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Dynamic earth pressures acting on LNG in-ground storage tank during earthquakes

K.Koyama
Production Engineering & Development Center, Tokyo Gas Co., Ltd, Japan

H.Ueno
Information Processing Center, Kajima Corporation, Japan

N.Kusano
Civil Engineering Design Division, Kajima Corporation, Japan

T.Kondoh
Ohsaki Research Institute, Shimizu Corporation, Japan

ABSTRACT: In order to better understand the seismic behavior of LNG in-ground storage tanks, and to make contributions to constructions of economical and safely designed storage tanks, earthquake observations and numerical analyses have been carried out on two LNG in-ground storage tanks for about ten years. The objective of this study is to examine the qualitative and quantitative characteristics of dynamic earth pressures acting on the side walls of storage tank. Data from over seventy earthquakes have been collected and analyzed. As a result, the following major conclusions were reached.

1. Dynamic earth pressure has a relatively high correlation with the acceleration, as well as the relative displacement between the tank and the ground.
2. Acting patterns of dynamic earth pressures can be classified, being consistent with patterns of tank deformations.
3. It is possible to explain the observed dynamic earth pressures by using two-dimensional FEM models to some degree.

1 OBJECTIVES

This paper reports on earthquake observations and analysis for two large scale LNG in-ground storage tanks taking into account the influence of adjacent storage tanks. Earthquake observations have been carried out since the beginning of 1983 on the C1 and C2 LNG in-ground storage tanks and their surrounding ground at Tokyo Gas Sodegaura Works. The characteristics of this earthquake observation system are that, by using 101 sensors, as well as being able to measure both tanks simultaneously, it is also able to measure dynamic earth pressure during an earthquake. The main objectives of this series of observations are:

1. to grasp the behavior of large in-ground storage tanks during earthquakes,
2. to evaluate aseismic design methods for in-ground storage tanks,
3. to develop more precise and efficient aseismic design methods.

Especially in the design of in-ground

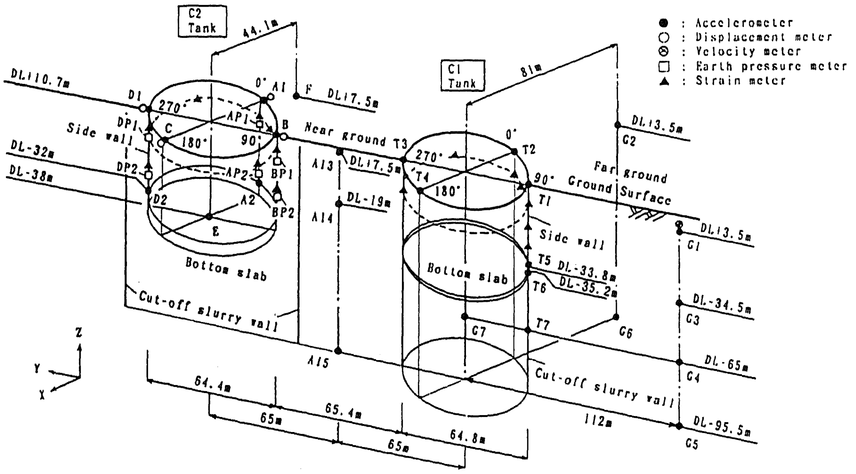


Figure 1. Earthquake observation system

storage tanks, dynamic earth pressures that acts on the side walls of the storage tank has important implications as a load during earthquakes, but until now little has been known of its actual behavior. That's why we mainly examine characteristics of dynamic earth pressures in this study.

2 STORAGE TANKS AND EARTHQUAKE OBSERVATION SYSTEM

An overview of the two in-ground storage tanks, C1 and C2, on which earthquake observations were carried out, and the locations of sensors are shown in Figure 1. Both tanks are cylindrical storage tanks, 64 m internal diameter, maximum fluid level of 40.5m, storage capacity of 130,000kl, distance between the centers of the two tanks 130m. The side walls and bottom slabs are made of reinforced concrete with the roof made of steel. The cut-off slurry walls for cutting off ground water are placed so that they touch the side walls of C1, but are placed away from the side walls with C2. The surrounding ground is a relatively flexible sand layer to around DL-10m, and below that is sand and silt. Down to a depth of around DL-50m, the shear wave velocity Vs is above 400m/s.

The items measured are the acceleration and displacement of the storage tank bodies, strain of the side walls, the acceleration and velocity of the surronding ground and dynamic earth pressure on the side walls. 101 elements are recorded, including 55 accelerations, 2 velocities, 4 displacements, 34 dynamic strains of the tank wall and 6 dynamic earth pressures. The sensors used are servo-type accelerometers, differential transducer type dynamic strain meters, Carlson type dynamic earth pressure meters etc.

