DAMAGE ANALYSIS OF OIL STORAGE TANKS FOR OFF MIYAGI PREFECTURE EARTHQUAKE OF JUNE 12, 1978

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SUMMARY

The off Miyagi Prefecture Earthquake of June 12, 1978 caused five tanks among the eighty tanks or so of the Tohoku Oil Sendai Refinery to fail or crack at the annular bottom plate and shell plate joint, causing the contents to flow out or leak. Various studies and stress analyses of the tank foundations and tank bodies were conducted to investigate the cause of damage. Stress analyses confirmed that the five damaged tanks received severer stress conditions at the annular bottom plate corner than the other tanks. The cause of damage is explained mainly from the stress analysis point of view.

1. INTRODUCTION

The Tohoku Oil Sendai Refinery is located near Shiogama City where the maximum horizontal acceleration at ground surface recorded about 300 gals during the off Miyagi Prefecture Earthquake that occurred on June 12, 1978. Five tanks among the eighty or so cylindrical steel tanks in the refinery failed or cracked at the annular bottom plate at the joint with the shell plate and the contents flowed out or leaked[1)]. To investigate the cause of the failure, various studies and stress analyses were performed on the tank foundations and tank bodies. This paper outlines the studies and stress analyses made of the tanks with emphasis placed on the latter.

2. METHOD OF STRESS ANALYSIS AND ASSUMPTIONS MADE

The stress analyses were made on the basis of the small deflection theory under the following assumptions:[2)]

1) Shell plate: Cylindrical shell
2) Bottom plate and annular bottom plate: Circular flexural plate on elastic spring
3) Tank foundation: Winkler foundation (the coefficient of uniform elastic spring was given as 15 kg/cm^3, referring to the results of a loading test on the mound)

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3. STRESS ANALYSIS CONDITIONS AND TANKS ANALYZED

The various loads and conditions employed for the stress analysis are as follows:

1) Static liquid pressure
2) Tank body weight
3) Uneven settlement of annular bottom plate along perimeter
4) Thermal load of contents
5) Seismic load (horizontal acceleration = 0.3 G)

The physical parameters and the dimensions of the nine tanks subjected to stress analysis are shown in Table 1. These tanks consist of the five damaged tanks and four other tanks which were located near the damaged tanks and damaged slightly by the earthquake. The thickness of the annular bottom plates measured after the earthquake revealed that the plates in some of the tanks were corroded on the bottom surface. The corroded condition of the annular bottom plates and the model of stress analysis correlated to the corroded condition are shown in Table 2.

4. STRESS ANALYSIS RESULTS

The damage caused to the tanks by the earthquake was catastrophic failure of the annular bottom plate along the inside fillet weld toe at the shell plate joint. Therefore, only the bending stresses at the annular bottom plate at the joint with the shell plate were extracted from the results of the stress analysis of the tank structure and are discussed as follows:

1) The bending stresses just before the main shock at the annular bottom plate perimeter joint of the nine tanks analyzed for various loads were as shown in Fig. 1. It can be seen that the range of maximum bending stress analyzed in the annular bottom plate at the joint with the shell plate of each tank was predicted to be 24 thru 42 kg/mm^2, except for tank T-223 which had a low level of contents. From this, with the exception of tank T-223, it can be said that the stress amplitude for loads and conditions such as uneven settlement and thermal stress is rather small compared with stresses caused by static liquid pressure plus the tank body weight.

2) The maximum stress and the maximum stress range under seismic conditions at the annular bottom plate at the joint with the shell plate have the relationship shown in Fig. 2. These results are mapped in the plot plan of the refinery as shown in Fig. 3. The A_s class in the figure are defined as those with maximum stress (σ_B) exceeding the yield stress (σ_y) and the maximum stress range ($\Delta\sigma_B$) exceeding twice the yield stress under seismic load conditions. The A class are defined as those with maximum stress exceeding the yield stress and the maximum stress range not exceeding twice the yield stress.

