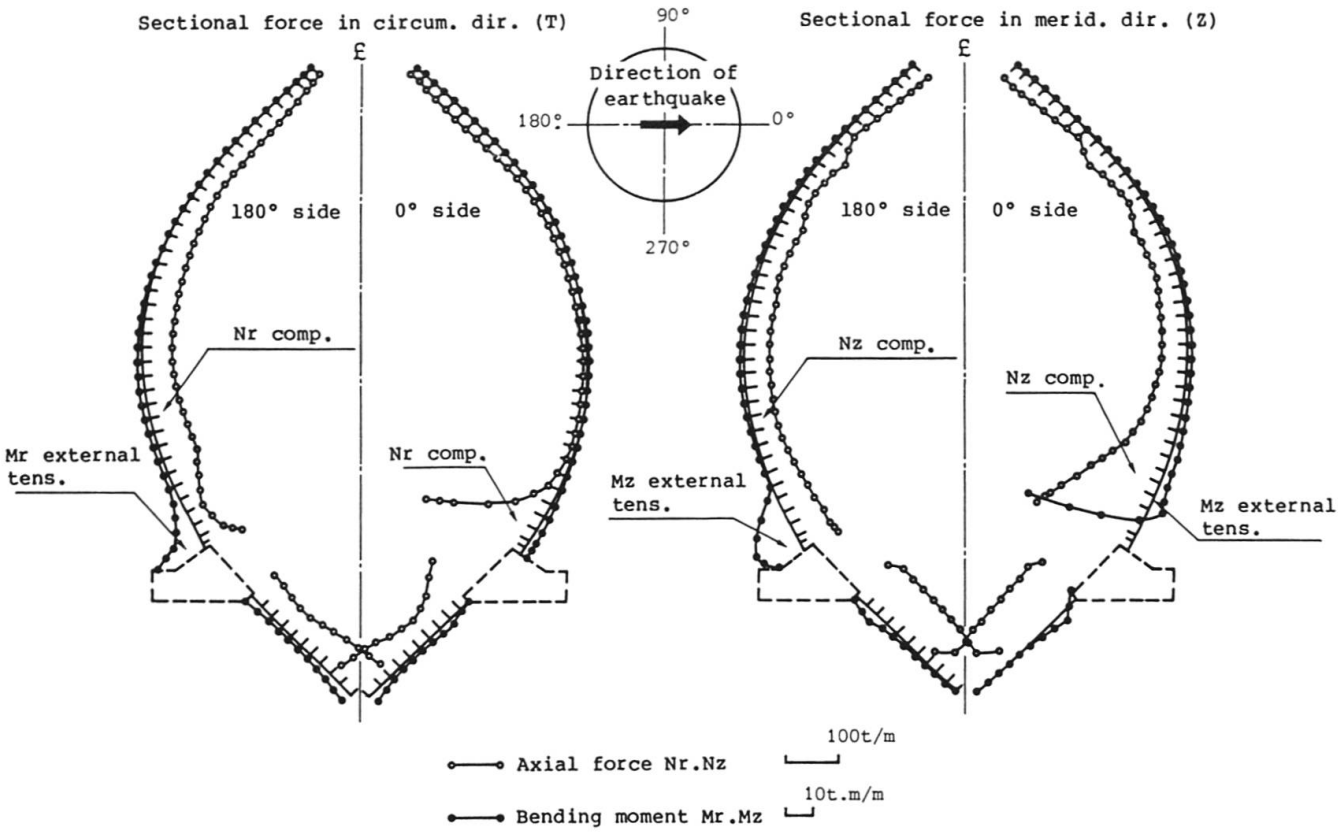


Fig. 8 Sectional Force under Full Liquid Condition during Earthquake (Winter)

3.1.2 Tank Resistance to Earthquakes

The tank is made resistant to earthquakes by limiting the reaction forces and the stresses of the piles within the allowable values.

Safety of structural members is confirmed by checking that the stress on the tank body generated during an earthquake is within the allowable stress. The sectional force under the full liquid condition during an earthquake is shown in Fig. 8.

