APPROXIMATE SEISMIC RESPONSE ANALYSIS OF SELF-SUPPORTED THIN CYLINDRICAL LIQUID STORAGE TANKS

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SUMMARY

There are a great number of liquid storage tanks in the petrochemical complexes. The safety of these tanks against seismic motions must be considerably investigated in the design stage.

Most of the conventional liquid storage tanks are low as compared with their diameters. Recently, tall thin tankers such as refuelling water storage tank at nuclear power plant have come to be used for special purposes. The seismic responses of such a tank are those of a coupled vibration system consisting of tank structure and liquid and a sloshing vibration system consisting of liquid surface oscillation, for which the conventional method of analysis is inapplicable.

In order to make an accurate analysis of the seismic responses of tall thin tanks of this kind, the authors assumed that the motions of the liquid in the tank would be in accordance with the velocity potential theory and derived a method of approximate analysis of their seismic which was applicable to both the liquid-tank coupled vibration system and the sloshing vibration system.

That is, as to the behavior between liquid and tank under earthquake, seismic response analysis was devided into the following two cases.

(1) In case seismic load is evaluated in regard to coupled vibration system between liquid and tank, liquid surface oscillation is neglected and pressure fluctuation of liquid is considered as virtual mass to the tank wall, when its deflection is taken into consideration.

(2) In case seismic load is evaluated in regard to sloshing vibration system, only pressure fluctuations by liquid surface oscillation is considered supposing that the tank wall is rigid.

We proposed that the tank total seismic responses of thin wall tank containing liquid are obtained by adding these both seismic response.

Furthermore, to investigate the appropriateness of this analytical method, we made a reduced-scale plastic model of a cylindrical tank and obtained the vibration characteristics and seismic response characteristics of the model by using a shaking table. The experimental values showed a good agreement with their respective theoretical values, proving the appropriateness of the analytical method.

So, it is recommended that this new analytical method be employed for the sale and reasonable design of tall thin tanks for special purpose. Strictly speaking, the approximate seismic response analysis method including the coupled vibration system and the sloshing vibration system proposed in this paper should be adopted instead of the common method when the natural frequency of the coupled vibration system is in the resonance region to earthquake.

1. Introduction

Recently, as the investigation for the industry equipments damaged by earthquakes is put forward, the state of these damage is made clear gradually. For example, as a result of the investigation connected with Niigata earthquake occurred at 1964, Tokachioki earthquake at 1967 in Japan, and San Fernando earthquake at 1971 in the United State, more reasonable aseismic design becomes to be necessary keenly.

So, a liquid storage tank is pointed out to be one of important structure on aseismic design. A great number of such liquid storage tanks are installed in the petro-chemical complexes and the nuclear power plants and so on.

Most of the conventional liquid storage tanks are low as compared with their diameters. But, lately, tall thin tanks such as refueling water storage tank as shown in Fig. 1 at nuclear power plant have come to be used for special purposes.

The seismic responses of such a tank include both of a coupled vibration system consisting of tank structure and liquid and a sloshing vibration system consisting of liquid surface oscillation, for which the conventional method of analysis is inapplicable.

In order to make an accurate analysis of the seismic responses of tall thin tanks of this kind, we assumed that the motions of the liquid in the tank would be in accordance with the velocity potential theory and derived a approximate seismic response analysis method which was applicable to both the liquid-tank coupled vibration system and the sloshing vibration system.

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(2) In case seismic load is evaluated in regard to sloshing vibration system, only pressure fluctuations by liquid surface oscillation is considered supposing that the tank wall is rigid.

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Furthermore, to investigate the appropriateness of this analytical method, we made a reduced-scale plastic model of a cylindrical tank and obtained the vibration characteristics and seismic response characteristics of the model by using a shaking table. The experimental values showed a good agreement with their respective theoretical values, proving the appropriateness of the analytical method.

2. Approximate Seismic Response Analysis Method of Self-supported thin Cylindrical Tank

As to behavior of liquid and tank under earthquake, the approximate seismic response analysis method consists of the following two cases using the modal analysis method supposing that the behavior of liquid in tank follows the velocity potential theory.

2.1 Coupled Vibration System between Liquid and Tank

At first, a thin cylindrical tank shown in Fig.2 will be considered. Supposing that a ground displacement $Z(t)$ is added to the tank bottom which is fixed to a foundation, a relative displacement of position of height x from the foundation of tank is $y(x)$ and an absolute displacement is $Y(x)$. Where, (r, θ, x) is cylindrical polar coordinate, R is an inner radius of tank, ℓ is a height of tank, h is a depth of liquid.