   The five tanks damaged with catastrophic failure of the annular bottom plate were classified as A_s class.[1)3)] The reason for the damage could be explained clearly from the viewpoint of high stress in the annular bottom plate, even though stress analyses were made on the small deflection theory basis. Tanks T-131 and T-221 with penetrated cracks in the annular bottom plate at the joint which leaked oil were classified as A_S class in stress level under seismic load conditions. Tanks T-130, T-215, and T-216 which did not fail or crack at the annular bottom plate because the corrosion was slight were classified as A class.

5. CONSIDERATIONS AND DISCUSSION OF VARIOUS STUDIES AND ANALYSES

To investigate the cause of tank damage, various studies, tests, and analyses in addition to the above stress analyses were performed. The results are discussed and considered as follows:

1) The possibility of abnormal characteristics in response and amplification against the earthquake in the C-3 and C-4 areas where the damaged tanks were concentrated as shown in Fig. 3 were studied by response analyses on the basis of data obtained from physical tests made on the site. However, it was found that no abnormal ground motion attacked these areas.

2) The liquefaction phenomenon was found at an old riverbed and at a seaside area that was reclaimed comparatively recently in the Sendai area, but this phenomenon could not be observed in any part of the refinery area.

3) To study the phenomena of tank settlement under ground motion, model tanks placed on sand mounds were shaken on a shaking table as shown in Fig. 4. It was observed that the tank shell bottom settled quickly into the sand mound along the perimeter uniformly as shown in Photo. 1 when horizontal acceleration reached some critical value. Also, it was observed that the critical value became smaller as the static vertical load at the tank shell bottom became larger, and that as the distance between the tank shell and the outer edge of the sand mound became shorter, the settlement occurred easier. Qualitatively, this explains the reason why tank settlement occurred along the perimeter during the earthquake.

4) Observation of the fracture at the broken part of the damaged tanks showed that it could be classified into several types as shown in Fig. 5. The types A-1, B-1, and D which were most common among the fracture types had vertical flat surfaces in the upper half or the whole section of the plate and had a laminated fracture. Also, observations by the electron microscope indicated patterns like elongated dimples in the upper and lower parts of the fracture in the plate as shown in Photo.2. From the above, it is quite possible that the crack occurred from the area near the inside fillet weld toe at the joint. In testing the materials of the damaged tanks, the material of the annular bottom plate met the standards of WES135-1970, HW50.

5) Stress analyses were performed by assuming an input horizontal acceleration of 0.3 G, referring to the acceleration recorded during the earthquake on the ground surface near the refinery. The results revealed that the tanks that were damaged, T-217, T-218, and T-224, and the tanks that developed penetrated cracks, T-131, and T-221, were classified as A_S class, defined as those with both maximum stress exceeding

yield stress (σ_y = 50 kg/mm^2) and maximum stress range exceeding twice the yield stress under seismic load conditions. The main reason that calculations for these tanks resulted in high stress values is considerations were made for corrosion in the annular bottom plate.

6) A proposal[4] for API 650, Appendix P presents the method of evaluating the uplift, buckling, and instability of tanks by assuming two plastic hinges in the annular bottom plate. The results of the studies on uplift made by this method for the nine stress analyzed tanks and the other tanks are as shown in Fig. 6. It was evaluated that tanks T-217, T-218, T-224, T-131, and T-221 which were severely damaged by the earthquake were subjected to uplift. Also, only tank T-221 was ascertained to exceed the allowable buckling stress.

6. CONCLUSION

To investigate the cause of failure of the cylindrical steel oil storage tanks, various studies, tests, and analyses on earthquake characteristics, site foundation characteristics, and behavior of tank foundation and tank body under seismic conditions were widely conducted. As a result, constructive knowledge was obtained for seismic design of cylindrical steel oil storage tanks, and especially the cause of tank failure was predicted by stress analysis with both maximum stress and maximum stress range under seismic conditions being considered.