3.2 Check by Dynamic Analysis

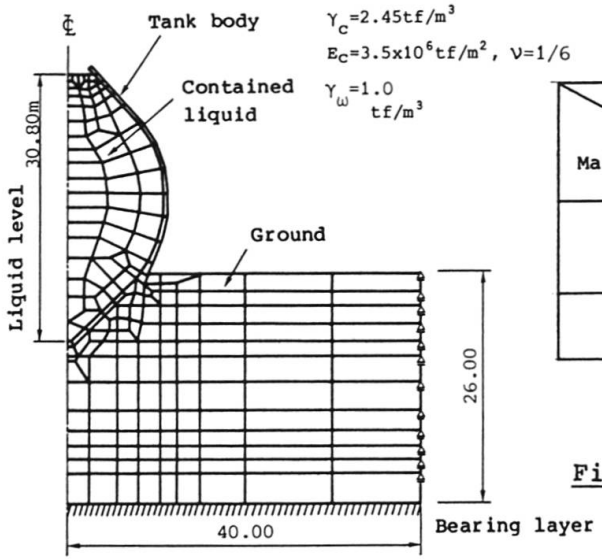
Time history response analysis by modal method is adopted for the dynamic analysis. The analysis model is the axisymmetric finite element model, which includes the surrounding ground as shown in Fig. 9, so that interaction among the ground of the construction site, structure and the contained liquid can be considered. The contained liquid is assumed to behave in accordance with the velocity potential theory.

The input seismic waves are the Kaihoku-kyo wave (June 1978, the Miyagi-ken-oki Earthquake, Japan) and the EL. CENTRO wave. The maximum input acceleration of the bearing layer is set so that the maximum response acceleration at pile top is 200 gal.

Additionally, as the modulus of rigidity and damping factor of ground are generally known to depend on ground strain, only the ground system is analyzed to determine these factors.

3.2.1 Result of Natural Vibration Analysis

From the result of the natural vibration analysis, the predominant natural modes are shown in Fig. 10. In the primary mode, the digestion tank sways following the vibration of the ground. In the 4th mode, rocking of the tank body predominates over sway of the ground. The primary natural period of contained liquid is 2.3 sec. This is longer than that of the tank body, so the possibility of resonance with the structure system is extremely small.



Material \ Scale	Number of elements	Number of nodal points
Ground/ structrual system	140	177
Contained liquid	62	84

Fig. 9 Dynamic Analysis Model

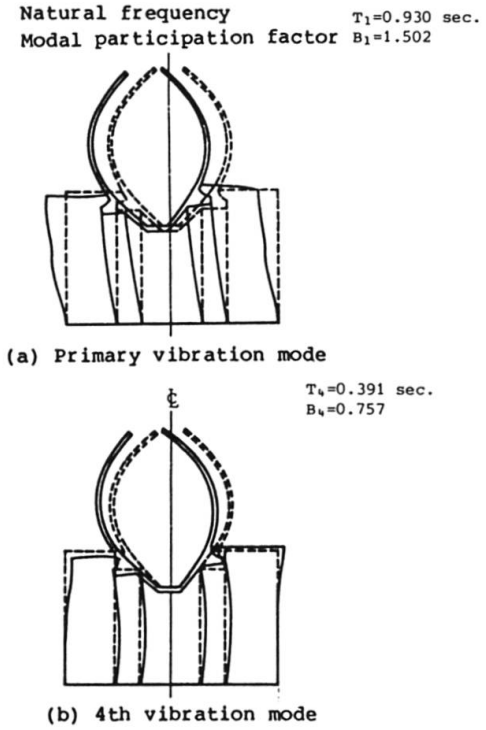


Fig. 10 Natural Vibration Mode (Full liquid condition)

