STUDIES ON EARTHQUAKE-RESISTANT DESIGN OF GROUPED UNDERGROUND TANKS IN SOFT GROUND

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SUMMARY

Model vibration tests and numerical studies are carried out in order to clarify the behaviors during earthquakes of grouped underground tanks of vertical cylinder type constructed close together in relatively soft ground. As a result, grouping effects on the earthquake response of the tanks are brought to light, and fundamental concepts to be considered when designing earthquake-resistant tanks in underground groupings are presented. Moreover, a coupled-system seismic coefficient method which is introduced in this study is revealed to be effective when three-dimensional analysis is applied to underground tank earthquake problems.

INTRODUCTION

In Japan, in recent years, large numbers of cylindrical underground tanks of radii and depths as much as several tens of meters have been constructed in alluvium and reclaimed ground in order to store liquefied natural gas. The bodies of these underground tanks are of reinforced concrete construction, and projects to store crude oil in tanks of the same type are being started.

Tanks for storing such raw fuel materials must possess high levels of safety against earthquakes. Moreover, in Japan, it is desired that a large number of tanks be built in concentrated groups within limits that would be safe, thereby achieving effective utilization of land. Consequently, it has become necessary to clarify the earthquake response characteristics of grouped underground tanks and to have a well-defined idea of how their influence should be considered in design.

Hence, making reference to the results of previous studies which have been made with regard to a single tank (Refs. 1, 2), the authors took the following approaches to the grouped tanks problems. Firstly, experiments in which models of grouped tanks and ground were vibrated on a shaking table were conducted and the dynamic response characteristics when the seismic waves were incident from vertically below were identified. The results of these experiments have already been reported (Ref. 3), but will be briefly reviewed in this paper. Next, a three-dimensional finite element method was employed. The results of the experiments and effective factors concerning earthquake response of grouped tanks were analyzed by a pseudo-dynamic calculation method utilizing the characteristics of underground structures.

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OUTLINE OF EXPERIMENT

Fabrication of Model and Particulars of Experiments

Cases were assumed where up to six vertical-cylinder type reinforced concrete underground tanks are constructed at spacings of 0.5D (one half diameter). The ground was considered to be alluvial ground as is often seen at waterfront industrial zones in Japan.

Fig. 1 shows an outline of the model fabricated. The model ground is of three-layered construction and is increasingly hard from top layer to bottom layer. The material of the ground is acrylamide gel. Fig. 2 shows a cross section of the model tank. The bottom plate is a stiff polyvinyl resin board, while the side walls were fabricated with silicone rubber. Geometrical similarity of the model and prototype is more or less satisfied. The reduced scale of length is 1/150 and that of time is set to be 1/3 so that the similarity laws concerning elastic restoring force and inertia force would be satisfied.

Vibration tests were first carried out with only the ground, following which one, two, four and six tanks were added and the same tests were repeated.

Test Results and Considerations

1. Response Characteristics of a Single Tank

Fig. 3 shows a comparison of resonance curves for the cases of ground only and installation of a single tank in the ground. The first-order to third-order resonance points of the two appeared in common at 2.0 Hz, 4.8 Hz and 7.8 Hz, and it can be confirmed that the tank shows the same motion as the ground and does not produce self-oscillations.

2. Influence of Grouping on Response Characteristics of Tanks

On installing six tanks, the resonance curves on bottom plate sway in Tank A and Tank C, were compared as shown in Fig. 4. The figure also shows the case of steel blocks corresponding to the weight of the liquid contained in the tank added to the tanks. As the movements of the two tanks are of more or less the same trend, it is estimated that the inertias of the tanks do not affect the response characteristics of grouped tanks.

3. Influence of Group Installation Appearing in Response of Side Wall

Fig. 5 shows distributions of deflections in the radial direction of the tops of side walls measured in a state of first-order resonance under stationary vibration. These deflection distributions can be roughly divided into the three fundamental modes shown in the figure. The combinations are shows in brackets.

In the case of a single tank, the ground is deformed symmetrically with the tank at the center, and the ring mode [A] is predominant among the deflection distributions of the side wall. When the tanks are increased to two units or more the symmetrical deformation of the ground around the tanks crumbles. Because of this, the load acting on the tank from the ground loses its symmetry, and a shear-type oval mode [B] and a compression-type oval mode [C] appear prominently in the deflection distributions.