REFERENCES

1) Technical Standard Committee for Dangerous Substances in the Fire Defense Agency; Report on Investigation of Cause of Tank Rupture in Tohoku Oil Sendai Refinery owing to Off Miyagi Prefecture Earthquake of 1978 (1979) (Japanese)

2) K. Kawano; Fundamental Research on Cylindrical Steel Tanks, Doctorial Paper, University of Tokyo (Sept. 1978) (Japanese)

3) K. Kawano et al; Damages of Oil Storage Tanks for off Miyagi Prefecture Earthquake of June 12, 1978, 7th World Conference on Earthquake Engineering (Sept. 1980)

4) Wozniak et al; Basis of Storage Design Provisions for Welded Steel Oil Storage Tanks, Proposed Appendix P to API Std 650, Seismic Design of Storage Tanks, API Refining Department 43rd Midyear Meeting, Advances in Storage Tank Design (1978)

Table 1   Physical Parameters of Analyzed Tanks

TANK NO.	AREA	ROOF TYPE	NOMINAL CAPACITY (KL)	INSIDE DIAMETER (MM)	SHELL HEIGHT (MM)	CONTENTS: KIND	CONTENTS: SPECIFIC GRAVITY	CONTENTS: 1) LEVEL (MM)	CONTENTS: TEMPERATURE (°C)	THICKNESS (MM): BOTTOM PL.	THICKNESS (MM): ANNULAR BOTTOM PL.	THICKNESS (MM) 2): SHELL PL.
T-217	C-4	CONE ROOF	31,500	43,588	21,855	HEAVY OIL	0.9264	18,782	74.5	9	⑨	⑲
T-218	C-4	CONE ROOF	31,500	43,588	21,855	HEAVY OIL	0.9309	17,434	76.0	9	⑨	⑲
T-224	C-4	DOME ROOF	23,700	37,776	21,855	VACUUM GAS OIL	0.9026	16,219	53.5	8	⑧	⑯
T-131	C-3	CONE ROOF	31,500	43,588	21,855	KEROSENE	0.7864	20,486	24.0	9	⑨	⑲
T-221	C-4	CONE ROOF	23,700	37,776	21,855	VACUUM GAS OIL	0.8880	18,519	57.5	8	⑧	⑯
T-130	C-3	CONE ROOF	31,500	43,588	21,855	KEROSENE	0.7933	19,017	20.5	9	⑨	⑲
T-215	C-4	CONE ROOF	31,500	43,588	21,855	HEAVY OIL	0.9492	16,417	63.0	9	⑨	⑲
T-216	C-4	CONE ROOF	31,500	43,588	21,855	HEAVY OIL	0.9568	18,410	74.0	9	⑨	⑲
T-223	C-4	DOME ROOF	23,700	37,776	21,855	VACUUM GAS OIL	0.9152	5,541	43.0	8	⑧	⑯

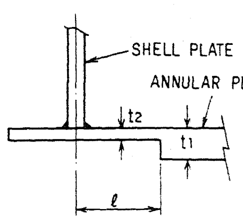
[NOTE] 1) LEVEL OF CONTENTS DURING EARTHQUAKE

2) WITHOUT CIRCLE : JIS G3101 ROLLED STEEL MATERIAL FOR GENERAL CONSTRUCTION (SS41)

WITH CIRCLE : WES 135 HIGH-TENSILE STRENGTH STEEL (HW50)

Table 2   Stress Analysis Model Considering Corrosion of Annular Bottom Plate

TANK NO.	t_1 (MM)	ℓ (MM)	t_2 (MM)
T-217	9	150	8.2
T-218	9	150	6.3
T-224	8	150	6.4
T-131	9	–	9.0
T-221	8	–	8.0
T-130	9	–	9.0
T-215	9	150	8.9
T-216	9	–	9.0
T-223	8	150	7.5



t_1 : DESIGN THICKNESS

t_2 : THICKNESS AFTER CORROSION

ℓ : CORROSION WIDTH

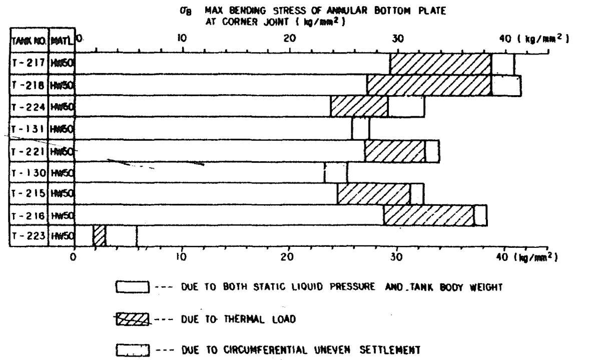


Fig.1 Bending Stress at Annular Bottom Plate Joint owing to Static Liquid Pressure, Tank Body Weight, Thermal Load and Circumferential Uneven Settlement just before Earthquake

