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EXPERIMENTAL STUDY ON UPLIFTING BEHAVIOR OF FLAT-BASED LIQUID STORAGE TANKS WITHOUT ANCHORS

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SUMMARY

Presented in this paper are the experimental results of tank uplifting behavior obtained from a series of static tilt tests using a very big model, which accords to an actual large-scaled oil storage tank. Because of the exact similitude to the prototype and the detailed measurement, the uplifting behavior of large-scaled unanchored tanks during earthquakes is clerified with the effects of tank and foundation rigidity.

INTRODUCTION

When a flat-based cylindrical liquid storage tank is shaked by an earthquake, it is acted upon by seismic forces of dynamic pressures, a horizontal base shear and an overturning moment. Various types of damage due to earthquakes have been observed, among which buckling or elephant foot bulge (EFB) at the part of axially compressive shell and yielding or breaking at the corner part between the axially tensile shell and the bottom plate have been considered to be very important for the seismic design. It has been clear that these phenomena are closely related with uplifting[1]. Oil storage tanks, especially of medium and large scale are not ordinarily anchored, so larger magnitude of uplifting is expected compared with other anchored tanks.

Considerably many studies[2-7] have been conducted from this point of view, but they have been still within qualitative understanding for large-scaled tanks because of the limitation of experimental scale and theoretical assumption. The purpose of the present study is to investigate the uplifting behavior by a series of static tilt tests with a very big model satisfying exactly the similitude to an actual large-scaled oil storage tank.

The main concerns are as follows;

1) Deformation and stress caused by uplifting at each part of shell and bottom plate.
2) Influence of foundation rigidity on uplifting.
3) Influence of shell rigidity including an above roof on uplifting.

EXPERIMENT

The tank model was made to satisfy the geometrical and statical similitude to a prototype of large-scaled oil storage tank on the basis of the Backingham's theory. The model and prototype are shown in Fig. 1. The similitude scale is 1:4 as shown in the figure.

In the experiment eleven unanchored cases were carried out as shown in Table 1. The parameters considered here are as follows: 1 with or without roof, 2 foundation rigidity and 3 water depth. In the roofed cases a rigid circular stiffened plate was set at the level 4,600 mm high to prevent the cross sectional deformation of shell. As the foundation rubber and plywood, both 25 mm thick, were used to represent a crushed stone ring foundation and a much harder foundation.

In addition to these eleven unanchored cases many anchored cases were tested[8]. Here one anchored case RC13 is referred to later for comparison. The detailed explanation on the experiment is given in Ref. 9, too.

EXPERIMENTAL RESULTS

Displacement Fig. 2 shows the increments of uplifting height at θ = 0° by tilting for the cases FO22, FC22, FO1 and FC1. It can be seen that the uplifting height for the roofed cases becomes much greater than the one for the unroofed cases from earlier stages and that the differences between the foundation regidity are not so significant except at earlier stages. The latter result seems to mean that the rubber foundation used here (crushed stone ring foundation) has considerably great rigidity.

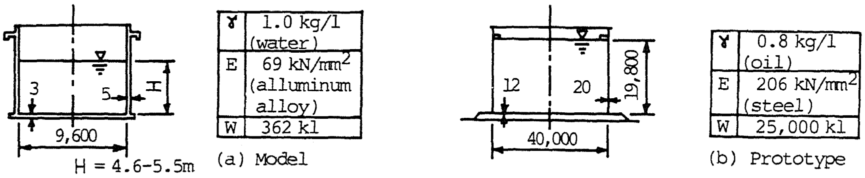


Fig. 1 Model and Prototype

Table 1 Experimental Cases

No.	Case	Roof	Foundation	
				Water Depth
1	FC2	exist	r	4.6 m
2	FC2D	exist	r	5.5 m
3	FO2	no	r	4.6 m
4	FO2D	no	r	5.5 m
5	FO1	no	p	4.6 m
6	FC1	exist	p	4.6 m
7	FC22	exist	r	4.6 m
8	FC23	exist	r	5.0 m
9	FO22	no	r	4.6 m
10	FO23	no	r	5.5 m
11	FO24	no	r	5.0 m

