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# EXPERIMENTAL STUDY ON LIFT-OFF BEHAVIOR OF FLEXIBLE CYLINDRICAL TANK

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## SUMMARY

Fundamental characteristics of dynamic uplift behavior in flexible cylindrical tank are studied by experiment for the sloshing mode. The model with dynamic similarity was tested using a shaking table and the dynamic contact pressure was detected by the direct strain measurement in the elastic foundation. The uplift condition, the separate region and the contact pressure distribution are discussed in relation with parameters of aspect ratio, defined by the ratio of water depth to tank diameter, and bottom plate thickness as well.

## INTRODUCTION

Quite a number of earthquake damages of aboveground tanks have been recorded since Long Beach Earthquake in 1933, and researches for earthquake resistant design have been conducted since then. The research trend is given in Ref.1 in detail and uplift of aboveground tank during earthquake is pointed out as one of the most important problem in the future.

We have two main approaches for tank uplift problem, namely, numerical analysis and model shaking test. However, uplift problem is hardly made clear. This follows from 1) difficult numerical analysis for dynamic contact problem, 2) difficult modeling with satisfactory similarities, 3) difficult measurement of dynamic contact pressures, and so on. There are two kinds of test for dynamic characteristics of uplift, namely, static tilt test by Clough (Ref.2), Sakai (Ref.3) and others, and shaking table test by Clough (Ref.4), Mimura (Ref.5) and others. These tests have inherent defects that static deformation modes do not always correspond to dynamic ones for the former and that extreme difficulties arise in dynamic measurement of the model with satisfactory flexibility similarity for the latter. On the other hand, the reasonable analysis employing the Cell Collocation Method is proposed by Zui et al.(Ref.6) for numerical analysis of tank uplift problem. This method shows reasonable agreement between numerical results and static tilt test results, and hopefully estimates the dynamic behavior of uplift to some extent. However, considering the strong nolinearity of this phenomenon it might not be likely that their numerical results can reflect the actual dynamic response.

In the present paper, the shaking table test is conducted for clarifying uplift behavior of aboveground tank using the model on the elastic foundation. Due attention is paid to dynamic similarity between model and prototype. Measurements are related with the contact pressure between bottom plate and foundation, the wave height of free surface at uplift, and the axial tank wall strain. Investigations are also made on the uplift condition, the separation region, and the contact pressure distribution in relation with parameters of water height and bottom plate thickness.

## HORIZONTAL EXCITATION TEST BY FLEXIBLE TANK MODEL

<u>Tank and Foundation Models</u>  Tank model (Fig.1) is so dimensioned that it may satisfy the satisfactory dynamic similarity to prototype as much as possible, 25cm in diameter, 40cm high. Polyethylene film is employed for tank material which has 0.3 for Poisson's ratio and 5 GPa for Young's Modulus. 0.18mm thick film is used for tank wall and both 0.10mm thick and 0.18mm thick films for bottom plate considering that the bending rigidity of bottom plate exerts the crucial effect on the dynamic contact pressure distribution and uplift property as well. Scale factor between this model and prototype is 1/41. So, from the geometric viewpoint of tank wall with excessive height, this test model seemingly corresponds to "Tall tank", but this prevents overspill by sloshing. The point is the aspect ratio of water height (H) to tank diameter (D). Particular attention is not paid to the similarity between actual and test foundations. Natural rubber with hardness 45° (JIS) is employed for elastic foundation and acrylic plate for rigid foundation for comparison. Little rubber blocks with 10mm×10mm×20mm are closely fitted for the elastic foundation, with 2mm clearance, which means the independent springs (Fig.2). Static load test shows that rubber blocks have 130N/cm average value for spring constant. The tank is placed as is on this elastic foundation.

<u>Test Procedure</u>  Test setup is given in Fig.3. The elastic foundation model is fixed on the shaking table with tank model on it. Sinusoidal excitation is horizontally given to the model and is measured dynamic contact pressure using the foregoing rubber block as sensor. Wave height and axial strain in lowermost tank wall are measured by video camera and by strain gauge, respectively. Dynamic contact pressure measurement is extremely difficult. Measured dynamic strain values in the rubber block sensor are converted to dynamic contact pressures by static loading test calibration. Letters in Fig.4 denote the position of rubber sensor used, totaling 29 pieces. Sensor location is limited in a quadrant from symmetry and concentrated along excitation direction and directly under tank wall. As for the rigid foundation, reactive force is converted to contact pressure by