A similar trend was seen in non-stationary vibration application of seismic wave input. If the number of tanks is increased, bending strains are markedly increased since they are mainly produced along with oval-mode deformations of [B] or [C].

NUMERICAL ANALYSIS

Method of Analysis

Based on the experimental results of this paper, it was shown that the response of an underground tank is governed by the response of the surrounding ground and the influence of the inertia force of the tank itself is small, and that in the case of grouped tanks there is no great change in this characteristic. This indicates that if the response of the surrounding ground were to be evaluated somehow, the response of a tank can be calculated statically. Therefore, the authors decided to use a method hereafter to be called coupled system seismic coefficient method (abbreviated to C.S.S.C.M.) where response is determined statically by causing a uniform and constant horizontal acceleration to act on a three-dimensional finite element model of a surrounding ground - grouped underground tanks coupled system.

Examination of Applicability of C.S.S.C.M.

The responses for the case of a single tank for which numerical calculation is relatively easy were calculated by dynamic analysis method. The model ground and tank were modelled by a finite element method on an axisymmetric structure with antisymmetric loading, and the stationary responses in the cases of inputting sinusoidal waves having first-, second- and third-order resonance frequencies of the system were calculated. Fig. 6 shows response values of side wall strains divided by γ_{ave}. This γ_{ave} is a value defined by the equation below.

$$\gamma_{ave} = (hr - he)/H \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where, hu : horizontal displacement of ground at ground surface
he : horizontal displacement of ground at depth of tank's embedment
H : depth of the embedment from ground surface

Fig. 6 also shows the values obtained by the C.S.S.C.M. The distributions of circumferential-direction strains and in-plane shear strains roughly agree with the C.S.S.C.M. until the response for the third-order resonance frequency. In contrast, vertical-direction strains are not in agreement when the third-order resonance frequency is reached.

Consequently, if the response of the ground during earthquake is one of the first-order and second-order modes being predominant, it may be said that the C.S.S.C.M. is applicable. It happens that the order of the mode which is predominant in dynamic analysis of the ground differs depending on the depth of the base rock of the model and the predominant frequencies of the seismic wave. Thus, on considering the condition that the C.S.S.C.M. is applicable depending on the concept of wave propagation, the main wavelength of earthquake motion propagated to the ground surface from below would be more than double the embedded depth of the tank. Since the embedded depths of underground tanks at present are less than 40 m, this condition is generally satisfied.

Simulation of Model Experiments

Analyses by the C.S.S.C.M. were performed and comparisons were made with experimental results. Fig. 7 is an example of a calculation model. This is a 1/4 model of six tanks case. The tanks dimensions, material constants and the stratification of the ground are the same as for the model.

Fig. 8 compares experimental values and calculated values of strains of the tank side wall. The ordinate indicates the values normalized with γ_{ave}, while the abscissa shows the numbers and locations of tanks. The γ_{ave} of the experimental values has been obtained from the displacement waveform integrating the records of accelerometers in the model ground. In the experiments, values approximately half of actual are measured where strains are large since strains gauges were to be attached to relatively soft rubber wall. In contrast, where strains are small, it is estimated that values larger than actual are being measured due to the influence of gauge length and experimental errors. When these points are considered, it is judged that there is good agreement not only qualitatively but also quantitatively.

The deflections of the side wall were obtained from the same calculation results, and are shown in Fig. 9 in the same form as Fig. 5. Oval-mode deformations due to the influences of adjacent tanks are distinctly shown in the calculation results also.

Influence of Distance Between Tanks

Additional calculations were performed on four-tank models with distances between tanks 0.75D and 1.0D. Fig. 10 compared side-wall deflection modes, and a trend for oval-mode deformation effect to be reduced is indicated as the distance between tanks becomes greater.

Fig. 11 shows the relationships between maximum strains of side walls and distance between tanks with the case of a single tank taken as reference. When the distance becomes smaller strains in the circumferential and vertical directions become larger due to the influence of oval-mode deformation.

