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OBSERVATION RESULTS AND A CONSIDERATION OF BEHAVIOR OF LNG STORAGE TANK DURING NORTHERN OSAKA EARTHQUAKE

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Abstract

A medium scale earthquake was successfully recorded in the whole tank system in operation of a full containment LNG storage tank for the first time in Japan. The Northern Osaka Earthquake (hypocenter depth: 12.98 km and moment magnitude: 5.6) which occurred at 7:58 on June 18, 2018 was recorded at the full containment LNG tank and its surrounding ground of Senboku LNG terminal No.2 (about 40 km southwest from the epicenter), which is an LNG receiving terminal of Osaka Gas Co., Ltd.. The acceleration of the ground (from GL-206 m to the ground surface) , the inner tank and the outer tank and the reinforcement strain of the base slab was recorded.

The maximum horizontal acceleration at GL-206 m, the ground surface, base slab, the top of the outer tank and the inner tank was 70.3 Gal, 138.7 Gal, 94.3 Gal, 114.3 Gal and 381.0 Gal, respectively.

From these records and the discussions including the analytical approach, the followings were clarified: The behavior of the inner and the outer tank were in the elastic range and the natural frequencies of the inner and the outer tank were about 3.8 Hz and 7.1 Hz, respectively. The behavior of the ground was within the elastic range and the natural frequency of the whole ground and the alluvial and reclaimed layers were estimated to be about 0.5 Hz and 3 Hz, respectively. The input loss from the ground to the base slab was remarkably confirmed in the frequency of 3~6 Hz. The main overall response mode of the outer tank was assumed to be “foundation sway”. The bending acts on the base were generated by vertical motion, and that the behavior changed by the horizontal motion.

Keywords: Northern Osaka Earthquake, Seismic record, Full containment LNG tank

1. Introduction

Liquefied Natural Gas (LNG) is one of the important energy sources for gas supply and power generation in Japan. Most of the LNG is imported and received at LNG receiving terminals. LNG tanks are one of the most important facilities in a LNG receiving terminal from the security and operation viewpoint, hence, earthquake observations at a full containment LNG tank in Senboku LNG Terminal No.2 has been being conducted to properly evaluate the impact on LNG tank after an earthquake.

Fig.1 shows structural outline of the full containment LNG tank, which mainly consists of an inner tank and an outer tank. The inner tank is made of 9 % Ni steel and contains cryogenic LNG in the normal operation condition. The outer tank is made of prestressed concrete and provides full containments of the LNG in the emergency situations of LNG spillage from the inner tank. The maximum design liquid level is 34.085 m. The LNG tank has been designed for two levels of earthquake accelerations: Level 1 and Level 2 based on “Recommended Practice for LNG Aboveground Storage”, as per the requirement of the Gas Business Act in Japan. Modified seismic coefficient method has been adopted for the seismic design. For the Level 1 seismic design, the peak ground acceleration (PGA) is 240 Gal in the horizontal direction and 120 Gal in the vertical while 480 Gal (horizontal) and 240 Gal (vertical) for the Level 2 seismic design. The response acceleration that considers the response magnification corresponding to the natural period of the structure is applied to the structure. The design criteria for the Level 1 seismic design is that “No harmful deformation remains and gas tightness is maintained, i.e, the structure behaves within elastic" and that for the Level 2 is "To maintain gas tightness even if deformation remains".

Fig.2 shows seismic monitoring instrumentation arrangement. Accelerometers are installed on/in the inner tank, bottom insulation layer, outer tank wall, base slab of outer tank and the ground. The ground accelerometers are installed at positions of about 20 m away from the tank so as not to be affected by the tank behavior. In the figure, legends "AI", "AO", "AB" and "AS" denote the accelerometer installed on/in inner tank, outer tank, base slab and ground, respectively; the measurement directions are NS, EW and UD. The strain gauges are installed at the horizontal (NS direction) upper and lower reinforcement within the base slab, which are denoted by "SB". Fig.3 shows soil profile with the installation depth of accelerometers.

The Northern Osaka Earthquake (hypocenter depth: 12.98 km and moment magnitude: 5.6) which occurred at 7:58 on June 18, 2018 was recorded at this full containment LNG tank and its surrounding ground (about 40 km southwest from the epicenter. See Fig. 4 [1]) and the operation liquid level when the earthquake occurred was 22.607 m. This is the first time a medium scale earthquake has been recorded in the whole tank system in operation of a full containment LNG tank in Japan.