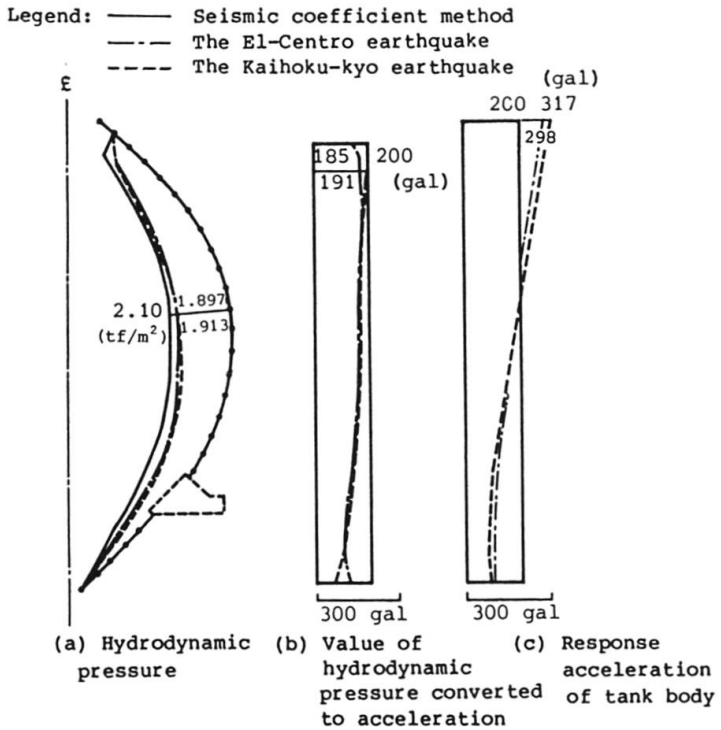


Fig. 11 Maximum Response

3.2.2 Comparison of Time History Response Analysis and Seismic Coefficient Method

Fig. 11 shows the distribution of the maximum response of the tank and contained liquid. The response acceleration is maximum at the top, indicating an influence of rocking slightly different from the uniform distribution supposed by the seismic coefficient method. As shown in Fig. 11 (b), the maximum hydrodynamic pressure is converted to acceleration in the horizontal direction in order to compare it with the acceleration distribution of the tank body. From this, the influence by rocking on the hydrodynamic pressure is less than that on the tank body.

To clarify the difference of seismic sectional force between evaluation by the seismic coefficient method and that by dynamic analysis, the sectional forces during earthquakes are shown in Fig. 12. From this, the difference is found to be 4 tf/m (NZ; Nodal point No. 41), or it reaches only 2 kgf/cm^2 even when converted into stress with bending moment.

As shown in Table 3, the load operating on the piles does not differ significantly. This is because the converted acceleration distribution of the hydrodynamic pressure is affected little by rocking and the distribution is nearly uniform, as shown in Fig. 11, and because the hydrodynamic pressure as seismic load predominantes over the inertial force of the tank body.

From the above we can conclude that distribution of sectional force based on dynamic analysis approximates that by the seismic coefficient method, so safety can be attained when the tank is designed based on this method.