Assuming the liquid in a cylindrical tank incompressible and inviscid, the behavior of liquid can be described by a velocity potential Φ as the following equation.

$$\Phi(r, \theta, x, t) = \sum_{m=1}^{\infty} \phi_m (r, \theta, x) \cdot Q_m(t), \quad Q_m(t) : \text{normal function in general} \quad \cdots\cdots (1)$$

As it is well known, eq. (1) satisfies Laplace equation in cylindrical polar coordinate.

$$\nabla^2\Phi = \frac{\partial^2\Phi}{\partial r^2} + \frac{\partial\Phi}{r\partial r} + \frac{\partial^2\Phi}{r\partial\theta^2} + \frac{\partial^2\Phi}{\partial x^2} = 0 \quad \cdots\cdots (2)$$

A solution of velocity potential satisfying eq. (2) obtained by paying attention to an impulsive force of liquid.

The boundary conditions can be expressed by the following equations.

(a) $$\left(\frac{\partial\Phi}{r\partial\theta}\right)_{\theta=0} = 0 \;, \quad \left(\frac{\partial\Phi}{r\partial\theta}\right)_{\theta=\pi} = 0 \quad \cdots\cdots (3)$$

(b) $$\left(\frac{\partial\Phi}{\partial x}\right)_{x=0} = 0 \quad \cdots\cdots (4)$$

(c) $$\left(\frac{\partial\Phi}{\partial r}\right)_{r=R} = -\dot{Y}_t(x, t)\cos\theta \quad \cdots\cdots (5)$$

(d) $$(P)_{x=h} = -\rho_0 \left(\frac{\partial\Phi}{\partial t}\right)_{x=h} = 0 \quad \cdots\cdots (6)$$

ρ_0 : liquid density

Also,

$$\dot{Y}_t(x, t) = \dot{y}_t(x, t) + \dot{z}(t) \quad \cdots\cdots (7)$$

The solution of eq.(2) satisfying the boundary conditions expressed by eq.(3) - (6) is given by

$$\Phi = -\sum_{i=0}^{\infty} \frac{2I_1\left(\frac{\lambda_i r}{h}\right)}{\lambda_i I_1'(\lambda_i R/h)} \cdot \cos\theta \cdot \cos\left(\frac{\lambda_i x}{h}\right) \cdot \left\{\int_0^h \dot{Y}_t \cos\left(\frac{\lambda_i x}{h}\right) dx\right\} \quad \cdots\cdots (8)$$

Where $I_1(x)$ is a modified Bessel function of the first order.

$I_1'(x) = dI_1(x)/dx, \qquad \lambda_i = (i + 1/2)\pi$

A pressure distribution of liquid in the tank is as follows.

$$P(r, \theta, x, t) = -\rho_0\dot{\Phi}$$

$$= \rho_0 \sum_{i=0}^{\infty} \frac{2I_1\left(\frac{\lambda_i r}{h}\right)}{\lambda_i I_1'\left(\frac{\lambda_i R}{h}\right)} \cdot \cos\theta \cdot \cos\left(\frac{\lambda_i x}{h}\right) \left\{\int_0^h \ddot{Y}_t \cos\left(\frac{\lambda_i \bar{x}}{h}\right) dx\right\} \quad \cdots\cdots (9)$$

When the motion of the tank wall is $y(x)$, a virtual mass m_v (x, y) of liquid corresponding to the mass ρA per unit length of the cylindrical tank can be expressed approximetely as follows.

$$m_v(x, y) = \frac{\rho_0 \pi R}{y(x)} \sum_{i=0}^{\infty} \frac{2I_1\left(\frac{\lambda_i R}{h}\right)}{\lambda_i I_1'\left(\frac{\lambda_i R}{h}\right)} \cdot \left\{\int_0^h y(x)\cdot\cos\left(\frac{\lambda_i x}{h}\right) dx\right\} \cdot \cos\left(\frac{\lambda_i x}{h}\right) \quad .. \ (10)$$

And, m_v (x, z) is also obtained in the same way.

Next, a kinematic equation of the coupled vibration system between liquid and tank under earthquake can be obtained by assuming that a deformation of cylindrical tank in the horizontal direction follows a beam theory.