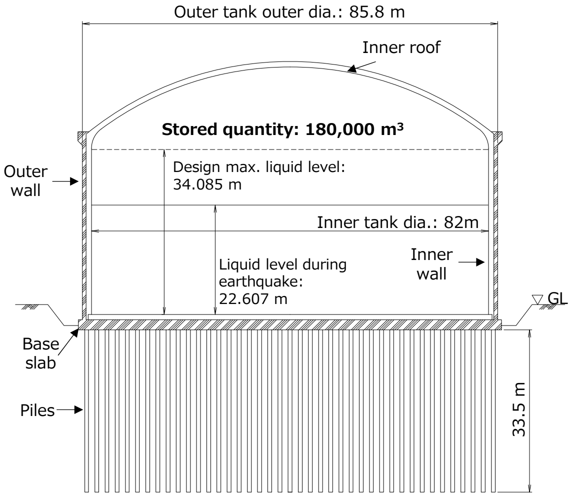


Fig. 1 – Structural outline

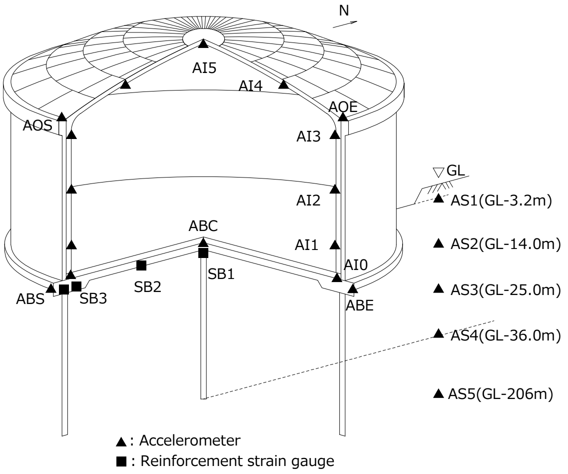


Fig. 2 – Instrumentation arrangement

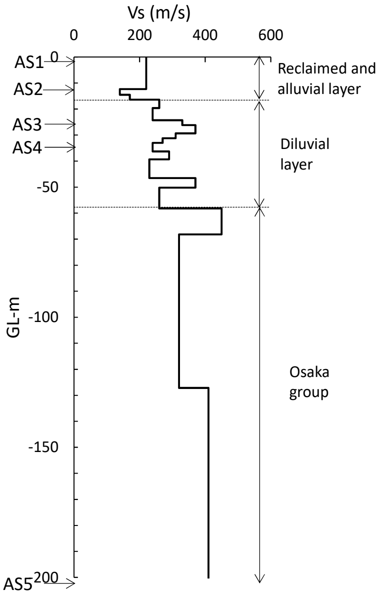


Fig. 3 – Soil profile

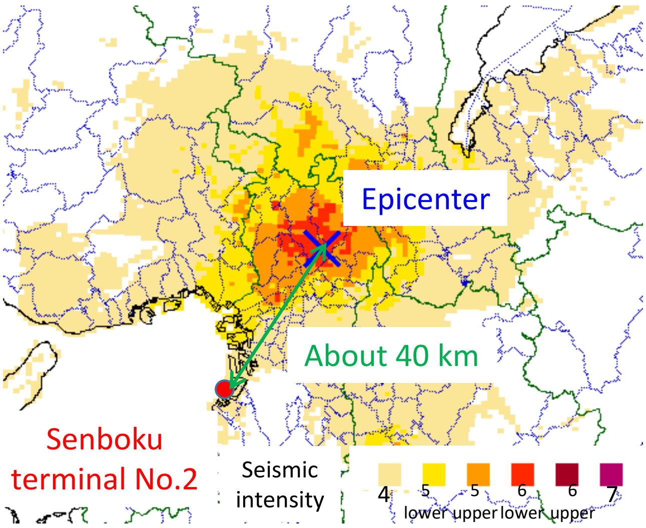


Fig. 4 – Position relation between tank and epicenter

2. Observation results of the accelerations

Fig. 5 shows representative acceleration time histories in the ground and the inner tank, outer wall and base slab, respectively. The EW direction acceleration is dominant, which is consistent with the record at K-NET Takatsuki, which is located about 6 km north of the epicenter [2].

Regarding the acceleration in EW direction, the recorded maximum acceleration at GL-206 m, where Vs value is large enough to be regarded as the design base bed, was 70.3 Gal. No significant increase in seismic acceleration was recorded in the Osaka group clay and sand layers and the diluvial layers, while significant responses were recorded in the alluvial and reclaimed layers shallower than about GL -16 m. The PGA recorded was 138.7 Gal. The recorded maximum acceleration at the base slab (“ABE”) was 89.3 Gal, i.e. input loss of more than 30 % was confirmed. In the inner tank, the acceleration at the “AI1” level was significantly amplified, and the recorded maximum acceleration was 381.0 Gal. “AI1” was installed at a height of 11.5 m from the inner bottom plate level, i.e., it is about half of the operation liquid level (22.607 m) when the earthquake occurred. In the outer wall, the recorded maximum acceleration at the top of the outer wall (“AOE”) was 114.3 Gal.

The recorded maximum acceleration at GL-206 m was 69.3 Gal in the NS direction. No significant increase in acceleration was recorded compared to that in the EW direction. The PGA recorded was 60.8 Gal. In the inner tank side wall, no significant amplification was recorded. It is considered that the observation points in the east side of the inner tank wall were not significantly affected in the NS direction by the dynamic liquid pressure.

The recorded maximum acceleration at GL-206 m was 26.0 Gal in the UD direction. Amplification of acceleration was confirmed for the diluvial, alluvial and reclaimed layers. The PGA recorded was 59.7 Gal. In the inner tank, the acceleration was almost unresponsive at the inner tank side wall. On the other hand, significant amplification of the maximum acceleration of the center of the inner tank roof (“AI5”) was recorded, and the recorded maximum acceleration was 208.0 Gal. It is considered that the roof is a planar member and responded to the vertical vibration.

3. Discussion

3.1 Overview of overall response characteristics

Fig. 6 shows maximum acceleration response distribution in the EW direction. The Level 1 seismic design accelerations at each position are also indicated in the figure. The response accelerations of both inner and outer tank are smaller than the Level 1 seismic design accelerations, i.e., it can be said that the behavior of the inner and the outer tanks is elastic. The response magnifications for the inner and the outer tanks are 4.27 and 1.28, respectively. Here, the response magnification is defined as the ratio of the maximum acceleration at a target point (“AI1” for the inner tank and “AOE” for the outer tank) to that at the base slab. The recorded response magnification of 4.27 for inner tank is larger than the design response magnification of 2.5. However, the maximum acceleration at point “AI1” was a pulse peak, and except for this peak, the acceleration was less than 200 Gal. If a response acceleration of 200 Gal is applied, the calculated response magnification is 2.3. Therefore, it is considered that the response magnification is basically within the design assumption. The recorded response magnification of 1.28 for the outer tank is smaller than design response magnification of 1.5.

The recorded maximum ground accleration at each depth is smaller than that considered for design. The ratio of maximum acceleration between ground surface (“AS1”) and GL-206 m (“AS5”) is 1.97, which is almost equivalent to 2.0 considered for design.