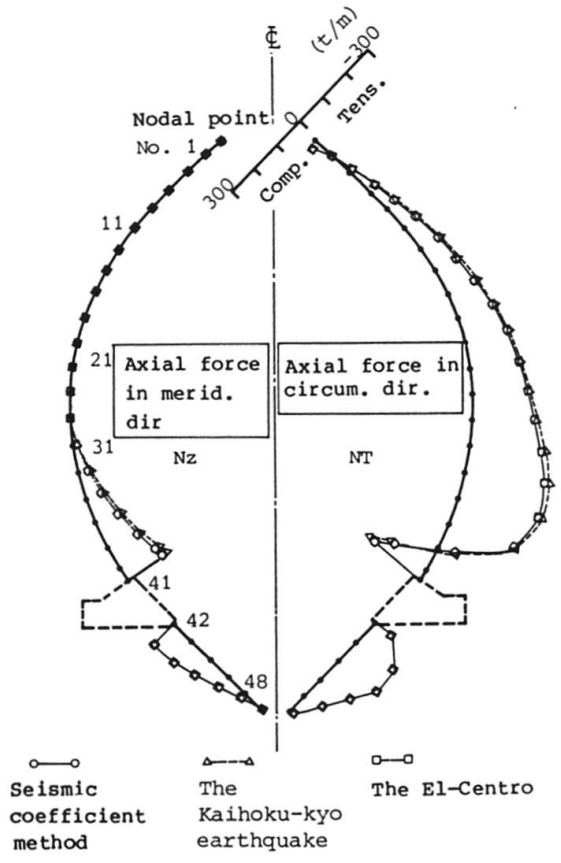


Fig. 12 Sectional Force

Table 3 Loads acting on Piles

Load \ Earth-quake	Seismic coefficient method	Kaihoku-kyo	EL. CENTRO
Vertical force V (tf)	9,830	9,830	9,830
Horizontal force H (tf)	2,150	1,730	1,680
Overturning moment M (tf.m)	24,000	23,600	21,720
M/H	11.2	13.6	12.9

3.3 Confirmation by Ambient Vibration Measurement

To confirm the suitability of the dynamic analysis model, ambient vibration measurement is performed by installing accelerometers on the tank body and surrounding ground.

The predominant frequency obtained from the measured power spectrum is plotted over the resonance curve of the tank top by dynamic analysis, as shown in Fig. 13.

From the sway mode in Fig. 13, it can be seen that measured values in the full liquid and empty conditions are nearly equal, indicating that the mode is governed by the ground.