Supposing that the vibration mode of tank is bending vibration mode (or shear vibration mode), the kinematic equation is expressed as follows.

$$EI \frac{\partial^4 y_t}{\partial x^4} + \{\rho A + m_v(x, y)\} \frac{\partial^2 y_t}{\partial t^2} = - \{\rho A + m_v(x,z)\} \frac{d^2 z}{dt^2} \quad \ldots\ldots\ldots\ldots\ldots (9)_1$$

or

$$- kGA \frac{\partial^2 y_t}{\partial x^2} + \{\rho A + m_v(x, y)\} \frac{\partial^2 y_t}{\partial t^2} = -\{\rho A + m_v(x, z)\} \frac{d^2 z}{dt^2} \quad \ldots\ldots\ldots\ldots\ldots (9)_2$$

Where, EI, kGA : Bending rigidity, shear rigidity of tank

ρA : Distributed mass of tank structure

A solution of forced vibration of eq. $(9)_1$, $(9)_2$ can be expressed by the linear connection of normal function for free vibration of the beam as shown in the following equation.

$$y_t(x, t) = \sum_{n=1}^{\infty} \alpha_n \cdot \psi_n(x) \cdot q_n(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

A kinematic equation of the s-th equivalent one degree of freedom system can be obtained by use of orthogonality between the normal functions and addition of a damped term.

$$\ddot{q}_s(t) + 2h_s\,\omega_s\,\dot{q}_s(t) + \omega_s^2\,q_s(t) = \beta_s\,\ddot{Z}(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Where, natural circular frequency ω_s, participation factor β_s for the coupled vibration system in s-th can be obtained by the following expression.

$$\omega_s = \sqrt{\frac{\rho A \omega_{os}^2 \ell_s}{\rho A \ell_s + \int_0^h m_v(x, \psi_s) \cdot \psi_s^2(x)\, dx}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$$\ell_s = \int_0^{\ell} \psi_s^2(x)\, dx$$

ω_{os} : natural circular frequency of empty tank

$$\beta_s = - \frac{\int_0^{\ell} \rho A \psi_s(x) dx + \int_0^h m_v(x, z)\psi_s(x) dx}{\alpha_s \{\rho A \ell_s + \int_0^h m_v(x, \psi_s)\psi_s^2(x) dx\}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

When the modal analysis method is adopted as one of seismic response analysis method, a response spectrum S_{AS} for the period ($= 2\pi/\omega_s$) and damping ratio (h_s) can be obtained from a response spectral curve, and $q_s = \beta_s \cdot S_{AS}/\omega_s^2$ can be obtained as the response value of the s-th order of eq.(11). When eq.(7), (10) are applied, the response acceleration at a point of tank $x = x_0$ in the vertical direction is expressed as follows.

$$\ddot{Y}(x_0) = \sqrt{\sum_{s=1} \{\alpha_s \, \beta_s \, S_{AS} \cdot \psi_s \, (x_0)\}^2}$$

$$\text{or} = \sum_{s=1} \left|\alpha_s \, \beta_s \, S_{AS} \cdot \psi_s \, (x_0)\right| \quad \cdots\cdots (14)$$

, the response pressure at a point $r = R$, $\theta = 0$, $x = x_0$ is as follows :

$$P(R, x_0) = \sqrt{\sum_s \{\rho_0 \sum_{i=0}^{\infty} \frac{2I_1 \, (\frac{\lambda_i R}{h})}{\lambda_i I_1' \, (\frac{\lambda_i R}{h})} \cdot \cos \, (\frac{\lambda_i x_0}{h}) \cdot \int_0^h \psi_s(x) \cdot \cos(\frac{\lambda_i x}{h}) dx \cdot \alpha_s \cdot \beta_s \cdot \, S_{AS} \, \}^2}$$

$$\cdots\cdots (15)$$

, the response bending moment at the tank wall $x = x_0$ is as follows :

$$M(x_0) = \sqrt{\sum_s \Big[\alpha_s \, \beta_s \, S_{As} \Big[\rho \, A \int_{x_0}^{\ell} \psi_s(x) \, x dx + \int_{x_0}^{h} m_v(x, \, \psi_s)\psi_s(x) \, x \, dx \quad * }$$

$$* \overline{\; - \, x_0 \{\rho \, A \int_{x_0}^{\ell} \psi_s(x) dx + \int_{x_0}^{h} m_v(x, \, \psi_s)\psi_s(x) dx\} \Big] \Big]^2} \quad \cdots\cdots (16)$$

2.2 Sloshing Vibration System by Liquid Surface Oscillation

In the same way as the coupled vibration, the tank shown in fig. 2 will be considered. For the seismic response analysis, the tank wall is assumed to be regid and only the oscillation of liquid free surface is taken into consideration. When the seismic displacement $Z(t)$ is applied to the tank foundation, the relative displacement seems to be zero approximately and the velocity potential which satisfies Laplace equation given by eq.(2) can be obtained by supposing that only oscillation of liquid free surface is induced.