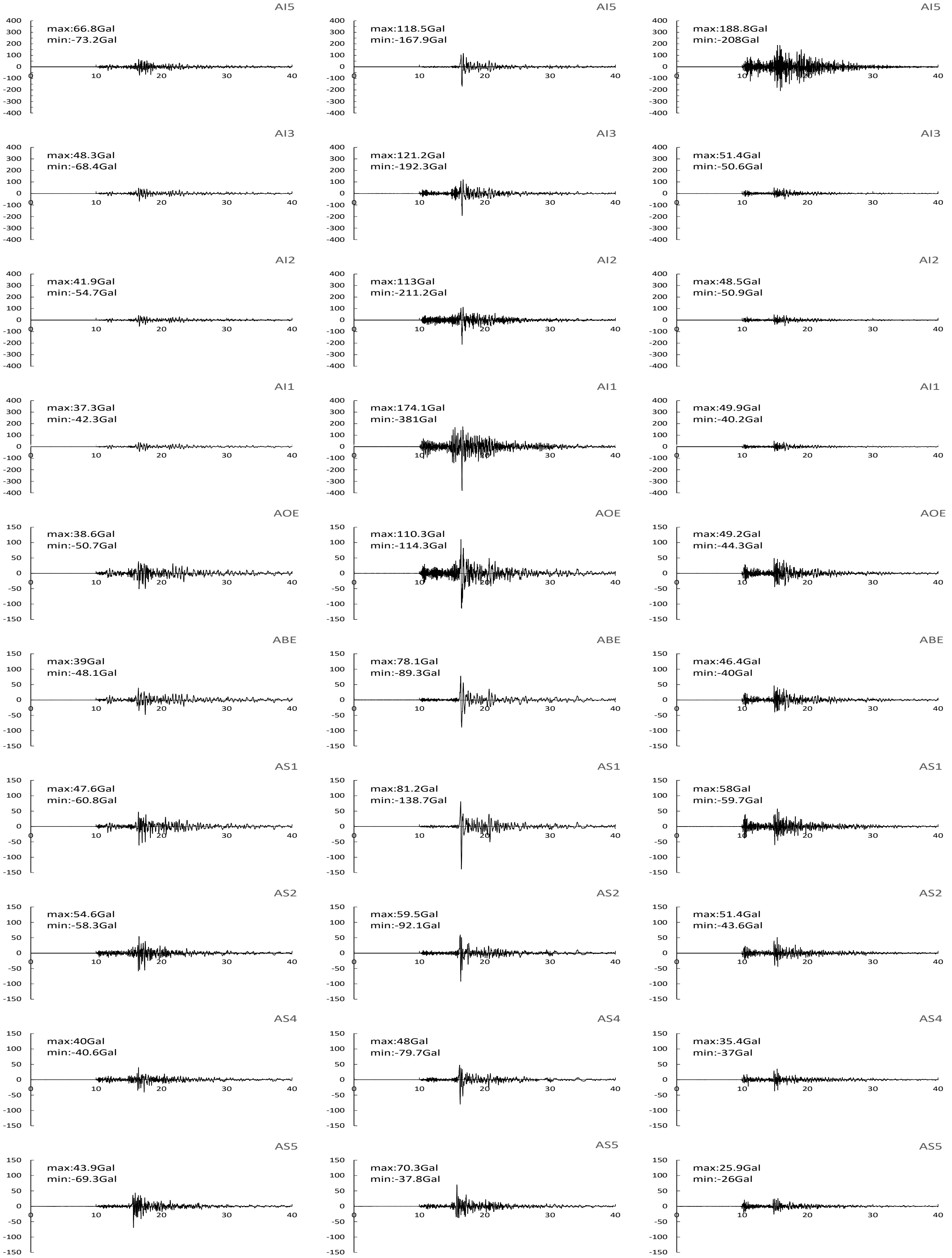
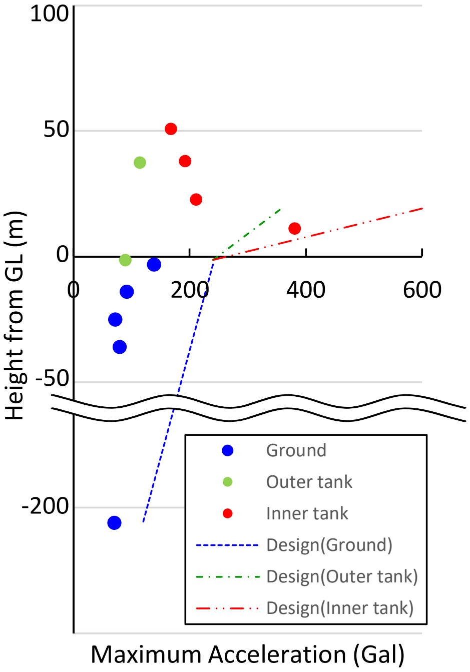


Fig. 5 – Acceleration time histories (Left to right: NS,EW,UD; X: time(sec.) and Y: acceleration (Gal))



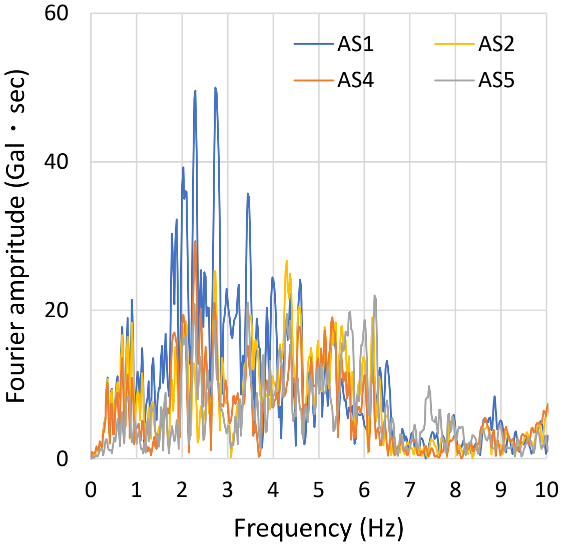


Fig. 6 – Maximum acceleration response distribution in EW direction

Fig. 7 – Fourier spectrum in ground (EW)

3.2 Ground response characteristics

The Fourier spectrums at “AS1”, “AS2”, “AS4” and “AS5” locations are shown in Fig. 7 for the EW direction. It can be confirmed that for the waves whose frequencies are around 2.0 to 3.5 Hz, significant amplification was observed by comparing the amplitude of “AS1” and “AS2”, which located across the alluvial and reclaimed layers.

For further discussions, one-dimensional seismic site response analysis by “SHAKE” based on an equivalent linear analysis has been conducted. Soil properties applied to “SHAKE” are based on the soil investigation results for this tank area. In this calculation, the recorded wave in the EW direction at “AS5” location has been used as the input wave. Fig. 8 shows the maximum acceleration comparison in depth direction between record and analysis. Fig. 9 shows the maximum shear strain against depth. From Fig. 8, the acceleration response tendency is closely reproduced by the analysis. It is also confirmed in the analysis that the responses in the alluvial and reclaimed layers (in which Vs are small compared to the other layers) are remarkable. From Fig. 9, the maximum shear strain is 0.066 %, i.e., the behavior of the ground is considered to be within the elastic range.