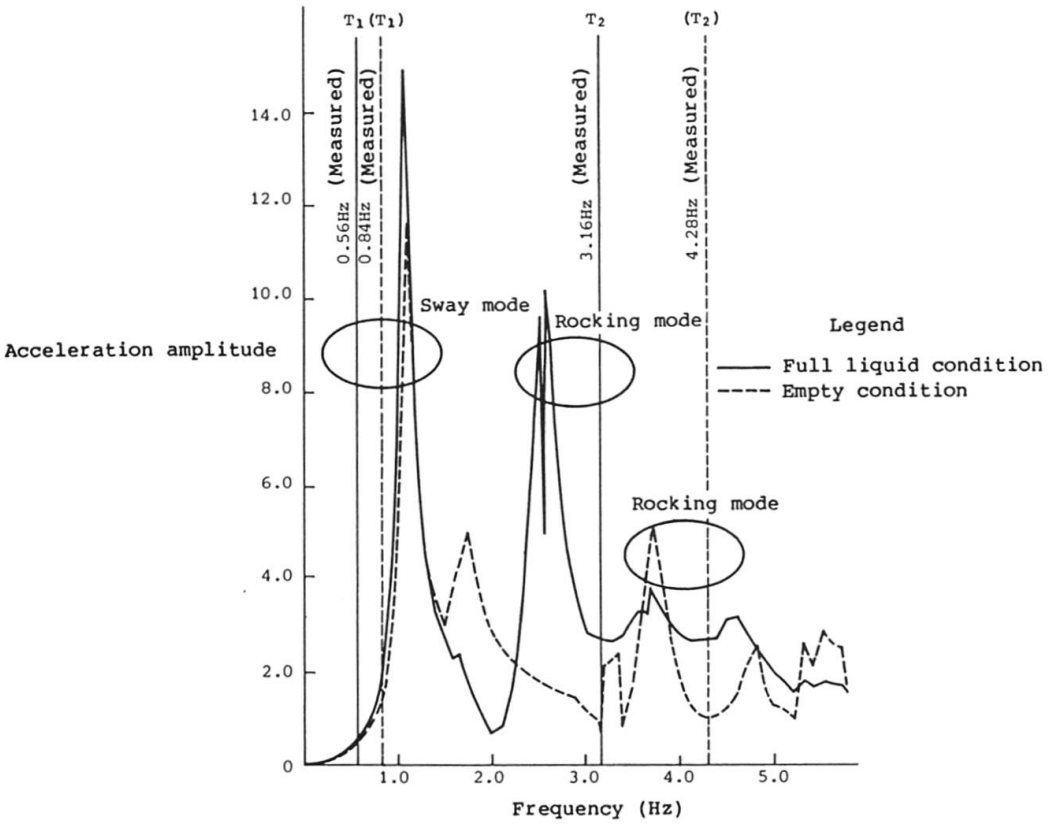


Fig. 13 Resonance Curve and Predominant Frequency at Tank Top

However, while analysis values have nearly the same frequencies under full liquid and empty conditions, measured values differ slightly, and the measured values are smaller than analysis values. This may be due to ground conditions. While the infinite ground is supposed in the analysis, the measured ambient vibration is influenced by adjacent structures and surrounding ground.

In the rocking mode, the measured predominant frequency is larger than the analysis value for both full liquid and empty conditions. It is assumed that the strain level of the ground during the ambient vibration measurement is far smaller than that during earthquake supposed by dynamic analysis. Therefore, the spring value of the ground during the ambient vibration measurement becomes larger than that during an earthquake because of the strain dependency

of the ground spring. When the ratios of frequencies under full liquid and empty conditions are compared from this viewpoint, the measured value of 1.35 and analysis value of 1.25 are nearly correspond, so both frequencies are considered to coincide when the ground spring is adjusted. Therefore, this dynamic analysis model is considered appropriate.

4. OUTLINE OF CONSTRUCTION

This work is to construct the first PC egg-shaped digestion tanks in Japan. The work is summarized below.

Outline : 12 PC egg-shaped digestion tanks with capacity of 6,800 m^3 each

Construction period: December 1983 to March 1987

Materials (for 12 tanks) :

Concrete	16,140 m^3
PC tendon	720 t
Reinforcing bar	1,320 t
PC piles 600 mm dia. ...	1,152 piles

The side walls are constructed using the climbing formwork system, and the bottom slabs are constructed arranging PC tendons helically and using special forms. Construction of the bottom slab is reported here.

The structural system changes with the construction progress, so it is very important to fully understand the stress conditions in each construction stage. For this purpose, stress is calculated during construction and measured during and after construction, as described in the following.

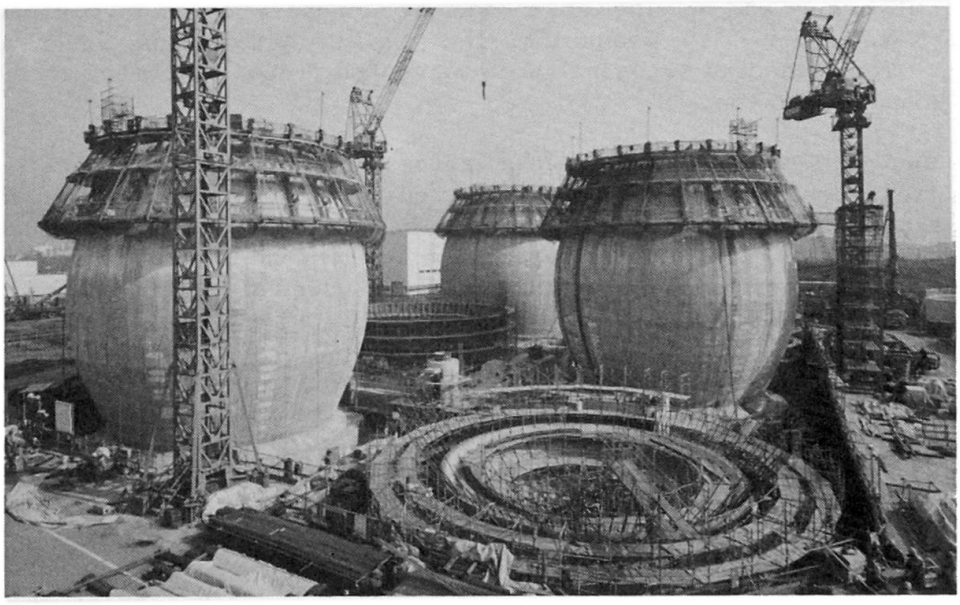


Photo 3 Construction in Progress

4.1 Construction of Bottom Slab

Earth work is first executed. The ground consists of sand containing silt with a high groundwater level. To prevent destruction of slopes during excavation of the bottom slab cone, the ground is improved by the cement mixing method. Concrete is also sprayed to protect slopes during excavation and to provide the outer form of the bottom slab.

