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STUDIES ON EARTHQUAKE RESPONSE OF ON-GROUND LNG STORAGE TANK BASED ON OBSERVED RECORDS

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SUMMARY

Earthquake responses of an on-ground LNG storage tank having a pile group foundation have been instrumentally observed. The purposes are to examine whether behavior patterns other than those considered in design exist, and to ascertain the safety margin in current aseismic design. The results obtained are: 1) the current design method properly estimates the amplifications of acceleration caused by the responses of superstructure and ground, 2) the current design overestimates the bending moment of piles, 3) liquid-tank coupled vibration, i.e., bulging, is observed to occur, but does not have a dominant effect on the responses of the tank and foundation structure.

INTRODUCTION

Since liquid natural gas, abbreviated as LNG, is one of the main heat energy sources for domestic and industrial use in Japan, its stable supply is of essential nature. Therefore, LNG storage tanks are required not only to remain undamaged during earthquakes, but also have high aseismicity to provide stable supply after earthquakes. About half of the LNG storage tanks in Japan are of on-ground type and have group pile foundations. They have been designed in accordance with the recommended practice put together by the Japan Gas Association1) to posses adequate aseismicity.

The modified seismic coefficient method is one of the methods recommended for designing and is mainly used because of its simplicity. The design acceleration amplitude is obtained by taking into account importance of structure, seismicity of site, ground conditions and amplification by superstructure response. The design acceleration for a superstructure occasionally becomes 0.6~0.7G. This large design seismic load, combined with the allowable stress method, provides sufficient safety allowing designers to use a simple but imperfect model to analyze such a complex structure as a liquid-tank-foundation coupled system.

The purposes of this seismic observation are

(1) to examine whether behavior patterns other than those which were considered during the design exist, and whether the effects of these behavior patterns are covered by the design value, and

(2) to examine how much margin of safety exists in the actually designed structure.

In this report, analysis of observed earthquake records mainly focuses on foundation behavior, which is still only vaguely known in part and may posses an excess margin of aseismic safety.

OUTLINE OF TANK, OBSERVATION SYSTEM, AND RECORDS

The observation location is situated on reclaimed ground in the city of Takaishi, on the shore of Osaka Bay. Fig. 1 shows a cross section of the tank where sensors were installed. The inner tank, of 57.6m diameter and 28.8m side-wall height, consists of 9% Ni steel of 8 to 27mm thickness, and holds LNG. The outer tank holds a thermal insulation material. The capacity is 75,000kl and the weight 3.63MN. The pile foundation consists of 546 steel pipe piles, each of 60cm diameter and 30m length, on which the stored liquid and tank shell rest through the medium of a double deck base slab.

Fig. 2 shows the instrumentation arrangement. Thirteen acceleration seismographs are arranged on the inner tank, base slab and adjacent ground. Eighteen high-sensitivity strain gauges are arranged on the center pile and 2 piles at the periphery of the pile group so that axial and bending strains at the pile tops can be detected. There is a total of 67 measuring points, measurements from which are transformed into 16 bit digital data and recorded on magnetic tape.

Table-1 shows the seismic data of recorded earthquakes and the corresponding liquid heights. Fig. 3 shows an example of the observed wave forms.