Fig.10 and Fig.11 show the transfer function between the “AS1” and “AS5” and that between the “AS1” and “AS2” locations, respectively. The observed and analyzed transfer functions in each figure is considered to be a close match. The natural frequency of the whole ground is estimated to be about 0.5 Hz, while that of the alluvial and reclaimed layers (where the amplification of acceleration were significantly higher) is estimated to be about 3 Hz.

3.3 Input loss from ground to base slab

In order to confirm the input loss to the base slab, the Fourier spectrum ratio of “ABC” and “AS1” in EW direction has been calculated as shown in Fig. 12. The remarkable input loss calculated is in the range

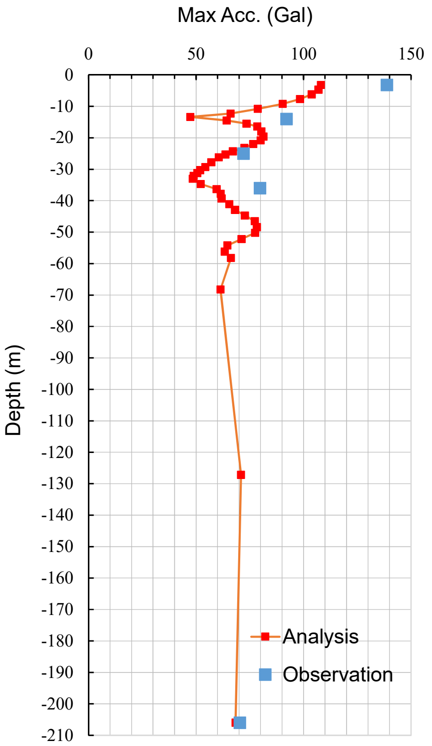


Fig. 8 – Max. acceleration vs depth (EW)

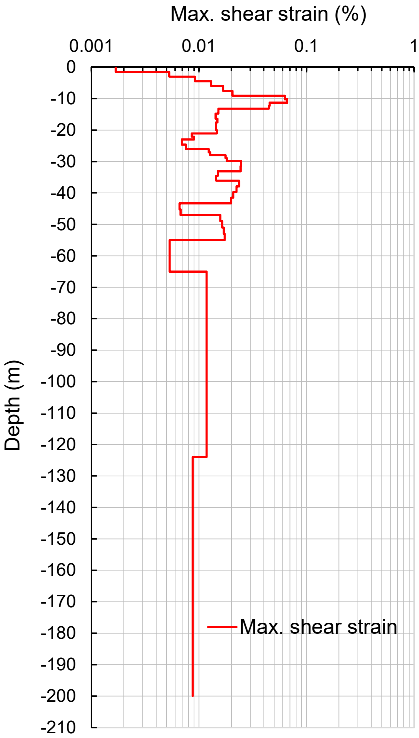


Fig. 9 – Max. shear strain vs depth (EW)

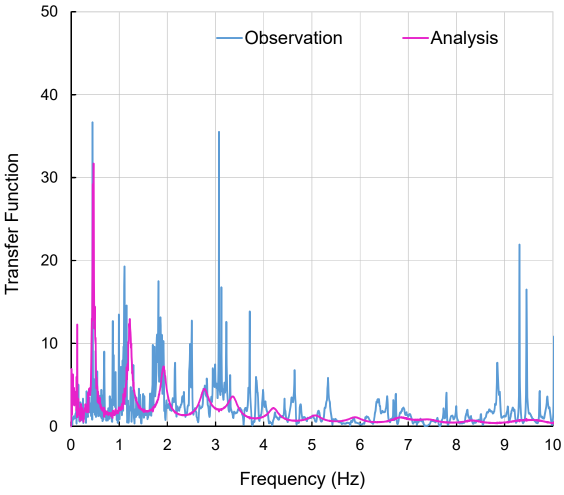


Fig. 10 – Transfer function between GL-3.2 m and GL-206 m (EW)

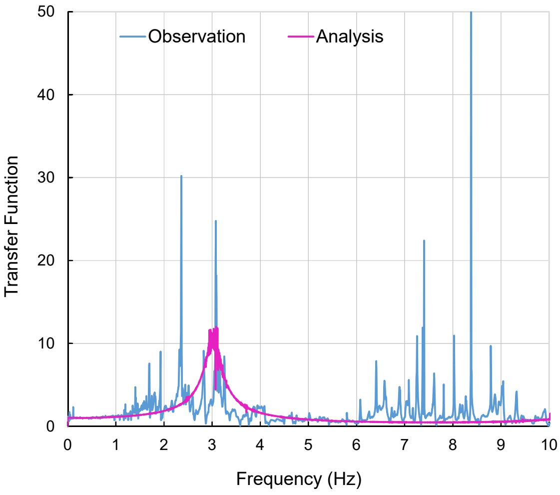


Fig. 11 – Transfer function between GL-3.2 m and GL-14.0 m (EW)

between 3 ~ 6 Hz for the tank with liquid level of 22.607 m. This range also matches to that of previously observed at this tank in empty during the Western Tottori Earthquake (PGA = 23.1 Gal), which occurred on October 6, 2000 [3]. Hence, the input loss depends on the characteristics of the structure, but not on the

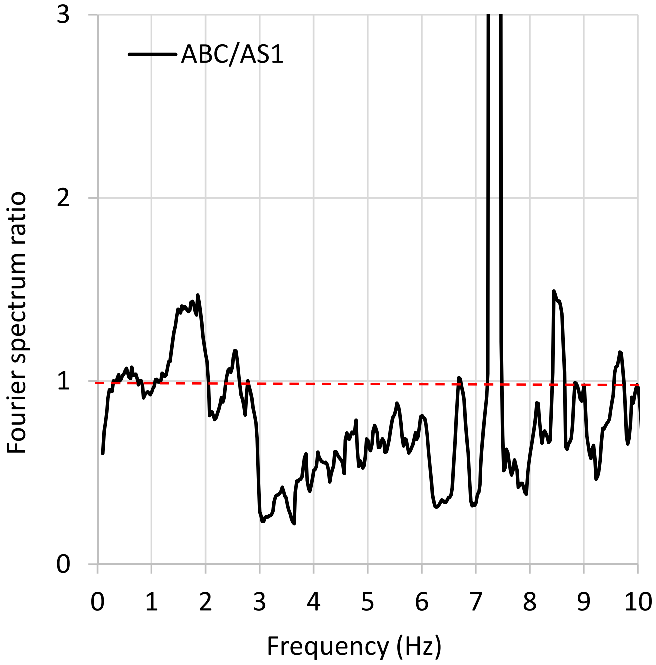


Fig. 12 – Fourier spectrum ratio between base slab and GL-3m (EW)

characteristics of the earthquake. The natural frequency of the inner tank is 3.8 Hz, which will be discussed in 3.4, lies within the frequency band where the input loss is observed. Therefore, the input loss may contribute to the reduction of the acceleration response of the inner tank as a result.