EARTHQUAKE-RESISTANT DESIGN METHOD CONSIDERING INFLUENCE OF GROUPING

Concepts in Current Earthquake-Resistant Calculations in Japan

The seismic earth pressure method or the seismic deformation method is normally used when obtaining earthquake load acting on the side wall of the tank from the soft ground (Ref. 4). The seismic earth pressure method concerns the increment of earth pressure during earthquake determined by the seismic earth pressure formula of Okabe (Ref. 5) made to act in the manner shown in Fig. 12. The seismic deformation method consists of taking the seismic deformation of the ground obtained by the free field response analysis and causing the deformation to act on the tank through the medium of the spring of the ground in the manner shown in Fig. 12. The direction of action of the deformation can be either the case of the same direction considering incidence of wave motion from vertically below, or the cace of the reverse direction considering planar nonhomogeneity of ground vibrations.

Examination of Seismic Earth Pressure Method

The horizontal earth pressures have been obtained from the calculation results shown in the preceding chapter. Fig. 13 shows horizontal components of actual-scale earth pressures for seismic magnitude of 0.2G. In the case of the end tanks in group earth pressures at the from and back surfaces can be considered that on antisymmetric component of 7.5 ton/m^2 and symmetric component of 2.5 ton/m^2 were composed together. The partial earth pressure which causes the oval-mode deformation due to influence of the group is the latter 2.5 ton/m^2.

In earthquake-resistant design of an actual underground tank, a partial earth pressure during earthquake of the order of 10 ton/m^2 based on calculations by the seismic earth pressure method is included in considerations. Therefore, the method takes into account partial earth pressure fairly larger than the partial earth pressure produced as an influence of the group.

Examination of Seismic Deformation Method

Calculation was performed by the seismic deformation method on a single tank and comparison was made. In this case, the direction of action of the seismic deformation was symmetric. Fig. 14 shows the side wall strain obtained by this seismic deformation method normalized by the γ_{ave} compared with the strain of grouped tanks obtained by the C.S.S.C.M. The strain according to the seismic deformation method is double the strain of grouped tanks.

As a result of the above examinations, it may be considered that these two methods are earthquake-resistant calculation methods which take into account the influences of grouping of tanks on conservative side.

CONCLUSION

It is thought that a concept to serve as a basis in carrying out earthquake-resistant design of grouped underground tanks has been presented by this study. Moreover, the coupled-system seismic coefficient method is also proved to be effective in analyzing the earthquake response of grouped, underground tanks. However, only cases of incidence of seismic waves from vertically below have been considered. Further, a predication was that the ground behaves elastically, while sliding and separation between ground and tank side wall have not been considered either. The influences of these factors on the response characteristics of grouped underground tanks remain as matters for further study.

ACKNOWLEDGMENTS

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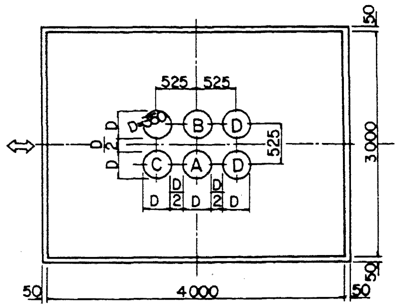


Fig. 1 Outline of Model (in mm)

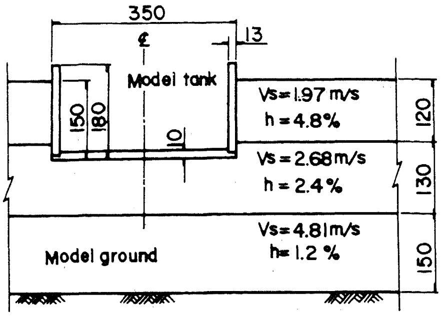


Fig. 2 Local Cross Section of Model (in mm)

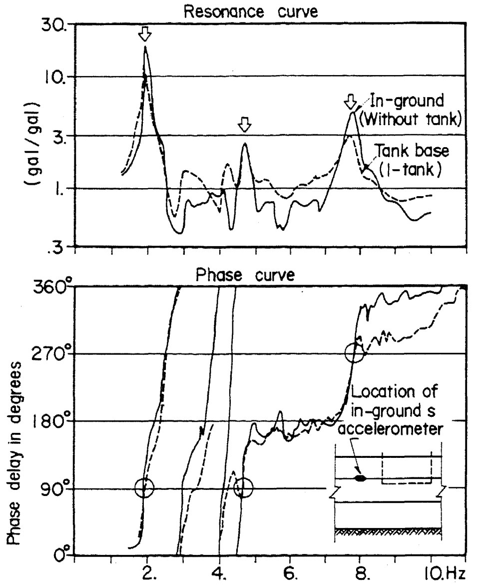


Fig. 3 Comparison of Resonance Curves: Ground Only vs. Installation of a Single Tank