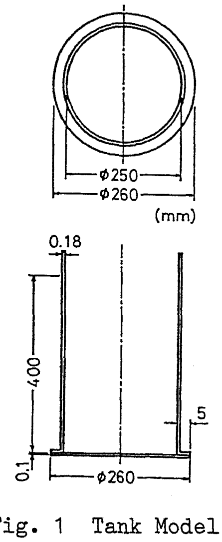


Fig. 1  Tank Model

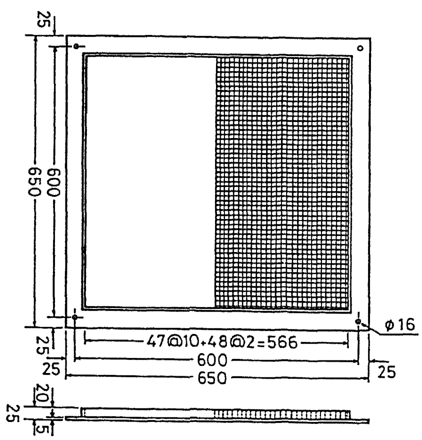


Fig. 2  Elastic Foundation Model

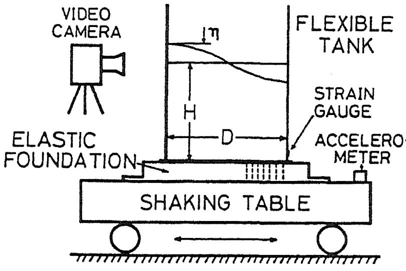


Fig. 3 Test Setup

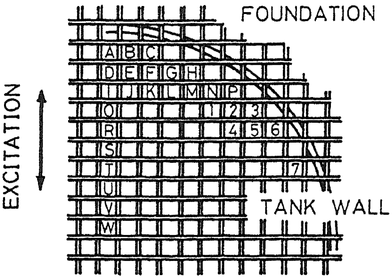


Fig. 4 Location of Rubber Block Sensor

projecting sensor, 1.5mm in diameter and 0.2mm high, with static test. Test procedure is as follows : To get the picture of dynamic property of flexible tank and uplift frequency band, measurements are made under various excitation frequencies and constant excitation accelerations. After narrowing down the frequency band at noticeable uplift phenomena, measurements are made on uplift condition, separate region and contact pressure as well, under gradually increasing excitation accelerations with constant frequency. Uplift is estimated by the abrupt change of axial strain in lowermost tank wall.

## UPLIFT CONDITION

Uplift Excitation Frequency Fig.5 shows frequency response of pressure ratio of elastic foundation in case of aspect ratio (H/D)=0.7 under 60 gal excitation. Abscissa and ordinate denote excitation frequency and nondimensioned fluctuating contact pressure by the static one. Resonance frequencies are observed at 1.8 Hz and 16 Hz, corresponding to the fundamental sloshing mode and the fundamental rocking motion (coupled motion of tank-fluid-elastic foundation system), respectively. Our measurement is made up to 35.0 Hz to find no significant bulging oscillation (coupled motion between elastic tank wall deformation and fluid). Fig.5 also shows the very narrow band of sloshing resonance compared with the resonant rocking frequency, however, sloshing gives rise to the large contact pressure and significant uplift as well. So our measurement is confined to the fundamental resonant sloshing frequency and around.

Wave Height at Uplift The relationship between wave height and aspect ratio is given in Fig.6. Aspect ratio is reduced from 1.0 by 0.1 pitch and positive and