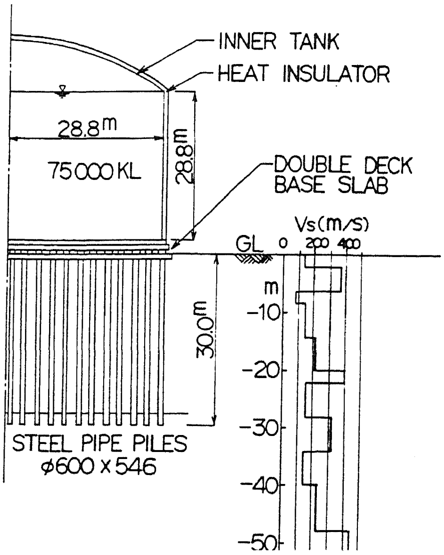


Fig. 1 Profile of the Tank

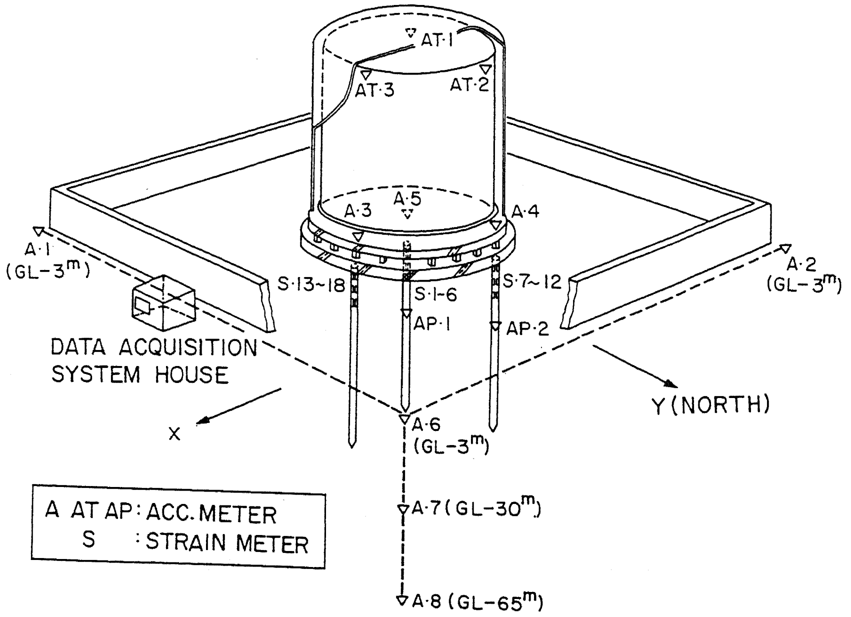


Fig. 2 Sketch of Instrumentation

ACCELERATION AMPLIFICATION DUE TO RESPONSE OF STRUCTURE

Fig.4 shows the distribution of response amplifications of acceleration taking the acceleration amplitude in bedrock as the unit. The marks in the figure are the observed amplifications and the solid line is the distribution of design response amplifications given by the recommended practice 1). Design values are slightly larger than observed values at the upper part of the tank, but there is good coincidence at other parts.

Two kinds of response modes may possibly contribute to this amplification: liquid-tank coupled vibration, bulging, and rocking-sway vibration of liquid-tank as one rigid body. Therefore, using the records of Earthquake No. 5 of high liquid level, the authors obtained the transfer function between tank and base slab, that is, the Fourier spectrum of the inner tank top horizontal acceleration (excluding the contribution of rocking) divided by that of the base slab, and this is shown in Fig. 5. An apparent peak is noted near 2.7Hz. Fig. 6 shows similar transfer functions using the records of Earthquake No. 2. The predominant frequency shifts to a higher frequency range. FEM analysis using liquid and shell elements 2) also indicates the existence of a resonant frequency of bulging near 2.7Hz in the case of a high liquid level. Consequently, the peak of 2.7Hz can be regarded as the contribution of bulging.

Table 1 List of Observed Earthquake

No.	DATE	EPICENTER DISTANCE (km)	MJ	LNG DEPTH (m)	MAX.ACC. GROUND (-3m)(gal)
1	84.2.11	91	5.5	18.6	10.9
2	84.5.30	102	5.6	8.1	16.8
3	84.8. 7	380	7.1	4.8	5.6
4	84.9.14	220	6.9	24.7	6.1
5	85. 1.6	88	5.9	26.3	10.7