(p: plywood, r: rubber)

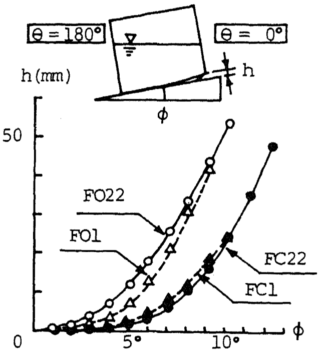


Fig. 2 Uplifting Height

Fig. 3 shows the deformation patterns along the circumference of tank, from which we can see big differences between roofed and unroofed cases. Those are: 1 The lowest end of shell remains a flat plane for the roofed cases, but forms a curved plane for the unroofed cases. 2 The uplifting area is narrow and longer for the roofed cases, but wide and less long for the unroofed cases. 3 The cross-sectional deformations at the level 1,000 mm and 2,500 mm high are very significant for the unroofed cases and not so for the roofed cases.

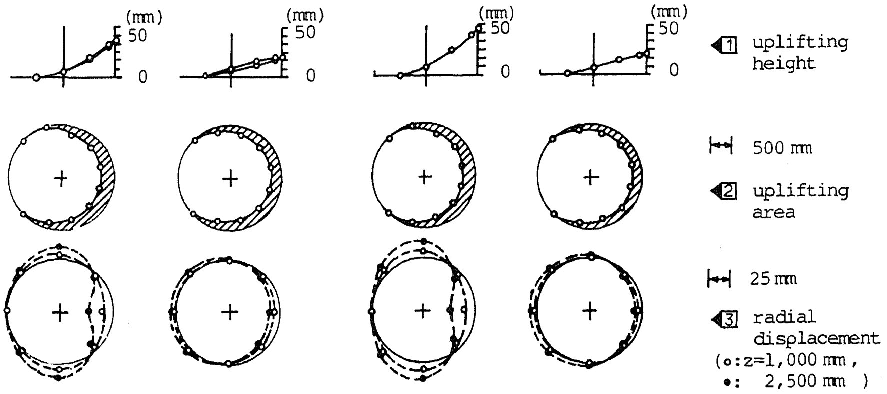
On the other hand, the differences between the foundation rigidity are not so remarkable.

Axial Stress in Shell Fig. 4 shows the axial stress distributions along the circumference of shell. In each case the experimental values from the level 30 mm to 400 mm are plotted together to avoid scattering of the experimental data. The differences between the foundation rigidity as well as between the shell rigidity are considerably recognized here.

For the rubber foundation, the axial stresses on the tensile side are almost the same between the roofed and unroofed cases, but the ones on the compressive side are very different between both cases. That is, the one for the roofed case FC22 is distributed in the narrow region and concentrated much more than the one for the unroofed case FO22.

For the plywood foundation, the experimental values are considerably scattered, and the axial stresses on the tensile side are not so different between the roofed and unroofed cases. But the one on the compressive side for the roofed case FC1 is concentrated in the much more narrow region and much sharply than the one for the unroofed case FO1.

From these results we can see that axial stresses in shell are governed by whole tank rigidity and foundation rigidity. The authors have developed the analysis program to consider whole tank stiffness and large deformation and separation between foundation of bottom plate. Here the analized results are compared with the above-mentioned experimental ones in Fig. 4, which illustrates fairly good agreement between both results.



(a) FO1 (ϕ = 9.2°)
(b) FC1 (ϕ =10.2°)
(c) FO22 (ϕ =10.2°)
(d) FC22 (ϕ =10.2°)

Fig. 3 Deformation along the Circumference

<u>Radial Membrane Stress in Bottom Plate</u> Fig. 5 shows the radial membrane stress distributions in the bottom plate, of which (a) and (b) indicate the roofed and unroofed cases respectively, and (c) does the case with anchor straps. It can be seen that the uplifting induces large radial tensile membrane stresses in the bottom plate.