After the earth work, PC work is performed. Accuracy of the arrangement of helical PC tendons is ensured by a special support with anchor bolts, which are preceedingly buried in the sprayed concrete.

The concrete is placed by pump. The inner form is composed by radial girders, ring beams, and form panels specially provided for the bottom slab cone.

4.2 Analysis of Stress During Construction

The side wall is constructed after the bottom slab and ring foundation, in the ring segment of 1.45 m in height using the climbing formwork system. The structural system and load conditions change during construction, so the model for the analysis of stress during construction is changed accordingly.

The proper amount of prestress and sequence of introduction suited for each construction stage are decided beforehand to avoid cracking due to bending tensile stress during construction.

4.3 Stress Measurement

4.3.1 Stress Measurement during Construction

The concrete stress is measured using a concrete stressmeter which can measure stress free of influence of creep and drying shrinkage of concrete. The stress of reinforcing bars is measured using a reinforcing bar stressmeter. Influences of creep and drying shrinkage of concrete on the reinforcing bar stressmeter are removed by measuring the strains before and after work for each step. The measured strains are converted into concrete stress using corrected Young's modulus.

Fig. 14 shows the stress of concrete after completion of the tank. These figures indicate that measured values are nearly equal to analysis values or slightly larger in the compression side. The influence of creep, such as the initial quick deformation, and a correction difference in Young's modulus can be considered as the major causes of this. However, since both generally agree, the designed prestress can be considered to have been introduced.

In particular, it is clearly indicated that the intended prestress has been introduced into the bottom slab in both circumferential and meridian directions by the helical arrangement developed for this work.

4.3.2 Stress Measurement after Completion (full liquid condition)

The measured and analysis values of concrete stress due to hydrostatic pressure are shown in Fig. 15. The measured value is slightly larger than the analysis value, like as Fig. 14. However, they values generally correspond favorably, so the design of the PC egg-shaped tanks was correct and the construction was conducted as intended.