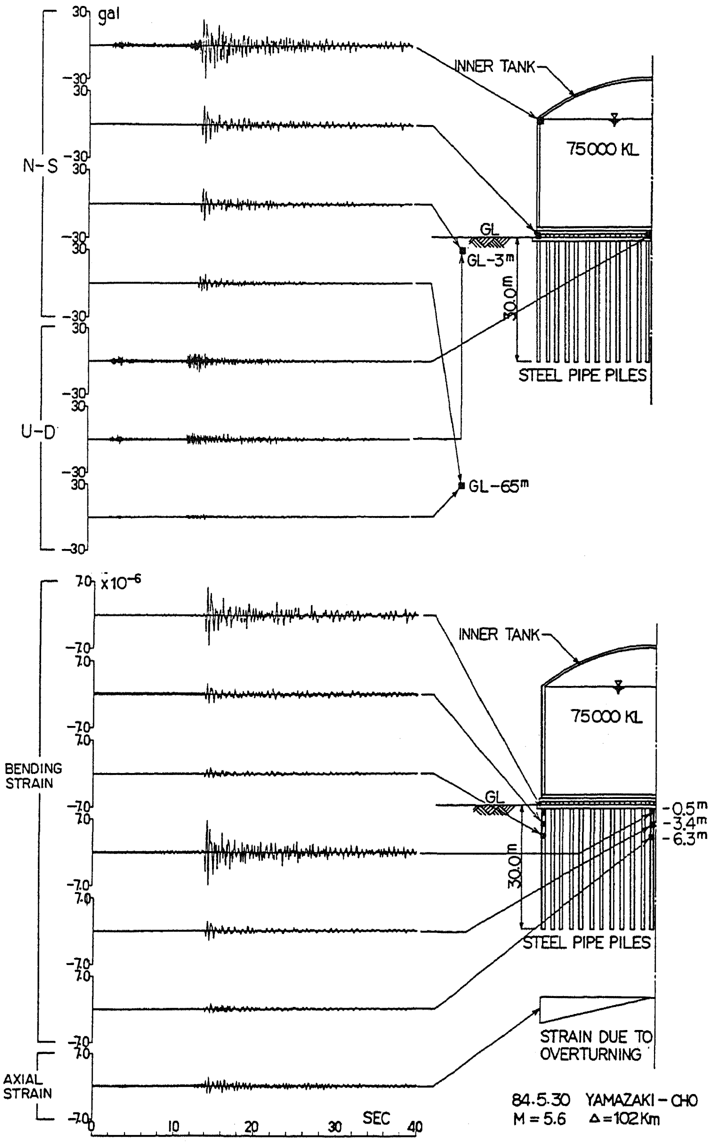


Fig. 3 Example of Observed Records

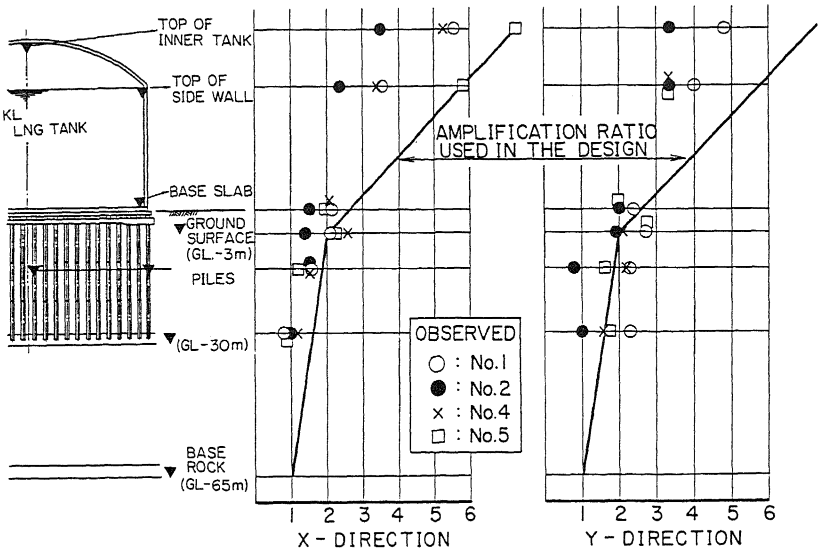


Fig. 4 Amplification of Maximum Acceleration

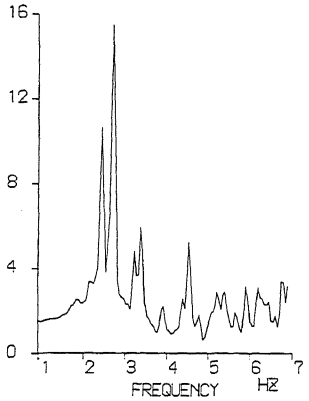


Fig. 5 Tank Top/Base Slab
(No. 5 Liquid Depth = 26.3m)

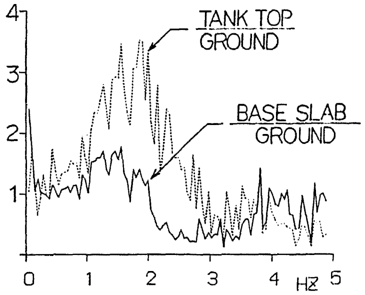


Fig. 7 Base Slab/Ground Surface and Tank Top/Ground Surface (No. 5 Liquid Depth = 26.3m)

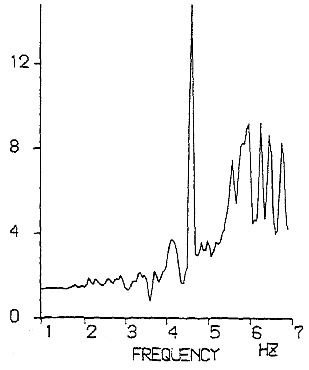


Fig. 6 Tank Top/Base Slab
(No. 2 Liquid Depth = 8.1m)

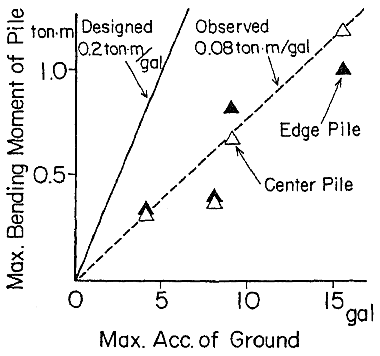


Fig. 8 Correlation between Acceleration of Ground and Bending Moment of Pile

Fig. 7 shows the transfer functions of horizontal components of acceleration between base slab and ground surface and between inner tank top and ground surface, obtained by the same method as mentioned above. When the liquid level is low, the tank responds as a rigid body without relative displacement to the ground in a wide frequency range below 4Hz. When the liquid level is high, the fixed rigid body response is limited to below 1Hz. In the predominant frequency range of ground response, namely 1 to 2 Hz, the tank top responds conspicuously. This amplification of response can be regarded as the contribution of rocking-sway vibration of liquid-tank as one body. Near the bulging frequency of 2.7Hz, the response amplification of the slab decreases, while the response ratio between tank and slab becomes relatively high. It should be noted that the tank top response at the bulging frequency is not the largest. The rocking vibration is assumed to make the main contribution to the acceleration amplification shown in Fig. 4.

BENDING MOMENT OF PILE

Fig. 8 shows the correlation between the maximum response acceleration of ground surface and the maximum response bending moment in the pile section 0.5m below the base slab. Bending moment of a pile can be determined by a pair of observed axial strains. Marks in the figure are observed values from 4 records and the broken line is their regression line. On the other hand, the solid line gives the correlation line of designed values, that is, its gradient is the ratio between design bending moment and design input acceleration. As far as bending moment is concerned, the current design method has a sufficient margin of safety.

Fig. 9 shows the Fourier spectra of pile bending strain and ground surface velocity in both cases of high and low liquid levels. In the case of Earthquake No. 2, when the liquid level was low, these two spectra closely coincided, suggesting that bending strain has a relation with ground strain. Meanwhile, in the case of No. 5, when the liquid level was high, the bending strain spectrum went up in the predominant frequency range of the rocking-sway vibration. This is considered to have been caused by the inertia force of the superstructure. It should be noted that there is no remarkable predominance around the bulging frequency of 2.7Hz in the pile bending strain spectrum.