3.4 Inner tank response characteristics

Fourier spectrums of "AI0", "AI1", "AI2" and "AI3" locations in EW direction are shown in Fig. 13. In addition, Fig.14 shows the Fourier spectrum ratio between "AI0" and "AI1", which is the position where significant amplification of acceleration was recorded. According to Fig. 13 and 14, the acceleration responses with frequency around 3.8 Hz, 7.1 Hz and 9.1 Hz are amplified, especially at "AI1" location.

For the analytical confirmation, an axisymmetric finite element (FE) model has been carried out utilizing "ABLE", a program developed by Obayashi Corp. The profile of FE model is shown in Fig. 15. Shell element is adopted for modelling the inner base plate and inner wall, with parameters of elastic modulus "E", thickness "t", density "ρ" and poisson's ratio "ν" shown in the model as well. To evaluate dynamic effect of content liquid, the liquid element based on the potential theory with small amplitude wave height is adopted for LNG. The boundary for the inner base plate is modelled as fixed in both horizontal and vertical directions. Fig. 16 shows the frequency response function between inner base plate and inner wall correspond to the measurement point "AI1". A frequency of 3.8 Hz corresponds to the natural frequency of the modelled inner tank including dynamic interaction between content fluid and side wall of the tank. Comparing with Fig. 14, observed peak of 3.8 Hz is assumed as the natural frequency of the inner tank.

Fig. 17 compares the recorded maximum acceleration distributions on the inner tank wall and that of the analyzed mode shape. Here, the acceleration is normalized so that the acceleration at "AI1" location becomes 1. The response modes of analysis and observation show good agreement. The maximum acceleration ratio is found to be at the height corresponding to about a half of the liquid height at the earthquake due to the effect of the dynamic liquid pressure. On the other hand, it can be seen that the value tends to be near constant above the liquid height.

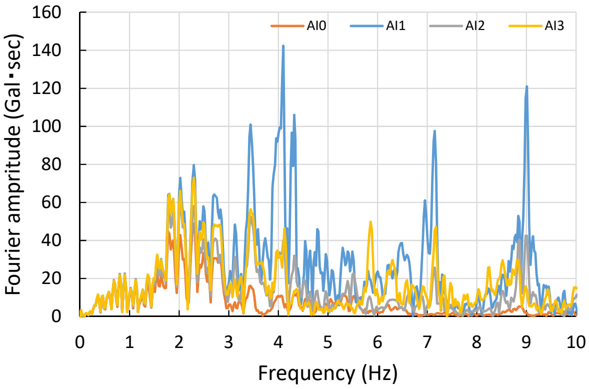


Fig. 13 – Fourier spectrum at bottom insulation and inner side wall (EW)

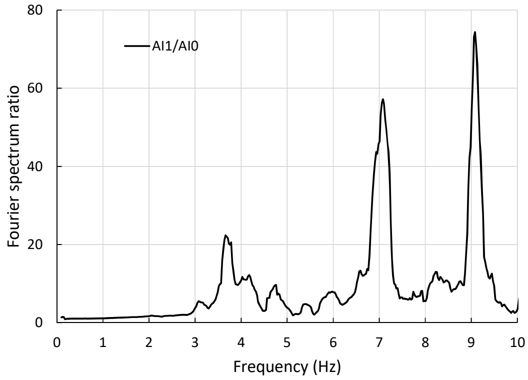


Fig. 14 – Fourier spectrum ratio between bottom insulation and lower inner side wall (EW)

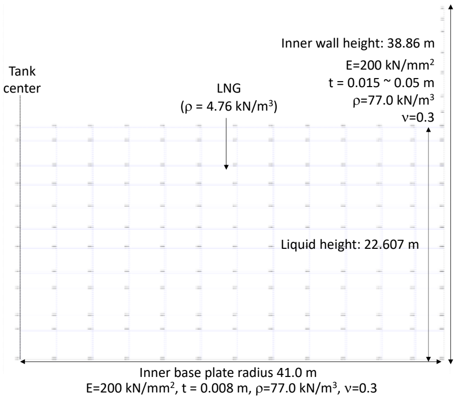


Fig. 15 – Analysis model of inner tank

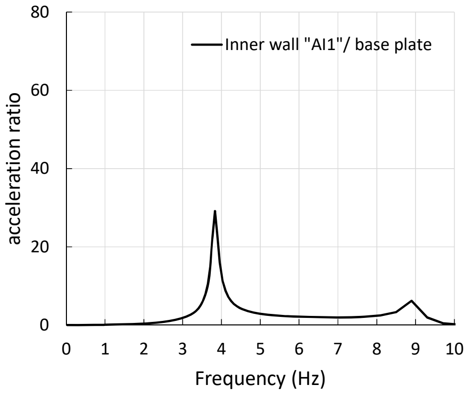


Fig. 16 – Frequency response function between base plate and lower inner side wall

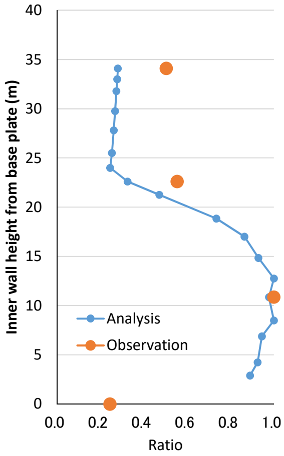


Fig. 17 – Comparison between analysis and observation acc. distribution

3.5 Outer tank response characteristics: The natural frequency

Fig. 18 and 19 shows the Fourier spectrum at “ABE” and “AOE” and the Fourier spectrum ratio between “ABE” and “AOE”, respectively, both in the EW direction. In the figures, amplification peaks at 3.7 Hz, 7.1 Hz, 8.2 Hz and 9.1 Hz, especially 7.1 Hz, can be observed.

