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AN EXPERIMENTAL VERIFICATION ON SEISMIC BEHAVIOR OF LARGE-SCALED LIQUID STORAGE TANKS

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SUMMARY

Presented in this paper are two kinds of modelling to satisfy as exactly as possible the similitude law between actual large-scaled flat-based cylindrical tanks and models, in order to grasp correctly their complicated seismic behaviors including the uplifting ones. One kind is made of layered thin plastic film, the scale of which is 1:40, and the other is made of aluminum alloy, the scale of which is 1:4. Static tilt tests were conducted as effective techniques for experimental verification, especially in the cases of big-sized model. The experiments indicate the importance of modelling and the limitation of some estimation methods proposed hitherto.

INTRODUCTION

Various types of damage due to earthquakes have been experienced concerning flat-based cylindrical liquid storage tanks, on which many experimental and theoretical researches have been carried out. Especially in case of unanchored tanks usually employed for oil strage tanks, their seismic behaviors are characterized by uplifting of bottom parts.

The uplifting behaviors are so three-dimensional and complicated that they should be dealt with exactly. In this context, from the view-point of grasping correctly the behaviors of actual tanks, there are some problems in almost all the studies conducted hitherto. Those are mainly: the experimental models used in the past studies were too small or too stiff to represent the behaviors of actual large-scaled tanks, and the assumptions adopted in the analyses were not always verified.

In this paper, for the purpose of clarifying the seismic behaviors of large-scaled tanks including the uplifting ones, the authors will discuss about an experimental verification by static tilt tests with two kinds of tank model which satisfy as exactly as possible the similitude to actual large-scaled prototype tanks.

Similitude The non-dimensional parameters to be considered in the similitude law are as follows:

$$H/D,\ t/D,\ \gamma H/E,\ \gamma/k_b,\ \nu$$

in which D is tank diameters, H liquid depth, t shell or bottom plate thickness,

γ weight per unit volume of liquid, E and ν Young's modulus and Poisson's ratio of shell or bottom plate, and k_b coefficient of foundation reaction force respectively. The similitude of models to prototypes is satisfied if all the non-dimensional parameters of model are equal to those of prototype. When the similitude with respect to geometrical parameters is satisfied, the statical parameters $\gamma H/E$, γ/k_b and ν should be adjusted. Since the effects of ν may be negligible, $\gamma H/E$ and γ/k_b are left unadjusted.

$\gamma H/E$, related with the superstructure is the most difficult quantity to be adjusted in tank modelling. As water is employed usually for contained liquid (γ = 9.8 kN/m^3), it is very difficult to find any tank material with the value of Young's modulus according to the dimension. In order to overcome this difficulty, the authors devised two kinds of tank modelling here. One kind is made of layered thin plastic film, the scale of which is 1:40, and the other is made of aluminum alloy, the scale of which is 1:4.

<u>Static Tilt Tests</u>[1-3) In order to investigate the seismic behaviors including the uplifting ones two series of static tilt tests were conducted with these two kinds of model. Static tilt tests have advantages over dynamic tests in that we can measure in details and need not big vibrating facilities for big models. Through the two series of test uplifting height and area along the circumference of the bottom part were investigated carefully. Especially in the latter series the model of about 4 x 10^3 kN total weight was tested and the measurement of over 600 components was carried out.

SMALL MODEL TILT TEST

This experiment[4)] was conducted in 1983 to grasp the uplifting behaviors qualitatively, and can be taken preparatory for next experiment with the big model.

<u>Model</u> Two models were made of layered thin plastic film. The models and prototypes are shown in Table 1. The aspect ratio H/D of Model A and Tank A is 1.0 and that of Model B and Tank B is 0.4. The former and latter ones are so-called "tall" and "broad" tanks.

<u>Experimental Result</u> The experimental cases are shown in Table 2. In the case A uplifting became remarkable after the tilt angle ϕ = 5°, and crack occurred at the corner between shell and bottom plate around ϕ = 13°. As the tilt angle was increased without any remedy, the model was overturned by buckling of the bottom shell on the compressive side at ϕ = 20.8° (equivalent to the seismic force coefficient K_h = 0.54). In the case B uplifting arose a little earlier than in the case A, and as the tilt angle was increased, the cross-sectional deformation of the circular shell became significant. Finally it was collapsed by falling down of the shell on the tensile side into inside at ϕ = 17.8° (K_h = 0.91). Fig. 1 shows the collapse modes for the cases A and B, from which a clear difference is recognized between both cases.

Fig. 2 shows the comprison of uplifting behaviors for the cases B1, B2 and B3, from which we can see the differences of uplifting distribution and cross-sectional deformation. In the figures the difference between with and without roof is very significant.

The above-mentioned results indicate that the uplifting behaviors are significantly influenced by tank rigidity such as whether "tall" or "broad" and "roofed" or "unroofed".