As for the boundary conditions, the following expression must be satisfied besides the condition of eq. (3), (4).

$$\text{(a)} \quad (\frac{\partial \Phi}{\partial r})_{r=R} = - \dot{Z}(t) \cos \theta \quad \cdots\cdots (17)$$

$$\text{(b)} \quad (\frac{\partial^2 \Phi}{\partial t^2} + g \frac{\partial \Phi}{\partial x})_{x=h} = 0 \quad \cdots\cdots (18)$$

A solution of eq.(2) which satisfies the boundary conditions given in eq.(3), (4), (17) is obtained as follows.

$$\Phi \, (r, \, \theta, \, x, \, t) = \sum_{i=1}^{\infty} \alpha_i \, J_i \, (\kappa_i r) \cosh \, (\kappa_i x) \cdot \cos\theta \cdot \dot{q}_i \, (t) - \dot{z} r \cos\theta \quad \cdots\cdots (19)$$

Where, $J_1(\kappa_i r)$ is Bessel function of first order.

$$\{ J_1'(x)\}_{x=\kappa_i R} = \{ \frac{dJ_1(x)}{dx} \}_{x=\kappa_i R} = 0$$

A pressure distribution of liquid in the tank is as follows .

$$P(r, \, \theta, \, x, \, t) = -\rho_0 \{ \sum_{i=1}^{\infty} \alpha_i \, J_i \, (\kappa_i r) \cdot \cosh \, (\kappa_i x) \cos\theta \, \ddot{q}_i(t) - \ddot{z} \, r \cos\theta \, \} \quad \cdots\cdots (20)$$

Since eq.(19) must satisfy eq.(18), the following equation is obtained.

$$\sum_{i=1}^{\infty} \alpha_i J_1(\kappa_i r) \cosh(\kappa_i x) \cdot \ddot{q}_i(t) + g \sum_{i=1}^{\infty} \alpha_i J_1(\kappa_i r) \cdot \kappa_i \cdot \sinh(\kappa_i x)\, \dot{q}_i(t) = r\dddot{Z}(t) \quad \ldots (21)$$

Multiplying $J_1(\kappa_s r)\cdot r$ on both sides of eq. (21), it is integrated as for r from 0 to R. As the next relations exist,

$$\left.\begin{aligned} &\int_0^R J_1(\kappa_i r)\cdot J_1(\kappa_s r)\cdot r\, dr \\ &= \frac{R^2}{2}\{1 - \frac{1}{(\kappa_s R)^2}\}\{J_1(\kappa_s R)\}^2 \quad (i = s) \\ &= 0 \quad (i = s) \end{aligned}\right\} \quad \ldots (22)$$

and

$$\int_0^R J_1(\kappa_s r)\, r^2 dr = \frac{R^3 J_1(\kappa_s R)}{(\kappa_s R)^2} \quad \ldots (23)$$

the following kinematic equation of the s-th equivalent one degree of freedom system can be obtained with addition of a damped term.

$$\ddot{q}_s(t) + 2 h_s \omega_s \dot{q}_s(t) + \omega_s^2 q_s(t) = \beta_s \ddot{Z}(t) \quad \ldots (24)$$

A natural circular frequency ω_s and a participation factor β_s of s-th are obtained by

$$\omega_s = \sqrt{g\kappa_s \tanh(\kappa_s h)} \quad \ldots (25)$$

$$\beta_s = \frac{2R}{\alpha_s \{(\kappa_s R)^2 - 1\} J_1(\kappa_s R) \cosh(\kappa_s h)} \quad \ldots (26)$$

where, g : gravity acceleration

When the seismic response analysis is made by a modal analysis method, a response pressure at a point of tank wall $r = R$, $\theta = 0$, $x = x_0$ is as follows :

$$P(R, 0, x_0) = \rho_0 \sqrt{\sum_s \{\alpha_s \beta_s J_1(\kappa_s R)[\cosh(\kappa_s x_0) S_{As} + \{\cosh(\kappa_s h) - \cosh(\kappa_s x_0)\}\ddot{Z}]\}^2} \quad \ldots (27)$$