3 OBSERVATION RECORDS AND DATA ANALYSIS METHODS

Over an 8-year period, since the beginning of 1983, observation data have been recorded from over 70 earthquakes. An outline of a typical earthquake is shown in Table 1. Also, an example of time histories is shown in Figure 2. The methods used for analyzing the data can be roughly divided into three types.

1. Time series data analysis (statistical analysis, spectral analysis, correlation analysis)
2. Simulation analysis (building of a numerical analysis model)
3. Processing the data and analysis results as moving images using computer graphics (CG) technology.

Analysis of dynamic earth pressures looks at the following three points.

1. Correlations between the dynamic earth pressure and other readings (acceleration, velocity and displacement).
2. Creation of animated graphics from measurements using CG technology.
3. Comparison of observed data with numerical analysis results using a two-dimensional FEM model.

4 ANALYSIS RESULTS

4.1 Regression analysis of observed dynamic earth pressure data

Up until now it has been thought that dynamic earth pressure has a strong relationship with the relative displacements between the structure and the surrounding ground. In the actual designs, dynamic earth pressure P have tended to be calculated using the concept of Response Deformation Method as shown in the following equation (1).

$$P = K \cdot \delta \qquad (1)$$

P: dynamic earth pressure (kgf/cm2)
K: coefficient of soil reaction (kg/cm3)
δ: relative displacement between the ground and the structure (cm)

However, as can be seen from Figure. 3 which shows the results of regression analysis between dynamic earth pressure and other data (absolute acceleration, relative displacement and relative velocity), there is relatively strong correlation between the dynamic earth pressure at the upper section of the side wall of the tank(BP1) and the absolute acceleration(B1). It is possible to evaluate more precisely the dynamic earth pressure using the following equation (2).

Table 1. Major observed earthquakes

Earthquake Name	Date	M	D(km)	△(km)
KANTOU-NANBU	Feb. 27, 1983	6.0	72	52
NIHONKAI-CHUBU	May 26, 1983	7.7	14	537
KANAGAWA-YAMANASHI	Aug. 8, 1983	6.0	22	92
TORISHIMA-KINKAI	Mar. 6, 1984	7.9	452	688
CHIBA-TOHO-OKI	Dec. 17, 1987	6.7	58	47

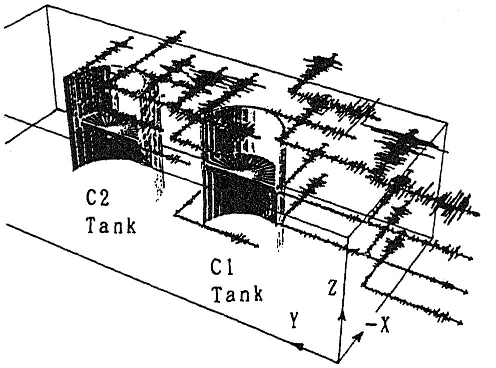
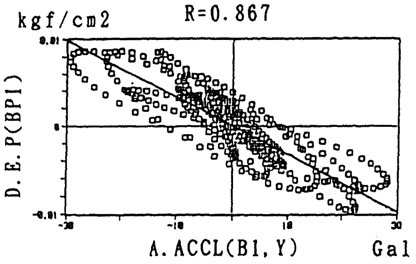
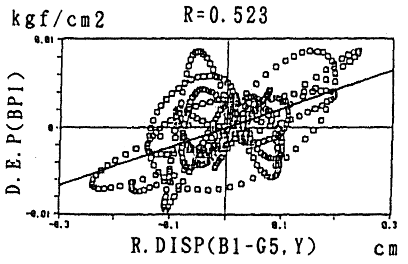


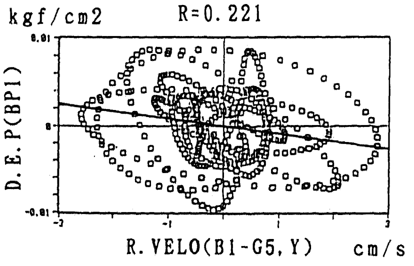
Figure 2. Time histories of KANTOU-NANBU acceleration