For the analytical confirmation of natural frequency, an axisymmetric FE model was adopted as for the inner tank. The analysis model is presented in Fig. 20 with parameters of shell elements for the base slab and the outer wall, of design concrete compressive strength “F_{ck}”, elastic modulus “E”, thickness “t”, density “ρ” and poisson’s ratio “ν”. To consider the roof load, line load of 82.4 kN/m has been attached at the top of the wall. The boundary for the base slab is modelled as fixed in both horizontal and vertical directions. Fig. 21 shows the frequency response function between base slab and top of the wall. The maximum value is 7.49 Hz. Considering these results, the recorded peak at 7.1 Hz is assumed to be the natural frequency of the outer tank of the response mode of “Tank sway” as shown in Fig. 22.

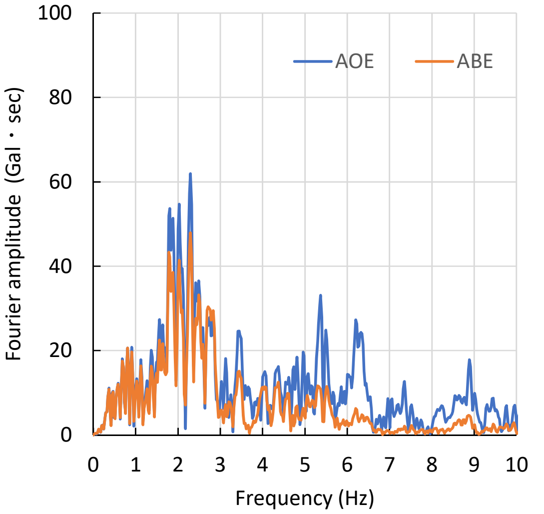


Fig. 18 – Fourier spectrum at the base slab and the top of the outer wall (EW)

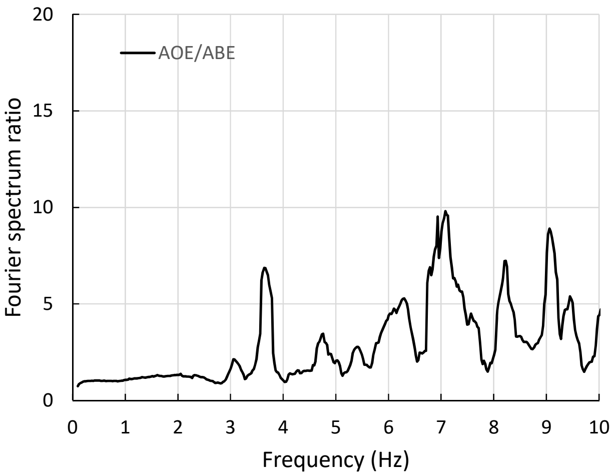


Fig. 19 – Fourier spectrum ratio between the base slab and the top of the outer wall (EW)

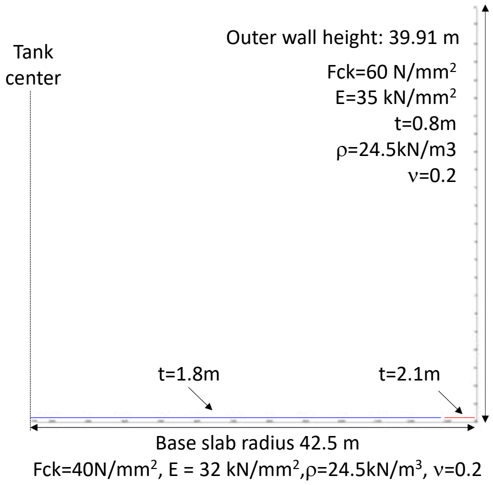


Fig. 20 – Analysis model of the outer tank

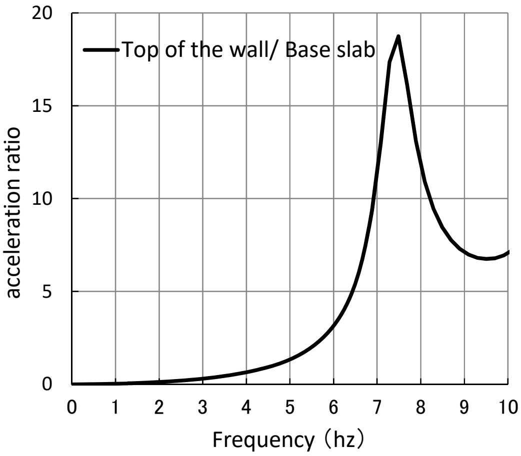


Fig. 21 – Frequency response function between the base slab and the top of the outer wall

3.6 Outer tank response characteristics: The response mode

The overall response mode of the tank structure will be discussed in this section. The representative response mode is shown in Fig. 22. Acceleration time histories of the tank are shown in Fig. 23 through Fig.28. Responses of base slab are compared in Fig. 23 through Fig.25 as “ABE” and “ABC” for the EW direction, “ABS” and “ABC” for the NS direction and “ABS” and “ABC” for the UD direction, respectively. Similarly, responses of ground surface and outer tank are compared in Fig. 26 through Fig.28, as “AS1”, “ABE” and “AOE” for the EW direction, “AS1”, “ABS” and “AOS” for the NS direction and “AS1”, “ABS” and “AOS” for the UD direction, respectively. These figures show the time range from 14 to 18 seconds after the start of the record, when both horizontal and vertical maximum accelerations are observed. From Fig. 23 and 24, the