, response bending moment at $x = x_0$ is expressed by

$$M(x_0) = \pi\rho_0 R \sqrt{\sum_s \{\alpha_s \beta_s J_1(\kappa_s R)\{\{\int_{x_0}^{h_s}\cosh(\kappa_s x) x\, dx\} S_{As} + [\int_{x_0}^{h_s}\{\cosh(\kappa_s h) - \cosh(\kappa_s x)\} x\cdot dx]\ddot{Z} - x_0\{\int_{x_0}^{h_s}\cosh(\kappa_s x)\, dx\} S_{As} - x_0 [\int_{x_0}^{h_s}\{\cosh(\kappa_s h) - \cosh(\kappa_s x)\} dx]\ddot{Z}\}\}^2} \quad \ldots (28)$$

Where the oscillation amplitude of liquid free surface is as follows.

$$h_s = h + (\eta)_{r=R}$$

$$(\eta)_{r=R} = \frac{1}{g}\left(\frac{\partial\Phi}{\partial t}\right)_{\substack{r=R\\x=h}} = \frac{1}{g}\{\alpha_s \beta_s J_1(\kappa_s R)\cosh(\kappa_s h) S_{As}\} = \frac{2R\, S_{As}}{g\{(\kappa_s R)^2 - 1\}}$$

2.3 Compound Method of both Seismic Response Values

The term $\ddot{Z}$ of eq. (27), (28) indicates the impulsive pressure component of liquid when a tank wall is considered to be rigid. So that, when an evaluation is made only by these expression, it become to be the same as common analysis based on the theory of velocity potential assuming tank wall rigid.

Therefore, the entire seismic response of a self-supported thin cylindrical tank considering about flexibility of tank wall can be concluded to be obtained by compounding both responses.

A maximum seismic response of the coupled vibration system tends to occur at the main motion of seismic acceleration. While, the one of sloshing vibration system don't necessary occur at same time, but it often occur at the end of seismic motion when the transient response of long period component graws up.

Therefore, we recommend the square root of the sum of squares as one of resonable compound methods here.

For example, the total seismic pressure response of liquid at a point of tank wall $r = R$, $\theta = 0$, $x = x_0$ is as follows.

$$P_T(R, 0, x_0) = \sqrt{P_I{}^2(R, 0, x_0) + P_{II}^2(R, 0, x_0)} \quad \cdots\cdots (29)$$

Where, suffix I shows the coupled vibration system, II shows sloshing vibration system. Moreover, we must pay attention to that the term $\ddot{Z}$ of sloshing vibration system is considered to be neglected when both responses are compounded.

3. Model Experiment

In order to certify that the theory of approximate seismic response analysis is valid, we made the reduced-scale plastic model of self-supported cylindrical tank which sizes are 2 m in height, 55 cm in inner radius and 2 mm in thickness as shown in Fig.3. These sizes are selected after considering the similarity law of reduced-scale model and the performance of shaking table.

As the vibration experiment, we conducted the vibration characteristic test by sweep shaking with sine wave, and the seismic response test on the shaking table.

The performance of the shaking table used in the experiment is 5 ton.G output and its size is 3 m x 3 m.

Fig. 4 shows the instruments block diagram in case of sinusoidal sweep test.

4. Comparison between Analytical Values and Experimental ones

4.1 Results of Vibration Characteristic Test

(1) Coupled vibration system between liquid and tank

(a) Regarding the natural frequency of the coupled vibration system between liquid and tank, Fig. 5 shows the comparison between experimental values and numerical values which are calculated by the method mentioned in Section 2. From this figure, it is clearly shown that the calculated values by our method well agree with the experimental ones. In paticular, it can be said that the evaluation by shear vibration mode is better for the comparatively low tank such as its height equivalent to the diameter or less. On the other hand, it is seemed that the evaluation by bending vibration have a good coincidence with experimental values when tank height is more than twice as the diamter. Besides, the difference between the values by shear vibration mode and experimental ones is also small for these sizes.

Moreover, Fig.5 shows the results of natural frequency calculated by assuming one degree of freedom system at the center of gravity of the tank using common calculation method based on Housner's method, which remarkably differ from the experimental values as shown in a one dotted chain line.

Fig.6 shows the effect of tank sizes on natural frequency of tank structure. From this figure, it is seemed that the thinner the thickness of tank is and the lower the height of tank, the lower the effect as virtual mass by impulsive pressure of liquid is. Where, f_1 is natural frequency calculated by regarding liquid as dead mass.

(b) As to the damping characteristic, Fig.7 shows that the damping is increasing as the water depth is increasing, and indicates that the increase of damping may be expected by the existence of liquid in tank.