(1)Dynamic earth pressure vs. Absolute acceleration

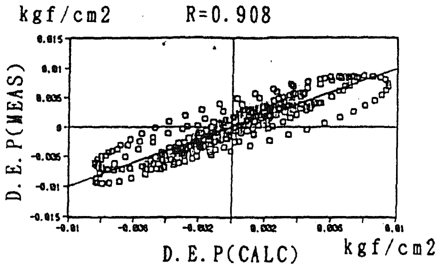


(2)Dynamic earth pressure vs. Relative displacement



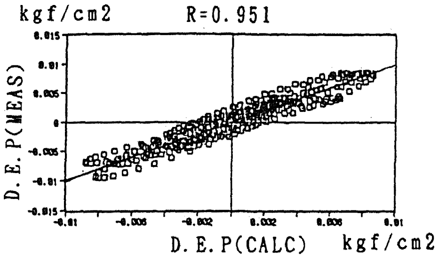
(3)Dynamic earth pressure vs. Relative velocity

Figure 3. Results of single regression analysis



D.E.P(BP1)=a*R.DISP(B1-G5,Y)
+c*A.ACCL(B1,Y)

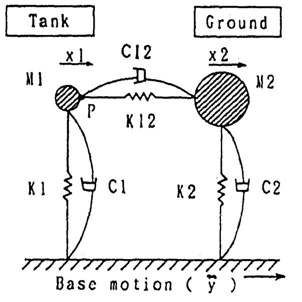
(1)Dynamic earth pressure vs. Absolute acceleration and Relatie displacement



D.E.P(BP1)=a*R.DISP(B1-G5,Y)
+b*R.VELO(B1-G5,Y)+c*A.ACCL(B1,Y)

(2)Dynamic earth pressure vs. Absolute acceleration, Relatie displacement and Relative velocity

Figure 4. Results of multiple regression analysis



M1 : Tank mass
M2 : Ground mass
K1, K2, K12 : Stiffness
C1, C2, C12 : Damper
P : Dynamic Earth Pressure

$$M1 * (\ddot{x}1 + \ddot{y}) = -K1 * x1 - C1 * \dot{x}1 - P$$
$$P = K12 * (x1 - x2) + C12 * (\dot{x}1 - \dot{x}2)$$

Figure 5. Simple model explaining dynamic earth pressures

$P = a \cdot \delta + b \cdot v + c \cdot \alpha$ (2)

a, b, c : coefficients
δ : relative displacement (cm)
v: relative velocity (cm/s)
α : absolute acceleration (cm/s2)

Thus, we looked at the degrees of influence on dynamic earth pressure of the variables (δ, v, α) by carrying out multiple regression analysis on the measurements. For this analysis, we used Kantou-Nanbu data as shown in Figure 2. Band pass filter (1～3Hz) was implemented on the time history data, the results of which are shown in Figure. 4.

Compared to single regression analysis, in general the correlation coefficients rise. In particular, multiple regression analysis using the three variables (δ, v, α) shows an extremely strong correlation with R = 0.951. From the simple vibration model shown in Figure. 5, the coefficients of the multiple regression method (2) can be given the following physical values.

$a = -K1, \quad b = -C1, \quad c = -M1$

4.2 Analysis of dynamic earth pressures using computer graphics

The points for measuring dynamic earth pressure during an earthquake are shown in Figure. 1. There are 3 (AP1, BP1, DP1) in the upper wall of C2 tank and 3 (AP2, BP2, DP2) in the lower section, making a total of 6. These produce animated pictures of the dynamic earth pressure, with the acceleration of the surrounding ground and deformation of the tank. A sample is shown in Figure 6.

The direction of dynamic earth pressure at each point is taken as being internal for directions pushing the tank in, and external for directions leaving the tank, and the vertical distribution of earth pressures is approximated as a straight line. The deformation of the tank is shown as mesh with the acceleration shown as arrows. The maximum of the dynamic earth pressure is around 0.4t/m2, being much smaller than the design earth pressure.

If we compare the earth pressure at the top and bottom sections of the tank using graphics, the pressure at the bottom is greater on average. If compare the earth pressure adjacent to the tanks, on the right of the graph, with the opposite side, the overall trend is that the earth pressure on the left side where there are no tanks is larger.

Using animation analysis, patterns of dynamic earth pressure acting on the tanks can be seen. These can be roughly divided into two types, where there is pulling and pushing in two directions, (as shown in Figure 6): the "two-way push-pull" type, and the "one-direction push-pull" type. In the latter type, two features can be seen: vertical in-phase and anti-phase. Generally, in the principal shock during earthquakes where the surrounding acceleration is great, the dynamic earth pressure is large and an outstanding feature is the oval mode of tank deformation which can be seen to be an effect of the dynamic earth pressure. The oval deformations of the tank, which are calculated from observed dynamic strains of the side wall, can be consistent with the acting pattern of dynamic earth pressures.