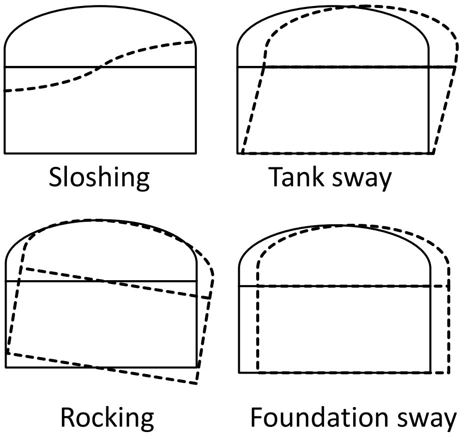


Fig. 22 – The representative response mode

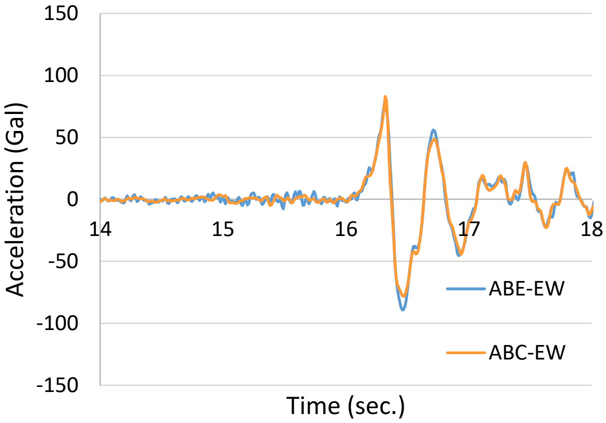


Fig. 23 – Acceleration at the base slab (EW)

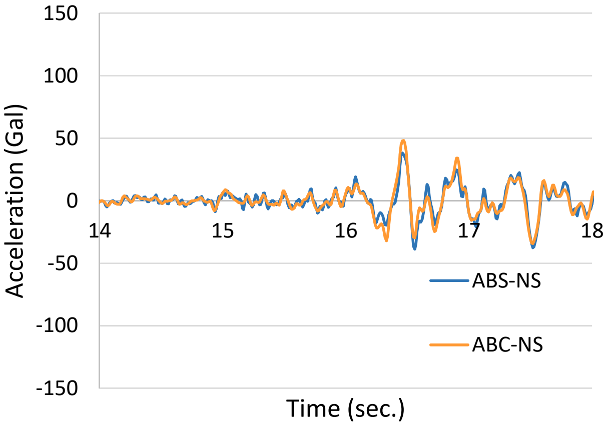


Fig. 24 – Acceleration at the base slab (NS)

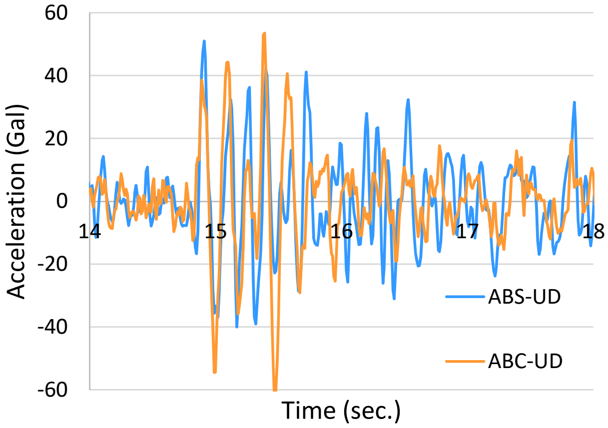


Fig. 25 – Acceleration at the base slab (UD)

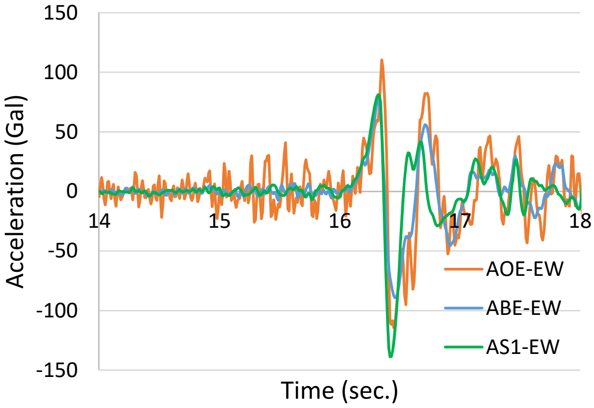


Fig. 26 – Acc. at base slab and top of the wall (EW)

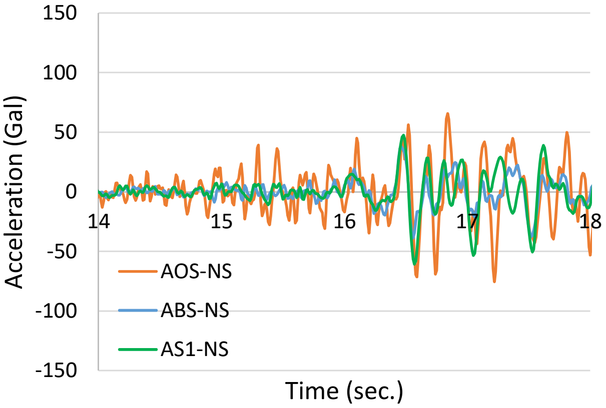


Fig. 27 – Acc. at base slab and top of the wall (NS)

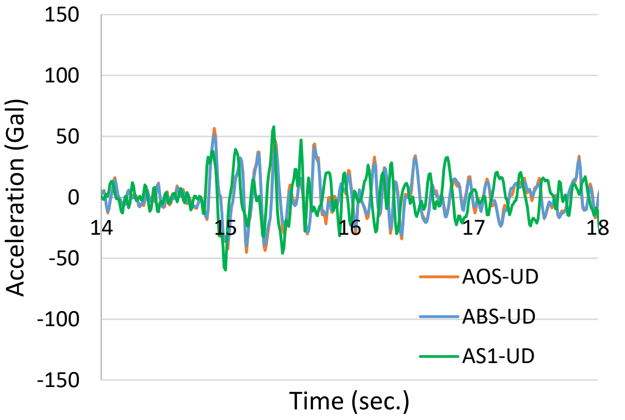


Fig. 28 – Acc. at base slab and top of the wall (UD)