(c) Fig.8 (a), Fig.8 (b) show the pressure mode and the acceleration mode of tank wall respectively. A solid line and a broken line are the calculation values by our theory described in section 2, a one dotted chain line shows the impulsive pressure mode by Housner, and round marks show the experimental values. It is seemed that the calculation values by our theory well agreed with the experimental ones, especially in case of shear vibration mode. While, according to Housner theory, it resulted that the impulsive pressure at the upper part of the tank is estimated smaller than that at the lower part.

From the above, it is understood that the evaluation by shear vibration mode is more adequate.

(2) Sloshing vibration system

(a) Fig.9 shows comparison of calculated values and experimental values of the natural frequency for the liquid surface oscillation with water depth tank in parameter, in which both values are well agreed. Besides, this calculation method is the same as the common one by Housner consequently.

(b) Fig.10 shows pressure mode of the tank side wall at the resonance of liquid surface oscillation, in which experimental values at the lower part of the tank are slightly larger compared to the calculated ones possibly by the effect of impulsive pressure.

(c) As shown in Fig.11, damping is approximately 0.4 ~ 0.5 % which indicates extremely small value.

4.2 Results of Seismic Response Test

(1) Fig.12 shows comparison of the experimental seismic response results in case of Eℓ centro seismic wave as input for shaking table and the calculated values by the approximate seismic response analysis described in this study. A solid line shows the calculated seismic response values in which combination of the coupled vibration system and the sloshing vibration system is performed by the square root of the sum of the squares. Also, A broken line shows the seismic response only by coupled vibration system and a one dotted chain line only by sloshing vibration system, and the experimental values are shown with small round marks.

As to the response acceleration, response pressure and response bending moment, it is clearly indicated that the tendencies of both experimental and theoretical values are quite agreed though the calculated values for each item are rather in the safety side. For the response bending moment, the tank structure is handled as beam in this study, so that, in the strict sense, the seismic load should be calculated by our method, then at the stage of stress analysis the detailed analysis had better be performed considering the tank as a shell.

(2) We have already explained in the previous section as to the defference in vibration response characteristic between analytical values based on Housner's method which is one of the common analytical method and the results obtained by our proposed analysis method.

Fig.13 shows comparison of the calculated results by Housner theory and the experimental ones. In this figure, when the impulsive pressure is calculated, we consider about two cases as follows. One is evaluated by the period T = 0 described in TID Report 7024 shown as a one dotted line, the other by the period obtained by experiment shown as a two dotted line. Also, round marks show experimental values, a broken line shows the convective pressure by Housner theory, and a solid line shows summation of these.

As a result, since the tank wall is assumed to be rigid when evaluating impulsive pressure of liquid by the conventional method based on Housner theory, it is well understood that it is inadequate when the natural frequency of the coupled vibration system is in the resonance region to earthquake.

5. Conclusion

In regard to the aseismic design of a self-supported thin cylindrical liquid storage tank, we introduce the approximate seismic response analysis including coupled vibration system and sloshing vibration system. Moreover, we performed the vibration experiment with the reduced-scale plastic tank model, then compared both experimental and analytical results. As a result, the following is concluded.

(1) Regarding the self-supported thin cylindrical tanks are tall as compared with their diameters, strictly speaking, the approximate seismic response analysis method proposed in this paper should be adopted instead of the common method described in TID Report 7024.

(2) As the calculated results by the approximate seismic response analysis method and the experimental ones obtained by using the shaking table are comparatively well aggreed, it can be said that it's validity is confirmed.

(3) As for the sloshing vibration system, we made sure that the oscillating free surface of liquid began to be disordered and to rotate at the same time when vibration amplitude become large. But we did not referred it in this study.

As described in the preceding sections, this study was made only on the behavior against horizontal earthquake, so there are still various technical problems remained to be solved. For example, they are the problems of vertical earthquake and long periodic component of seismic wave.

Therefore, this study was demonstrated only as one step to solve the whole remained problems, and it is expected that further study should be continued for safer and more rational design techniques.