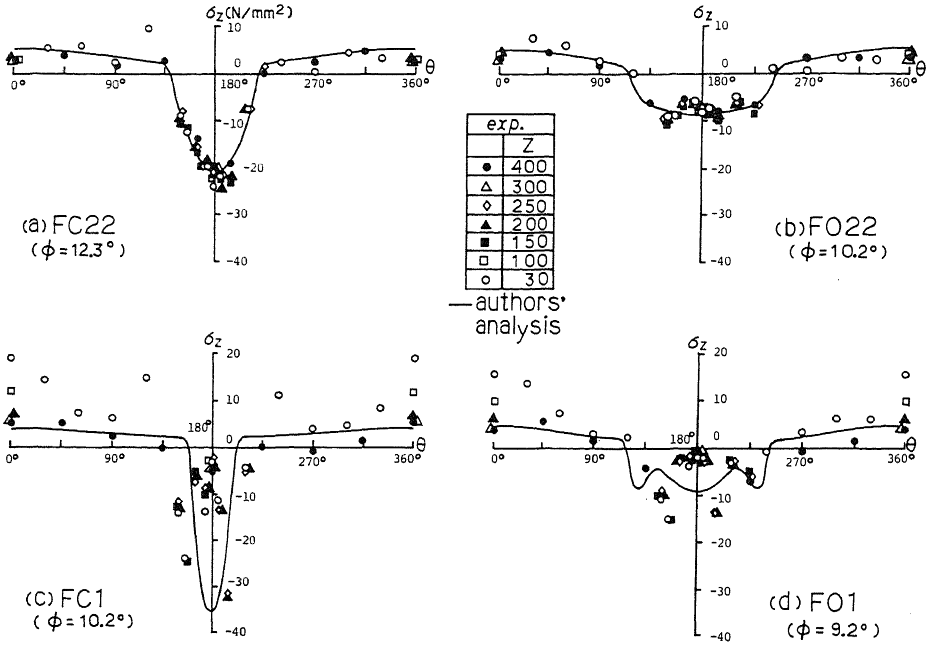
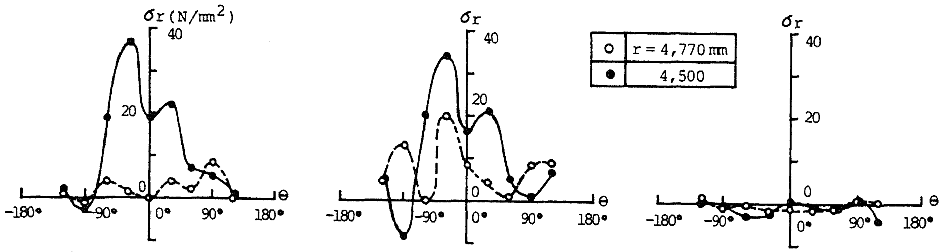


Fig. 4 Axial Stress Distributions in Shell

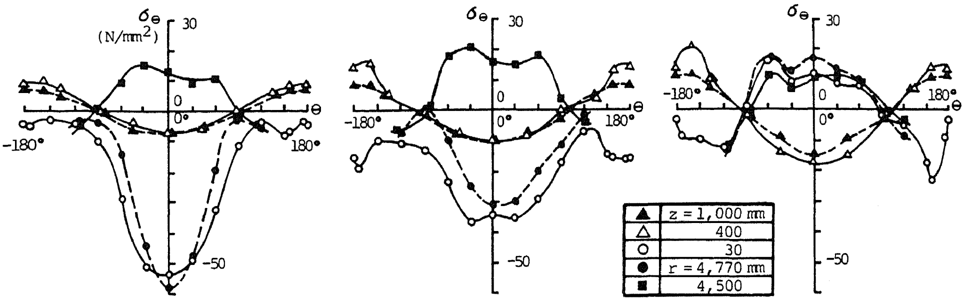


(a) FO22 (φ = 10.2°)
(b) FC22 (φ = 12.3°)
(c) RC13 (φ = 18.9°)