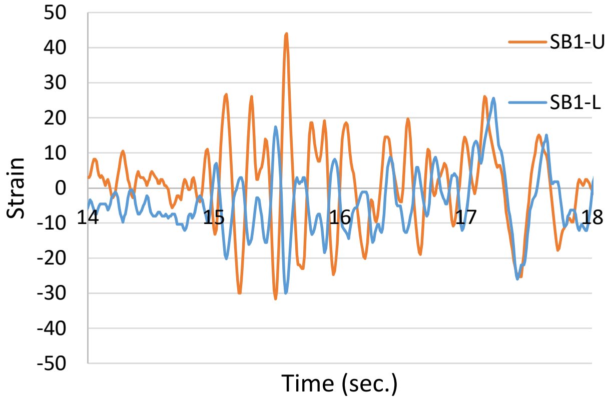


Fig. 29 – Strain of slab reinforcement (SB1)

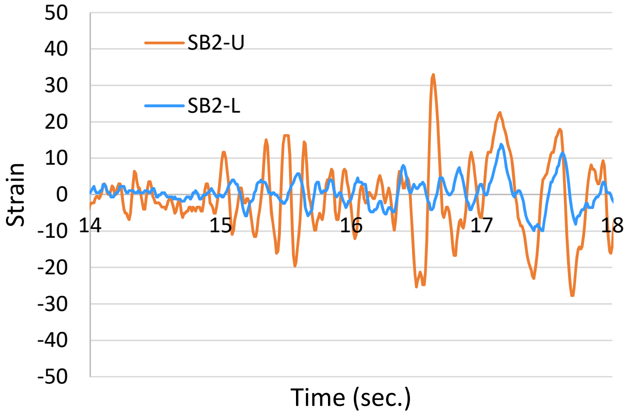


Fig. 30 – Strain of slab reinforcement (SB2)

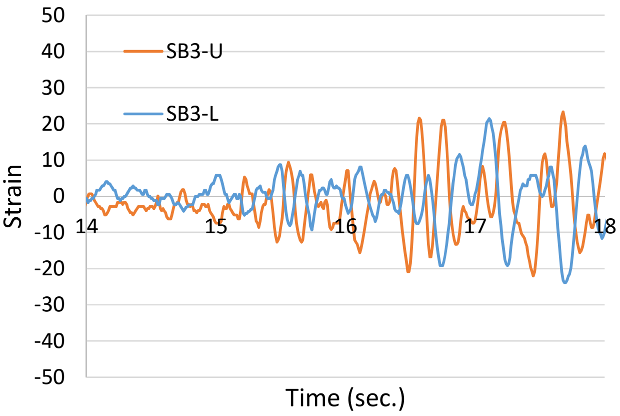


Fig. 31 – Strain of slab reinforcement (SB3)

phase and amplitude of EW and NS wave at the base slab coincide. On the other hand, according to Fig. 25, the phase of the UD wave of base slab at central and circumferential position is the same, in the time range of about 14 ~ 16 sec., when only the vertical motion is dominant. On the other hand, in the time range of about 16 ~ 18 sec., when relatively large horizontal motions are also observed, the phase is almost opposite. The latter phenomenon is considered to be caused by of a “rocking” of the foundation. Furthermore, according to the comparison between EW and NS waves among the ground surface, the base slab and the top of the wall, the global phase is coincidence among the ground surface, the base slab and the top of the wall although the amplitude has some differences. Based on the coincidence of the phase, the predominant response mode is assumed to be “foundation sway”.

Time histories of the reinforcement strain in base slab are compared in Fig.29 through Fig.31, as “SB1-U (Upper)” and “SB1-L (Lower)”, “SB2-U (Upper)” and “SB2-L (Lower)” and “SB3-U (Upper)” and “SB3-L (Lower)” for the NS direction, respectively. According to Fig. 29 and 30, during the time range of 14 ~ 16 sec., when only vertical motion domination due to unreached horizontal mainshock as shown in Fig. 23, 24 and 25, strain time histories of the upper and lower reinforcement are antiphase. There is a tendency to shift from the opposite phase to the same phase in the time range of 16 ~ 18 sec., when relatively large horizontal motions are observed. Because the reinforcement strains of SB1 and SB2 have been measured at the inter-pile position at which the base slab fixed by piles, it is considered that bending acts on the base slab were generated by vertical motion during the time range of 14 ~ 16 sec. as shown in Fig. 29 and 30. Then, the behavior changed with progress of the horizontal motion domination. On the other hand, the strains of the upper and lower reinforcement of SB3, of which strains measured at the edge of the slab, show opposite phases over the entire time period according to Fig. 31. This is due to the bending of the slab around the slab edge caused by a "rocking" motion, as shown in Fig.22, during the horizontal mainshock in succession to the vertical shock.

4. Conclusions

1. A medium scale earthquake was successfully recorded in the whole tank system in operation of Japanese full containment LNG tank for the first time.
2. The recorded acceleration for the EW direction was dominant. The maximum acceleration at GL-206 m was 70.3 Gal; PGA was 138.7 Gal. For the inner tank, the acceleration at the position of the height of 11.5 m from the inner bottom plate, where is about half of the operation liquid level at the earthquake, was significantly amplified, 381.0 Gal. For the outer tank, the maximum acceleration of the base slab and the top of the outer wall was 89.3 Gal and 114.3 Gal, respectively.
3. The response accelerations of both inner and outer tank was smaller than that of the accelerations of level 1 seismic design, i.e., the behavior of the inner and outer tank were in the elastic range. For the response magnification viewpoint for inner, outer tank and ground, the observation results were almost within the design assumption.
4. It is considered that the behavior of the ground was within the elastic range because the analyzed maximum sheare strain is 0.066 %. And the natural frequency of the whole ground was estimated to be about 0.5 Hz, and that of the alluvial and reclaimed layers, where the amplification of acceleration was remarkable, was estimated to be about 3 Hz.
5. Input loss from ground to base slab was confirmed. The maximum acceleration of the base slab was more than 30 % smaller than PGA. In frequency domain, the input loss was remarkably confirmed in the frequency range of 3~6 Hz. This observation result was the similar trend the results recorded by Western Tottori Earthquake.
6. About 3.8 Hz was assumed to be the natural frequency of the inner tank. The response mode is greatly influenced by the dynamic liquid pressure and the maximum value was confirmed at the position of about a half of the liquid height at the earthquake.
7. About 7.1 Hz was assumed to be the natural frequency of the outer tank. The main overall response mode of the outer tank was assumed to be "foundation sway".
8. It was confirmed that the bending acts on the base slab were generated by vertical motion, and that the behavior changed by the horizontal motion.

References

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