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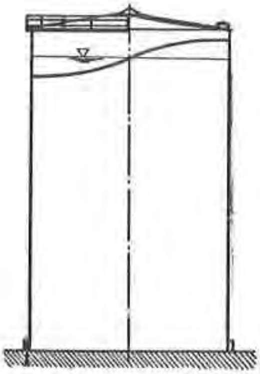

Fig.1 Refueling water storage tank

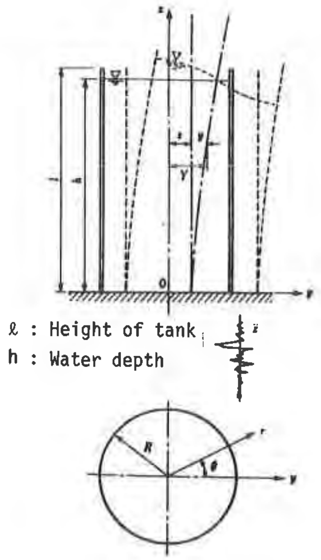

Fig.2 Self-supported thin cylindrical tank.

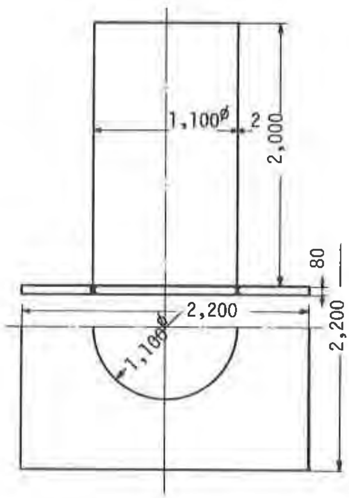

Fig.3 The reduced-scale plastic model of self-supported thin cylindrical tank.

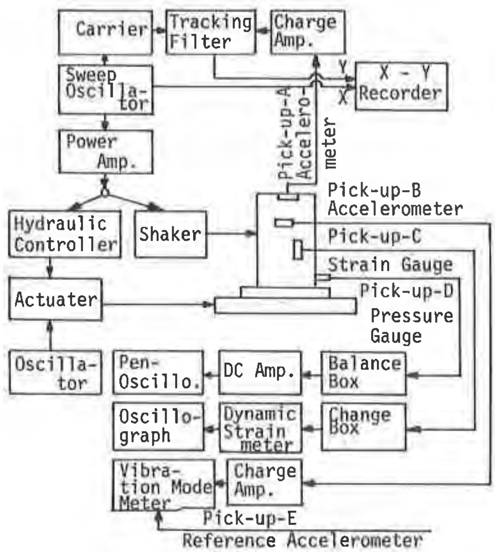

Fig.4 Instruments block diagram in case of sinusoidal sweep test.

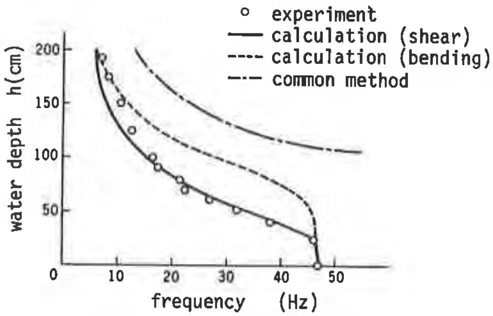

Fig.5 Comparison between experimental natural frequency and numerical one of the couple vibration system.

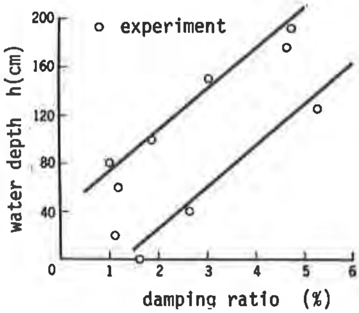

Fig.7 Effect of water depth on damping characteristic of the coupled vibration system.

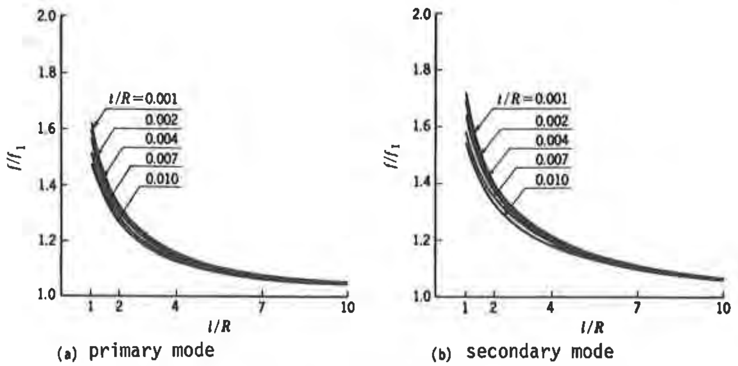

Fig.6 Effect of cylindrical tank sizes on natural frequency of tank structure.