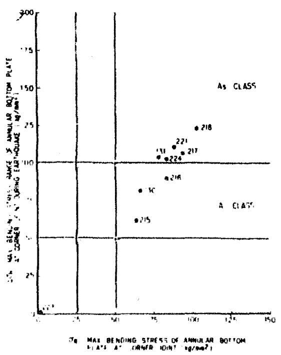


Fig.2 Max. Stress versus Max. Stress Range at Annular Bottom Plate Joint during Earthquake considering Corrosion of Annular Bottom Plate

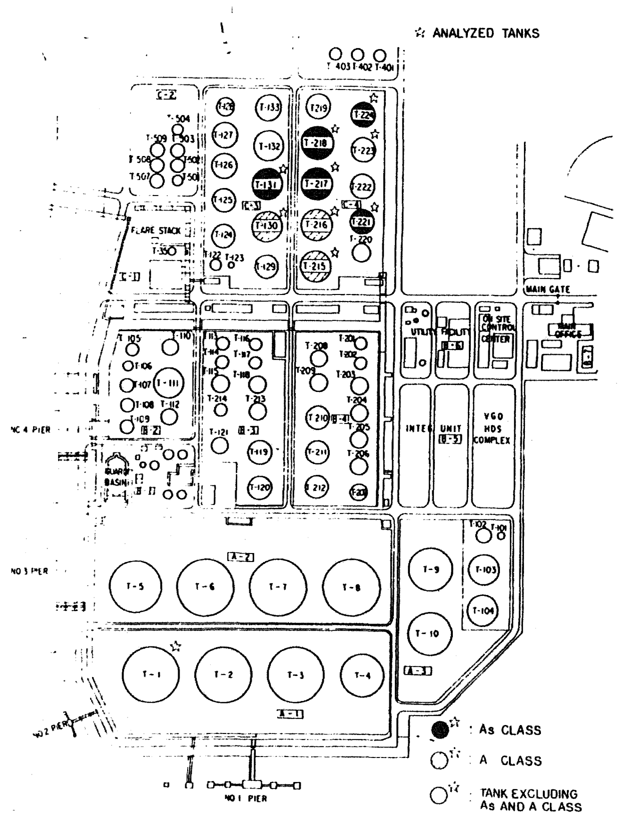


Fig.3 Tanks with High Tensile Steel HW50 Annular Bottom Plate and classified as As and A classes, considering Corrosion of Annular Bottom Plate