BIG MODEL TILT TEST

This experiment[5,6] was conducted in 1985 to grasp quantitatively the seismic behaviors including the uplifting ones, which succeeded the previous experiment with small models.

Model Table 3 shows the big model made of aluminum alloy together with the prototypes. This experiment included not only the unanchored cases for oil storage tanks, but also the anchored cases for low-temperature liquefied gas (LNG, LPG) tanks. But the former cases only will be mentioned here.

In Table 4 the authors' models are compared with the ones used in the experiments of the University of California, Berkeley. UCB model with 3.6 m diameter was the biggest one in the experiments hitherto. However it represents only a 10.8 m diameter and 400 m^3 tank. It can be seen how difficult it is to find appropriate models for representing large-scaled prototypes. In this case the material and dimensions of model are not arbitrary at all and almost limited to the combination in the table.

Experimental Method Thus the model has been very big-sized, weighing about 4×10^3 kN, to represent an actual large-scaled tank, and the authors adopted an experimental method of static tilt test. A shaking table test would be almost impossible for the model. This experimental method enabled the detailed measurement of over 600 components, too.

Considering an equivalency of overturning moment, the tilt angle can be reduced into the seismic response factors of the prototype. The relationship between both is shown in Fig. 3, in which K_h is the seismic force coefficient for bulging (fluid-elastic vibration) and η max the maximum elevation change for sloshing. In calculating the seismic response the Japanese Codes were used. When the over-turning moments from the tilting and the seismic response are the same, the accordance between the pressure distributions is fairly good.

Experimental Result The detailed explanation is done in Ref. 7, so in this paper the focus is placed on axial stresses in shell. Fig. 4 in Ref. 7 shows the axial stress distributions along the circumference of bottom shell for the cases with and without rigid top roof. A significant difference between both distributions should be noted. This indicates that the existence of roof, in other words the whole tank rigidity gives great influences upon the uplifting behaviors.

Hitherto a couple of methods by Clough et al. and others[1,8,9] were proposed to estimate axial stresses in shell arising accompanied with by uplifting. The distribution patterns proposed by these are shown in Fig. 4. Also Fig. 5 shows the change of the maximum axial compressive stress by tilting, obtained from the methods by Clough et al. and others as well as the authors' experiment and analysis.

In each estimation method there is a specific assumption respectively. For example, Clough et al. assumes that unuplifted region of bottom plate forms an inscribed circle against the original circle of bottom plate. Wozniak et al. does that the uplifted part of bottom plate is deformed with plastic hinges at two points by neglecting membrane action. Ishida et al. does that the plane of shell bottom end remains in a plane.

From both figures the experiment seems to verify that the validity of the assumptions adopted in the past studies depends on case and is not always reliable. On the other hand the results of the authors' analysis*), which takes into account whole rigidity of shell and large deformation and separation from foundation of bottom plate, show good agreement with the experimental ones in any case in Fig. 5.

CONCLUSION

From the viewpoint of satisfying the simulitude law the authors presented two kinds of modelling actual large-scaled tanks. To satisfy the similitude is especially essential for grasping complicated behaviors such as uplifting.

The results of the small model experiment indicated that whole tank rigidity, whether tall or broad and whether roofed or unroofed, gives more significant influences upon uplifting behaviors rather than foundation rigidity.

From the big model experiment, which was made it possible to conduct by static tilting, the uplifting behaviors of large-scaled tanks was grasped quantitatively and it was clarified that the uplifting behaviors are very three-dimensional phenomena, governed by whole tank rigidity and foundation rigidity. The experiment verified that the authors' three-dimensional and non-linear analysis can express the seismic behaviors better than the other estimation methods for the reason why there are less assumptions.

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* Because of shortage of space, the authors' analysis will be mentioned in another paper.

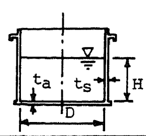
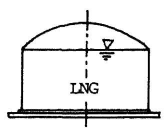
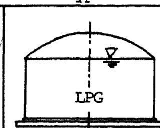
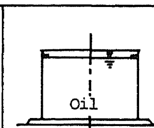
Table 1 Small Model and Prototype

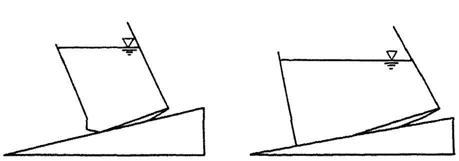
	Model A	Model B	Tank A	Tank B
D (mm)	488	1,220	19,500	48,800
H (mm)	488	488	19,500	19,500
H/D	1.0	0.4	1.0	0.4
t_s (mm)	0.36	0.54	14.8	22.1
t_b (mm)	0.28	0.36	11.5	14.8
γ (kN/ m^3)	9.8	9.8	9.8	9.8
E (kN/mm^2)	5	5	206	206

Table 2 Experimental Case for Small Model

	A	B	B1	B2	B3
foundation (N / mm^3)	rubber (0.15)	rubber (0.15)	sponge (0.13)	steel (∞)	rubber (0.45)
roof	No	No	No	No	Yes