Fig. 5 Radial Membrane Stress Distributions in Bottom Plate

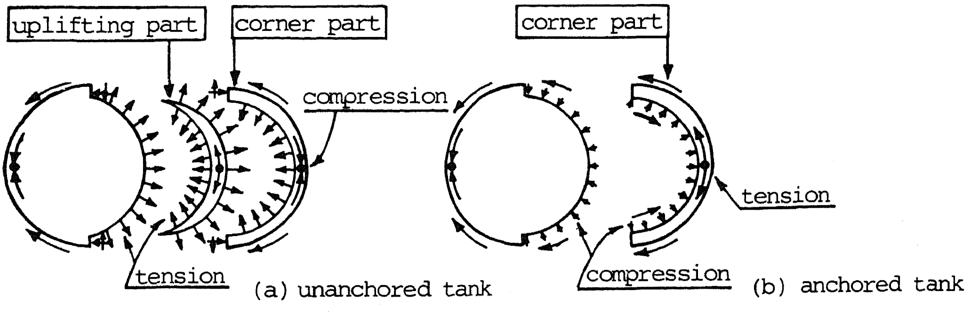
Hoop Stress around Shell-Bottom Corner Fig. 6 shows the hoop stress distributions in the circumferential direction around the shell-bottom corner. The distributions at z = 1,000 mm and 400 mm and r = 4,500 mm are similar for the three cases FO22, FC22 and RC13. But the ones at z = 30 mm and r = 4,770 mm are remarkably different for the unanchored and anchored cases. This means that great radial membrane stresses arising in the bottom plate by uplifting cause arch action to the shell-bottom corner part.

Consideration From the above-mentioned results the stress flow mechanism in bottom plates can be grasped well. The concepts of stress flow for anchored and unanchored tanks are illustrated respectively in Fig. 7. (a) and (b). In both figures the bottom plates are considered separatedly into the corner part, the uplifting part and the rest. When uplifting takes place, great radial membrane stresses are induced and they influence stresses at the corner part and so on. The difference from the unanchored case can be understood through the comparison between both figures.



(a) FO22 (ϕ = 10.2°)   (b) FC22 (ϕ = 12.3°)   (c) RC13 (ϕ = 18.9°)

Fig. 6 Hoop Stress Distributions in Shell and Bottom Plate



(a) unanchored tank   (b) anchored tank

Fig. 7 Stress Flow Mechanism in Bottom Plate

CONCLUSION

From the detailed experimental investigation using the biggest scale model in the past studies we come to the following conclusions:

(1) By tilting at about $\phi = 10°$ the model was lifted up to about 50 mm. According to the similitude law this means that in the prototype, 25,000 kℓ oil storage tank the uplifting height may be about 200 mm for the seismic force coefficient 0.4. This magnitude of uplifting height seems to be in the same order as the ones experienced in the past earthquakes such as the Alaskan and Off-Miyagi Prefecture Earthquakes.

(2) The influences of shell rigidity (with or without roof) on uplifting were very significant, but the ones of the foundation rigidity were less. The latter result may mean that crushed stone ring foundation modelled here is considerably hard.

(3) Uplifting is a remarkably three-dimensional and complicated phenomenon governed by whole tank rigidity and foundation rigidity. Therefore some conclusions derived from easy experiments and analyses lead in misunderstanding it. The authors' analysis with less assumptions agree fairly well with the experiment.

(4) When uplifting occurs, great radial tensile membrane stresses are induced in bottom plate on the uplifting side, which governs the stress condition at the bottom part.

(5) Although the results were not illustrated in this paper, local bending stress at the shell-bottom corner becomes very great on the uplifting side. This should be considered very carefully in seismic design of unanchored tanks hereafter.

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