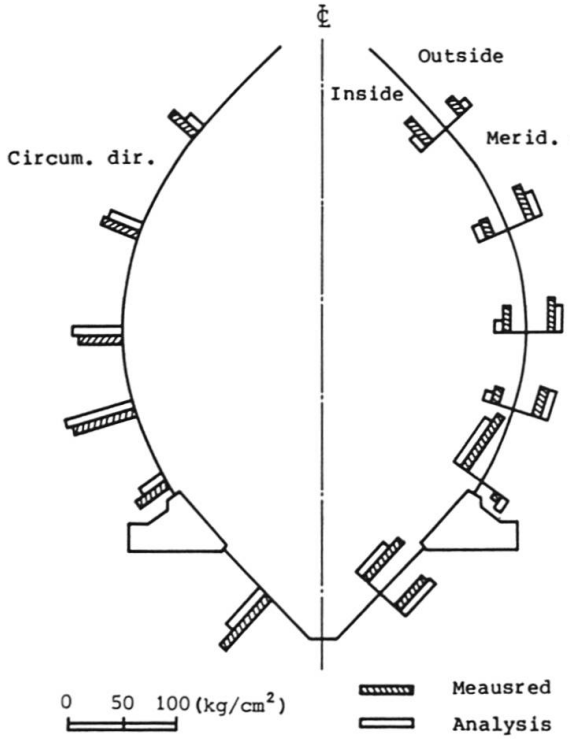


Fig. 14 Concrete Stress Immediately after Completion

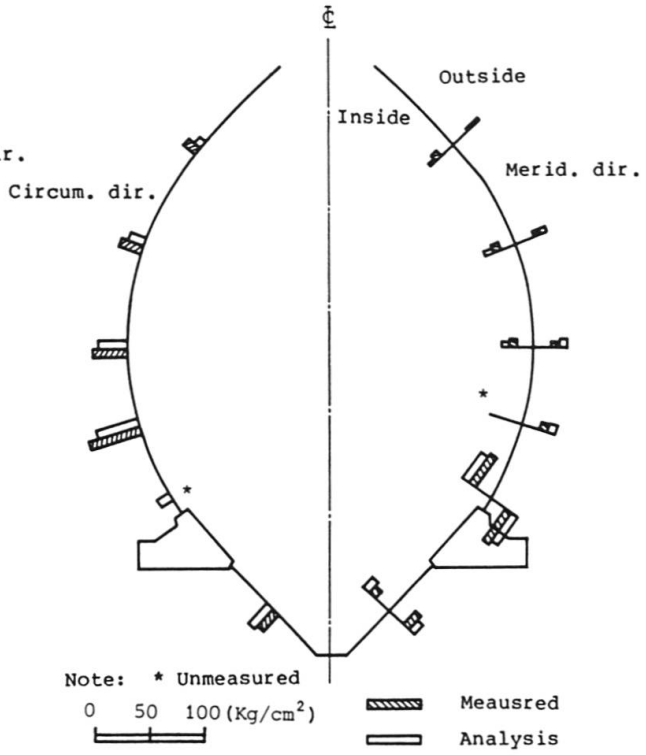


Fig. 15 Concrete Stress by Hydrostatic Pressure

5. CLOSING REMARKS

From the results of a series of studies on response to earthquakes, we see that the aseismicity of these tanks is sufficient. However, when influence of rocking cannot be disregarded due to tank features and ground conditions, it may be necessary to correct the seismic coefficient which was supposed to have a uniform distribution, before applying.

In December 1987, the completed tanks experienced a relatively strong earthquake (75 km to the hypocenter and 6.7 in magnitude), but no damage was observed.

After construction of these tanks, 17 PC egg-shaped digestion tanks, 70,000 m^3 in total, have been constructed in Japan. Other tanks are now under construction. This construction work initiated the development of PC egg-shaped digestion tanks in Japan. This report describes the tank design and construction mainly from the aseismic viewpoint. The authors hope that this report will serve as a reference for constructing egg-shaped digestion tanks in other seismic areas of the world.

It is noted that the tank won the Civil Engineering Achievement Award of the JSCE in 1987.

Before closing, the authors would like to express their appreciation to the staffs of Yokohama City, Kajima Corporation, Oriental Concrete Co., Ltd. and all others who were involved in the design and construction of these tanks.

Bibliography

1) Masaaki Saito, Takeshi Akutsu, Munetaka Kubota: Construction of PC Egg-Shaped Digestion Tanks in Yokohama City, JSCE Journal Vol. 71, No. 3, 1986

2) Kanji Imai et al.: Vibration Analysis of Fluid-Structure-Ground Integrated System, 35th JSCE Annual Lecture Meeting, 1980

3) Sakuji Yoshida, Hozumi Nakata, Munetaka Kubota, et al.: PC Egg-Shaped Digestion Tanks in Yokohama City, Vol. 26, No. 5, 1984

4) Sakuji Yoshida, Hiroshi Yamashita, et al.: Egg Shaped Digestion Tanks in Yokohama city (1), (2), Sewerage Association Journal, Vol. 22, No. 249, No. 25, 1985

5) Akira Katagiri, Takashi Yoshikiyo, Toru Yamamoto: Seismic Study of PC Egg-Shaped Digestion Tank, 40th JSCE Annual Lecture Meeting, 1985

6) Takeshi Akutsu and Hiroshi Yamashita: Design and Construction of Egg-Shaped Sludge Digestion Tank, Public Work Construction, 1985

7) Takeshi Akutsu, Hiroshi Yamashita, Akira Katagiri: Construction of Egg-Shaped Digestion Tanks in Yokohama City, Kensetsu no Kikaika, June 1986.