Table 3 Dimensions of Model Tank and Prototypes

	Model	Prototype		
				
W (m^3)	333 - 427	80,000	60,000	25,000
γ (kN/ m^3)	9.8 (water)	4.75	5.68	7.84
E (kN/mm^2)	68.6 (aluminum alloy)	206	206	206
L_m / L_p	———	1/6	1/5	1/4
H (mm)	4,600 - 5,900	28,800	29,600	19,800
D (mm)	9,600	59,500	50,000	40,000
t_a, t_s (mm)	3 , 5	18 , 30.5	18 , 28	12 , 20



ϕ_u = 20.8° (a) MODEL A

ϕ_u = 17.8° (b) MODEL B

Fig.1 Sketches of Model Collapse

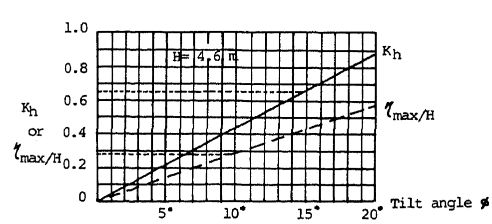


Fig.3 Relationship between ϕ and K_h or τ_{max}/H

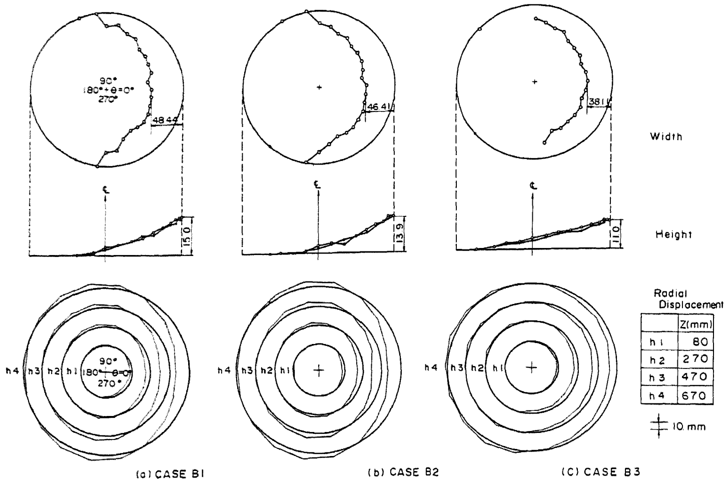
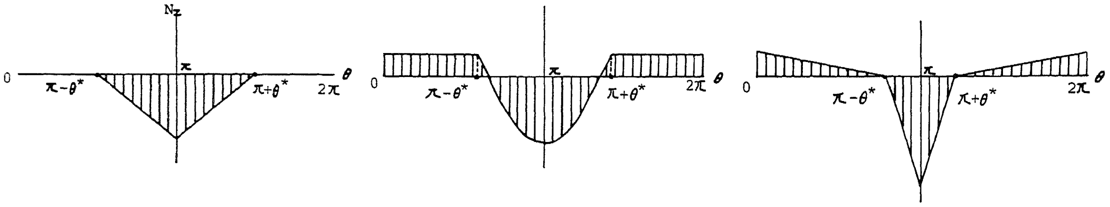
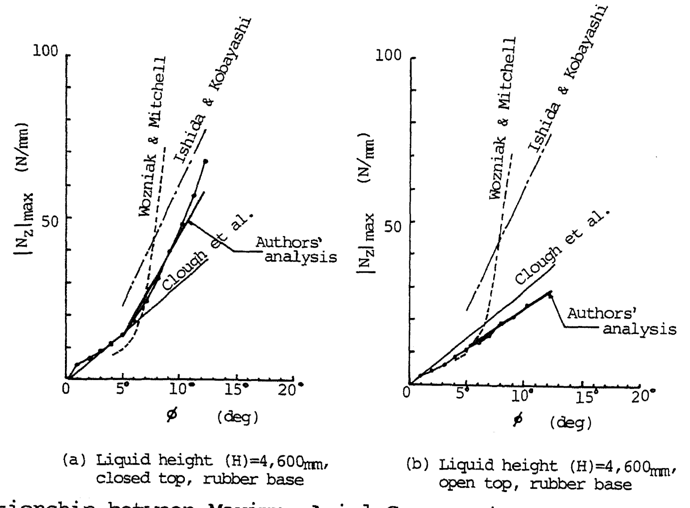


Fig. 2 Uplifting Behavior (Tilt angle=10°)



(a) Clough et al. (b) Wozniak & Mitchell (c) Ishida & Kobayashi

Fig.4 Comparison of Axial Stress Distribution



(a) Liquid height (H)=4,600mm, closed top, rubber base

(b) Liquid height (H)=4,600mm, open top, rubber base

Fig.5 Relationship between Maximum Axial Compressive Stress and Tilting Angle