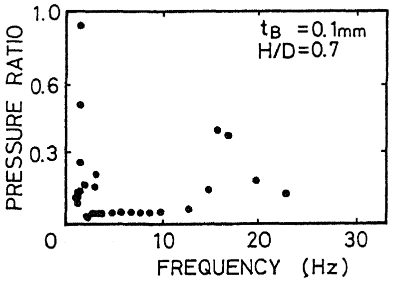


Fig. 5 Frequency Response of Contact Pressure

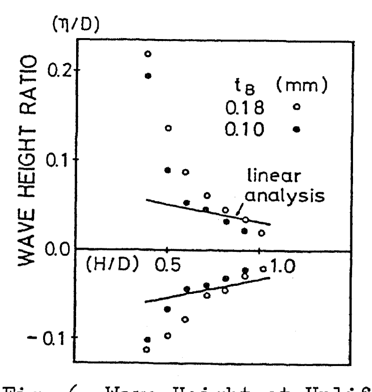


Fig. 6 Wave Height at Uplift vs. Aspect Ratio

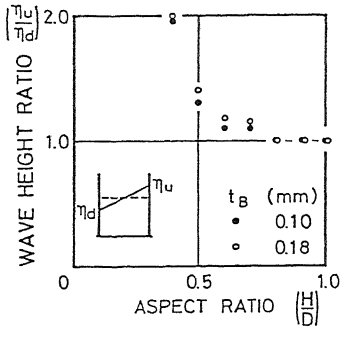


Fig. 7 Rise-Height-to-Fall Ratio vs. Aspect Ratio

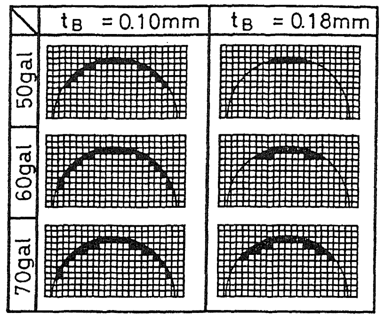


Fig. 8 Separation Distribution

negative values mean rise and fall of free water surface, respectively. This picture shows that the larger the aspect ratio is, the smaller the wave height at uplift becomes, and vice versa. The ratio of rise height to fall in Fig.7 shows that over 0.8 aspect ratio the sloshing surface shows symmetrical form meaning linear response, but under 0.5 the uplift is caused by unsymmetrical sloshing. It follows that the aspect ratio value 0.6 marks well-defined boundary which differentiate liner and non-linear response mechanism, confirmed by the linear analysis (Ref.7) in Fig.6. In the analysis the wave height at uplift is defined by the one when the dynamic contact pressure right under the tank wall equals the static one. Difference in wave height ratio due to bottom plate thickness ($t_B$) becomes noticeable toward the small aspect ratio value, resulting in that the thicker the bottom plate is, the larger the resistibility becomes. The wave height ratio $\eta_u/\eta_d$ shows little difference due to bottom plate thickness in Fig.7.

## SEPARATION DISTRIBUTION

Fig.8 shows the separation distribution in bottom plate at uplift estimated by the axial tank wall strain. Circular arc and lattice denote tank wall trajectory and rubber blocks comprising elastic foundation, respectively. The complete separation of bottom plate from rubber block means strain vanishing, from which the judgment of separation from rubber block is possible with response detection device. Dark area denotes the separation established in this way. These areas are given under the gradually increasing excitation acceleration, keeping aspect ratio 0.7 and excitation frequency 1.6 Hz. Separated areas are of sickle form, characterizing the wide distribution along tank wall edge in case of thin bottom plate. In case of thick plate, on the contrary, separated area shows to some extent the radial extension with no significant development along periphery. Development of separated area along periphery is given in Fig.9 with abscissa for excitation acceleration and ordinate for subtending angle of separated area. Fig.9(a) corresponds to the thin bottom plate showing that there are some differences in excitation accelerations at

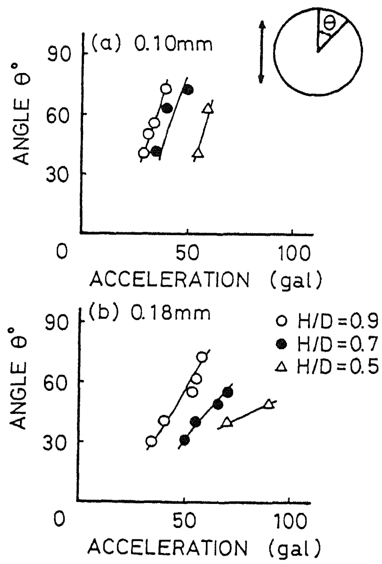


Fig. 9 Subtending Angle of Separation vs. Acceleration

uplift, however, the similar developments are observed for subtending angle. On the other hand , Fig.9(b) corresponds to the thick bottom plate, showing that there are remarkable differences in the development of subtending angle, depending on the aspect ratio. To be more specific, the larger the aspect ratio is, the more rapidly the separated area develops, and vice versa. Keeping aspect ratio constant, there is no remarkable difference due to plate thickness for large aspect ratio but remarkable for small aspect ratio.