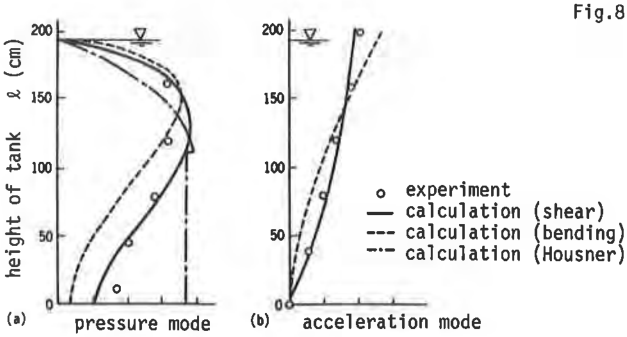

Fig.8 The pressure mode and the acceleration mode of tank wall.

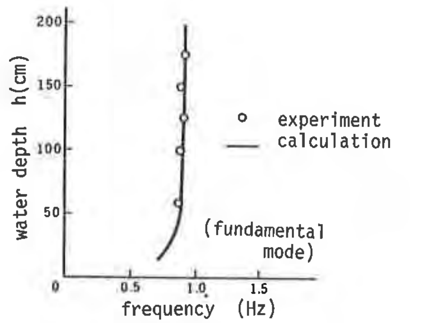

Fig.9 Comparison of the calculated natural frequency of sloshing vibration and the experimental one.

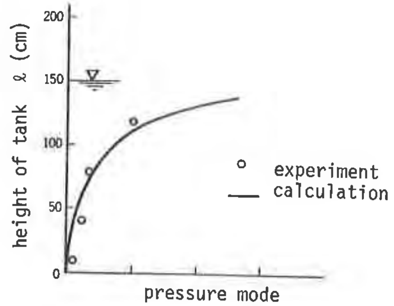

Fig.10 Comparison of the calculated pressure mode and experimental one at the resonance of liquid surface oscillation.

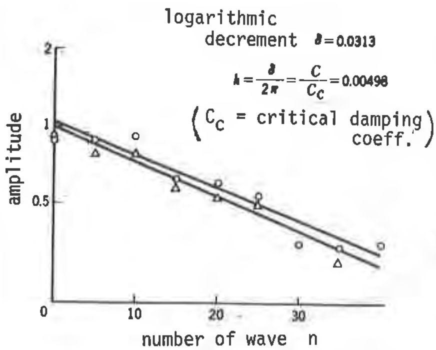

Fig.11 Damping characteristic of sloshing vibration system for cylindrical tank.

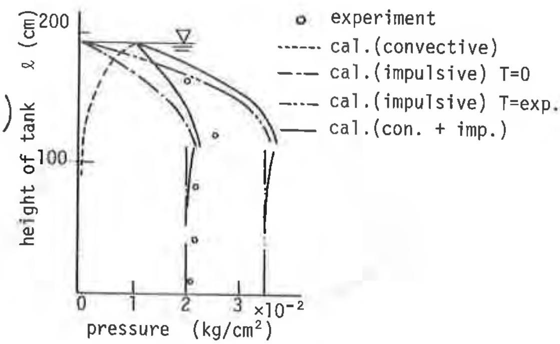

Fig.13 Comparison of the calculated results by Housney theory and the experiment one in case of Eℓ centro earthquake. (360 gal)

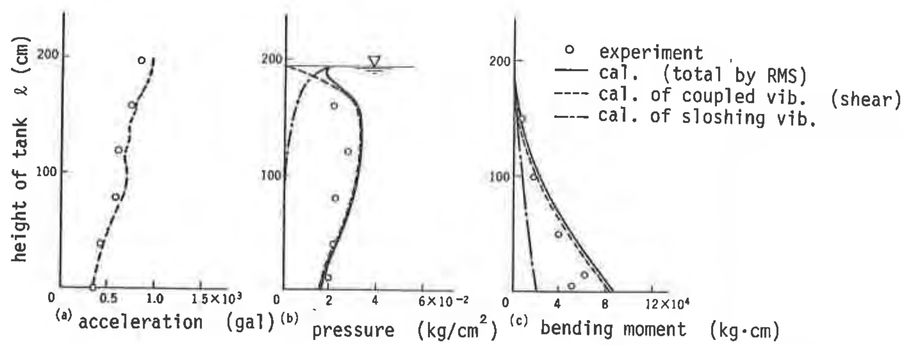

Fig.12 Comparison of the experimental seismic response results and the calculated ones in case of Eℓ centro earthquake. (360 gal)