4.3 Numerical analysis using FEM model

The analytical model, shown in Figure 7, is a model using two-dimensional mesh for the C1, C2 and the surrounding ground. The elements used are beam elements for the tank walls and cutt-off slurry walls, with the bottom slab of the tank and the surrounding ground as solid elements. As the tanks are cylindrical, physical properties of tank elements(beam elements) are evaluated so as to be equivalent to those of three dimensional cylinders.

Also, as boundary conditions, we took the side boundaries as the energy transmitting boundary, and the bottom boundary was fixed. Viscous boundaries were positioned in the external direction to take into account energy dispersion in an outward direction. The left and right side wall beam elements were connected with spring elements taking into account the characteristics as a cylindrical shape.

The calculated results were converted into animated graphics and the actual observed values were compared with the analysis values. Figure. 8 shows the acceleration and displacement. The diamond shapes are the analysis values and the circles are the actual values. It can be seen that for both the vibration mode and the amplitude of the tank and surrounding ground, the analysis values simulate the actual values well.

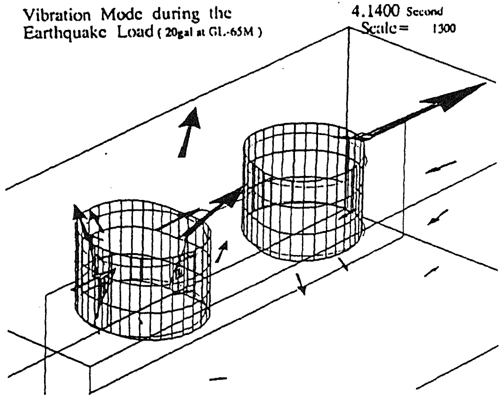
Also, the time histories of actual dynamic earth pressure and those of the analysis values are shown in Figure. 9. As for the absolute values of the earth pressure, it is not possible to give a simple comparison due to the limitations of a two-dimensional model and so the maximum value is normalized to 1. Observed data and calculated results have a good agreement qualitatively.

From the above results, we can see that it is possible to make quite precise simulations of seismic behavior by using two-dimensional FEM models, including evaluation of dynamic earth pressures to some degree.

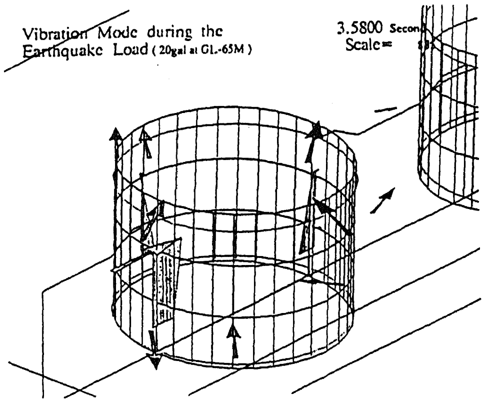
5 CONCLUSIONS

High density earthquake observations were carried out on two 130,000 kl in-ground storage tanks and the surrounding ground at Tokyo Gas Sodegaura Works. Data from over 70 earthquakes were recorded over a period of about 8 years. The qualitative and quantitative examinations on observed dynamic earth pressures were carried out. Using computer graphics(CG) technique, the relationship between dynamic earth pressures and other observed data has been visualized and classified. The results of this study can be summarized as follows.

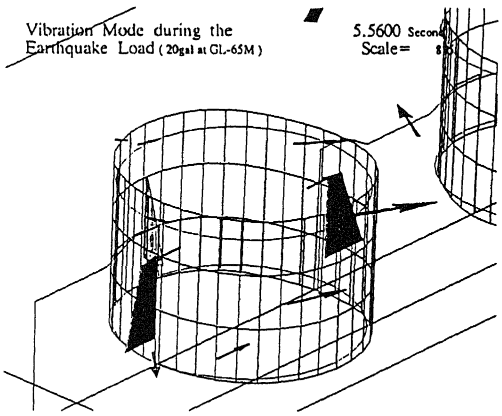
1. Dynamic earth pressure has a relatively high correlation to the acceleration, as well as the relative displacement between the tank and the ground.
2. Acting patterns of dynamic earth pressures can be classified, being consistent with paterns of tank deformations.
3. It is possible to explain the observed dynamic earth pressures by using two-