## CONTACT PRESSURE DISTRIBUTION

Contact pressure distributions between bottom plate and foundation at uplift are given in Fig.10 for 0.9 and 0.5 aspect ratios. Contact pressures at the location of rubber block sensor are nondimensioned by the static contact pressure and represented by block height. Contact pressure shows its rather large value along the periphery and relatively small value in the inner part. Pictures in Fig.10 characterize the different pressure distribution from the hydrodynamic pressure derived from the linear potential theory. They shows that sharp pressure concentration can be observed along periphery for the large aspect ratio, causing no significant effect due to plate thickness. For the small aspect ratio, the thin bottom plate causes the sharp contact pressure concentration along the periphery and the thick plate make the contact pressure distributed inward. As for the effect of aspect ratio on the contact pressure along periphery, there exists the qualitatively similar tendency between elastic (Fig.10) and rigid (Fig.11) foundations. Besides, the more pronounced effect is observed for rigid foundation, so contact pressure distributions are taken up for rigid foundation in Fig.11. The two figures in Fig.11 compare the contact pressure distributions along periphery for 0.7 and 0.5 aspect ratios. Small excitation acceleration (40 gal) causes the almost similar contact pressure distribution irrespective of aspect ratio, however, marked difference is observed in the pressure distribution at uplift, that is, contact pressure distribution shows the liner decrease from the maximum value on the excitation axis for 0.5 aspect ratio, while the largest pressure remains within fairly wide periphery region including excitation axis, followed by the abrupt

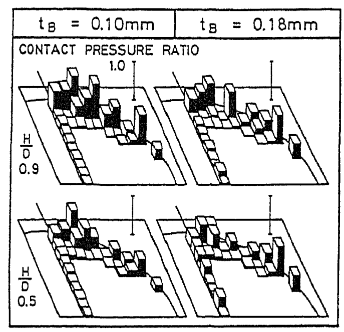


Fig. 10 Contact Pressure Distribution for Elastic Foundation

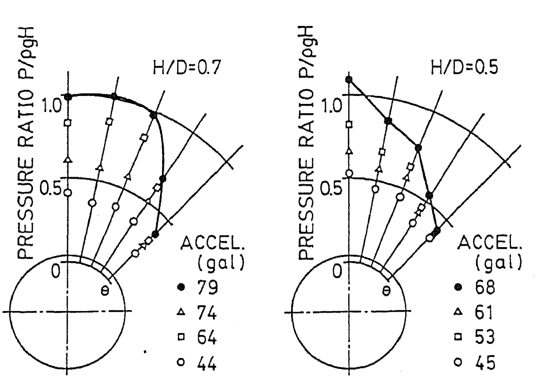


Fig. 11 Contact Pressure Distribution along Periphery for Rigid Foundation

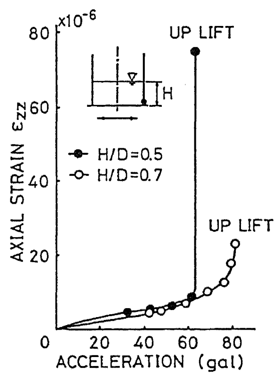


Fig. 12 Axial Tank Wall Strain vs. Acceleration

decrease. This means that the supporting mechanism against uplift is governed by aspect ratio. This difference in contact pressure distribution affects the axial strain. The response of axial strain in tank wall to excitation acceleration is given in Fig.12. It can be said from this figure that uplift causes support force concentration at $\theta=0°$ and extremely large axial strain for 0.5 aspect ratio, while support force dispersion and non significant axial strain for 0.7 aspect ratio.

## CONCLUSION

With intention of clarifying the dynamic uplift behavior during earthquake the following conclusions are drawn from the shaking table test of flexible tank-elastic foundation system.

(1) The larger the aspect ratio is, the less the wave height at uplift becomes, which means more liable to lift up. The wave height at uplift gets asymmetry below 0.6 aspect ratio, leading to changing in uplift mechanism.

(2) In case of large aspect ratio, bottom plate thickness has almost nothing to do with the resistivity to uplift, but the effect of bottom plate thickness becomes noticeable in the opposite case. The thicker the bottom plate is, the more the resistivity becomes.

(3) Separation area is of sickle form at uplift. The effect of bottom plate thickness on the development of separation area is the same as in (2). In case of thin bottom plate separation area spreads along periphery with increasing acceleration, while separation proceeds inward more readily for thick bottom plate.

(4) Contact pressure is concentrated in narrow strip right under tank wall in case of large aspect ratio. In case of small aspect ratio, contact pressure spreads inward.

(5) The abrupt increase of axial strain in tank wall arises after uplift in case of small aspect ratio, and has almost nothing to do with the bottom plate thickness.

In the present paper, the remarkable uplift phenomenon at fundamental sloshing mode absorbs our research interest under sinusoidal excitation. Although some dynamic aspects of uplift phenomenon are made clear, additional researches, including such as rocking motion on the soft ground, dynamic response at bulging, are indispensable for the various uplift phenomena of actual tanks.

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