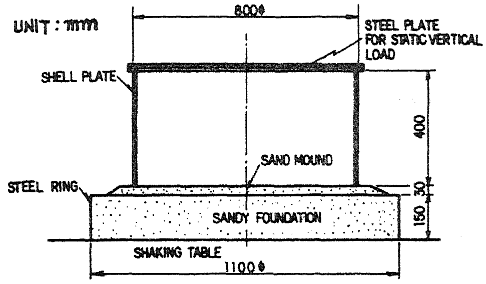


Fig. 4 Tank Model for Shaking

Photo. 1 Settlement of Tank Model after Shaking

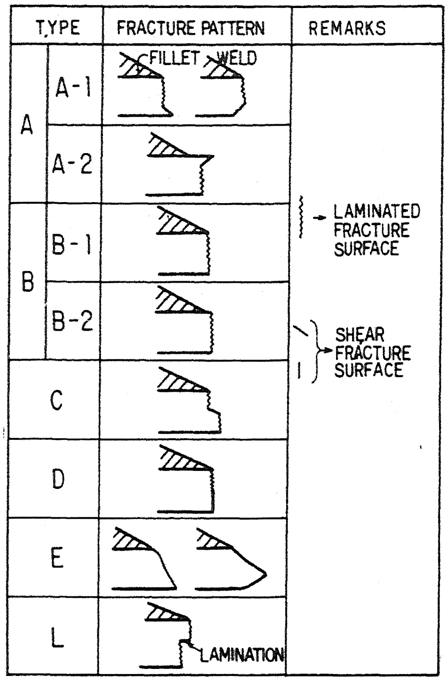


Fig. 5 Fracture Pattern

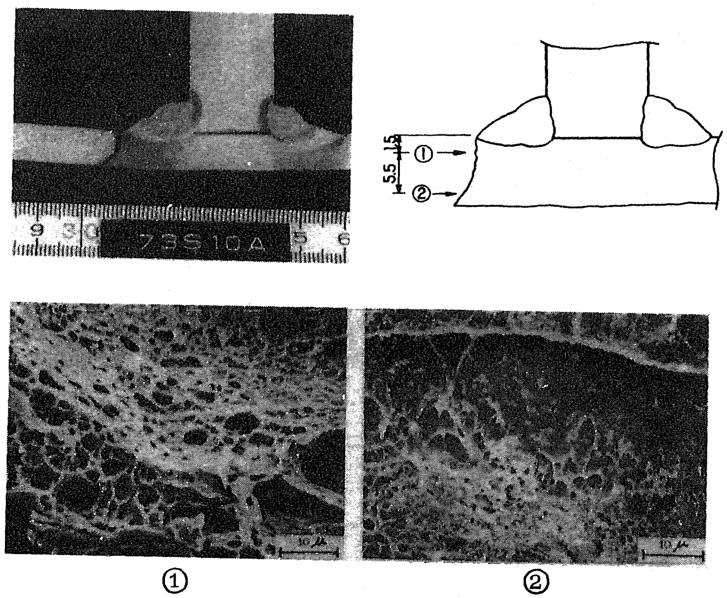


Photo.2 Typical Fracture Surface of Electron Microscope Observation (Fracture Pattern of Type A in Fig. 5)

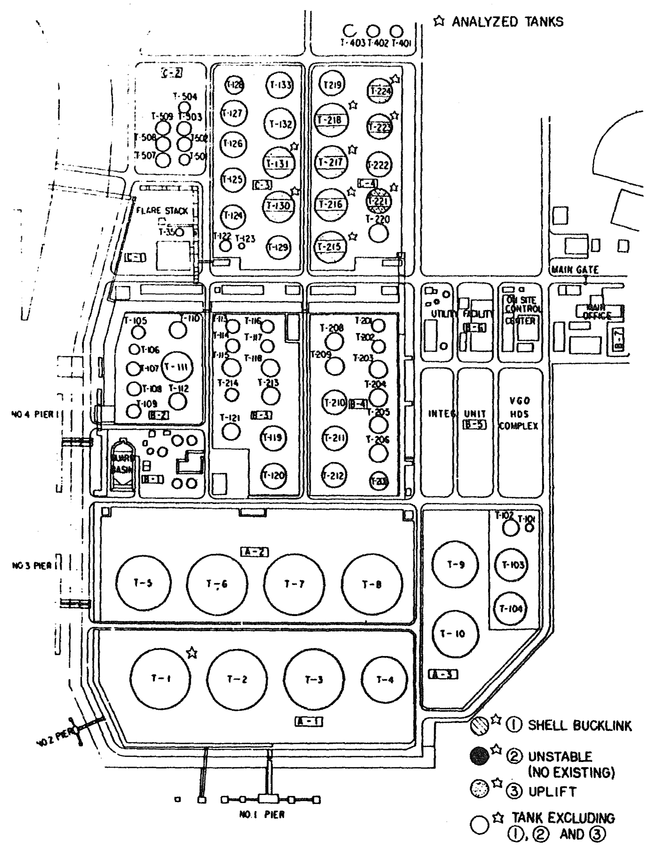


Fig. 6 Classification of Proposal to API-650 Appendix P