EFFECT OF PILE GROUP

To obtain a clear concept of pile group effect, subgrade reaction was derived as follows: bending moment time series data for 3 depths, -0.5m, -3.4m, and -6.3m near the pile top, were calculated, and the subgrade reaction among them was obtained by a second difference method. Table 2 shows the maximum values. It should be noted that subgrade reactions at the center pile were less than those at peripheral piles of the foundation. Except for Earthquake No. 2 occuring at a time of low liquid level, the ratios between subgrade reactions at the center and the periphery were lower than 1/2.

Taking the superstructure inertia force, i.e., the total sum of the masses of tank, stored liquid and base slabs multiplied by the base slab horizontal acceleration on the abscissa and the subgrade reaction on the ordinate, the result is Fig.10. It is clearly seen that inertia force of the superstructure has a correlation with the subgrade reaction. It is assumed that the difference of reactions between center and periphery comes from the different rigidities of the pile-ground interaction springs.

On the other hand, it should be stressed that in Fig. 8 bending moments at the center and at the periphery are not noticeably different. It is surmised that not only the superstructure inertia force but also the ground deformation influence the pile bendinmoment, and that the latter is dominant. The result of the shaking table tests by the authors[3)], in which a model of a tank and pile group foundation were vibrated with surrounding ground, supports this presumption.

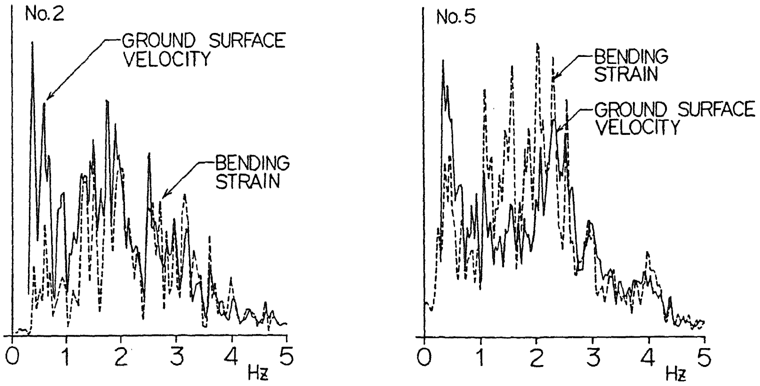
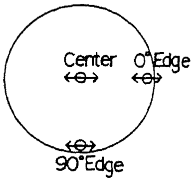


Fig. 9 Fourier Spectra of Pile Bending Strain and Ground Surface Velocity

Table 2 Observed Maximum Subgrade Reaction



	Earthquake No.			
	No.1	No.2	No.4	No.5
Center Pile	52.	70.	23.	39.
0°Edge Pile	141.	86.	47.	68.
90°Edge Pile	150.	73.	62.	113.

Kg/m·Pile

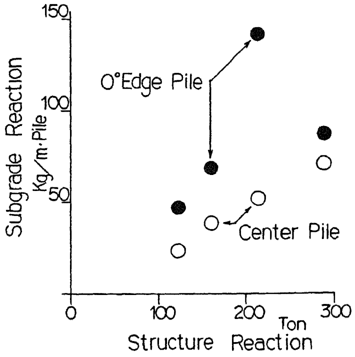


Fig. 10 Subgrade Reaction and Superstructure Reaction

CONCLUSION

This earthquake observation has revealed that bulging does not have much influence on the response of a tank and the current design method properly estimates response acceleration, but overestimates bending moments of piles. However, it must be noted that ground and structure deformations were within the elastic region in these records. It is necessary to clarify the characteristics of response in nonlinear behavior in order to obtain results that may influence the design of an on-ground LNG tank. Continued observation will further be required to analyze records of stronger earthquakes.

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