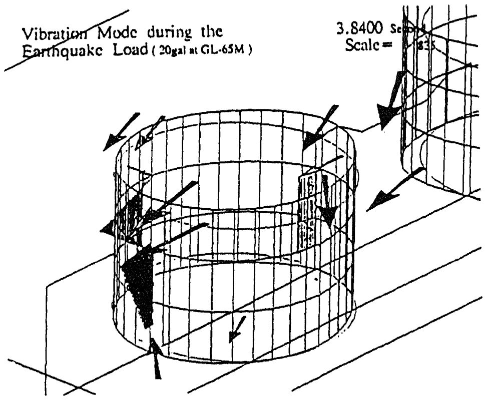
(1)Dynamic earth pressures, surrounding accelerations and tank deformations



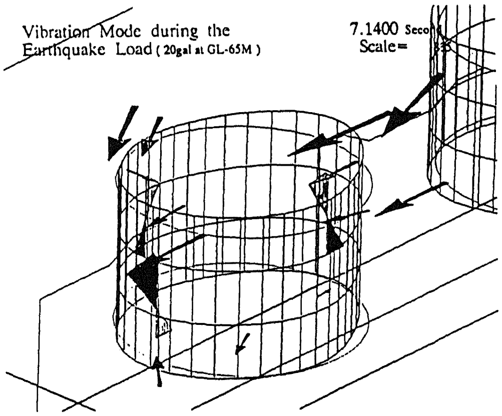
(2)Two-way push-pull pattern of dynamic earth pressures(both pushing)



(3)Two-way push-pull pattern of dynamic earth pressures(both pulling)



(4)One-way push-pull pattern of dynamic earth pressures(vertically in-phase)



(5)One-way push-pull pattern of dynamic earth pressures(vertically anti-phase)

Figure 6. Examples of Computer Graphics displaying observed data

dimensional FEM models to some degree.

It is believed that the analytical procedure used in this study will help to give a new dimension to the design practice of important structures.

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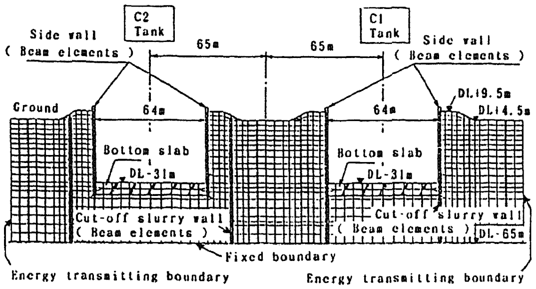

Figure 7. 2-D FEM simulation model

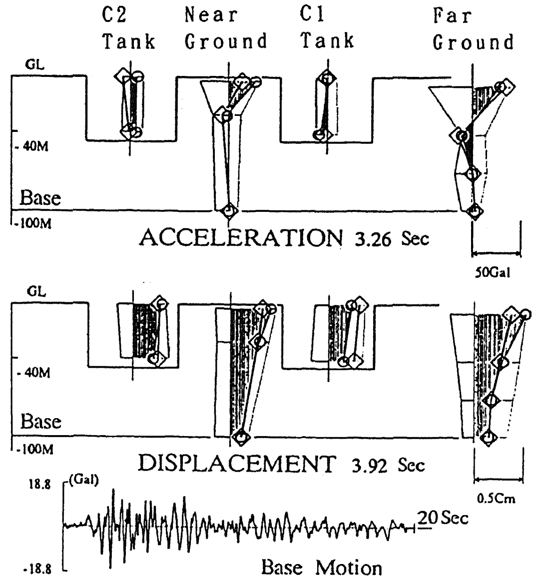

Figure 8. Comparison of measurements with analysis (Accelerations. Displacements)

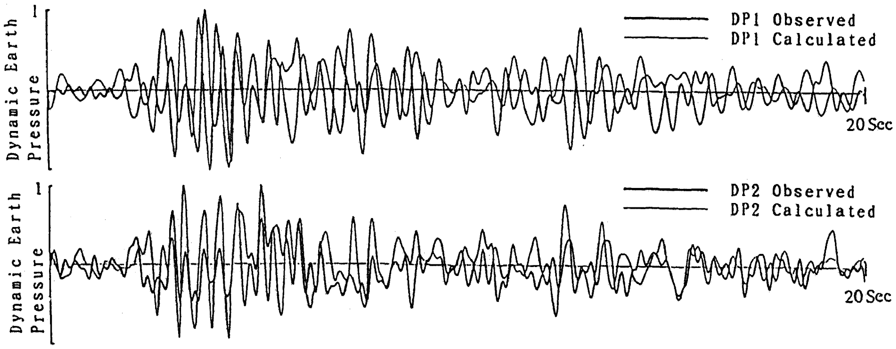

Figure 9. Comparison of measurements with analysis (Dynamic earth pressures)