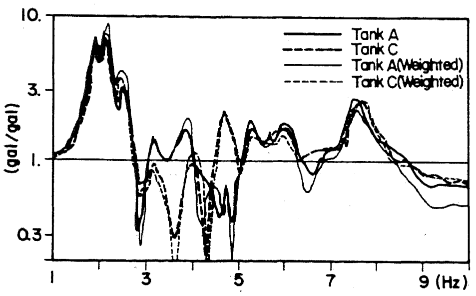


Fig. 4 Resonance Curves of A and C Tanks on Installing 6 Tanks

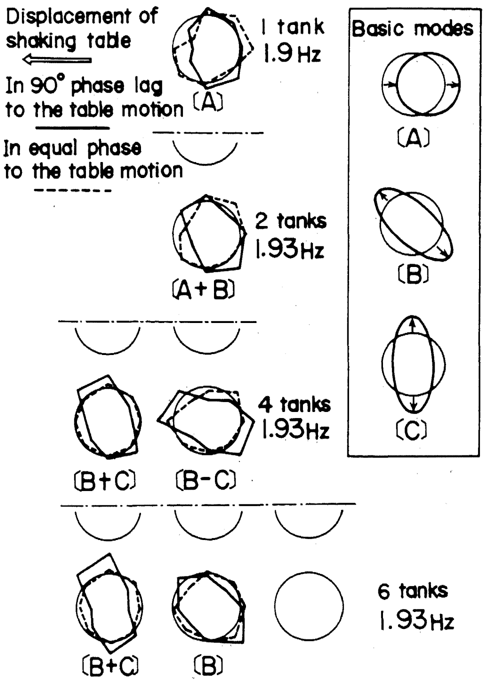


Fig. 5 Distributions of Deflections in the Radial Direction of the Tops of Side Walls

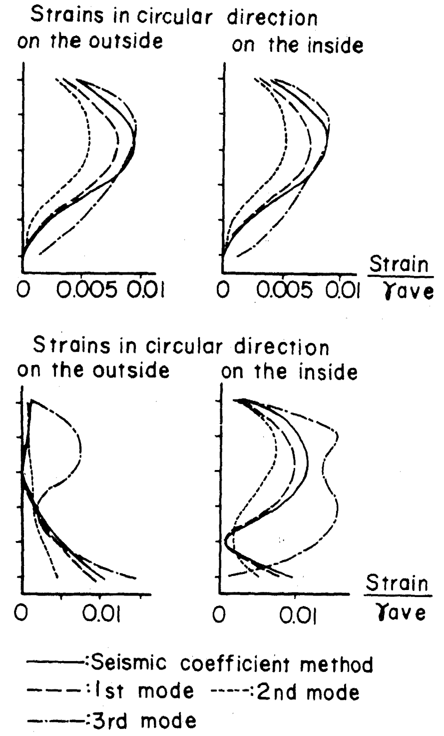


Fig. 6 Comparison of Vertical Distributions of Side Wall Strain: Dynamic Analysis vs. C.S.S.C.M.

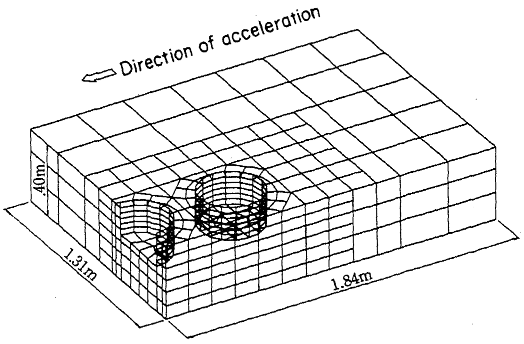


Fig. 7 1/4 Model of 6-Tanks Case used for Numerical Simulation

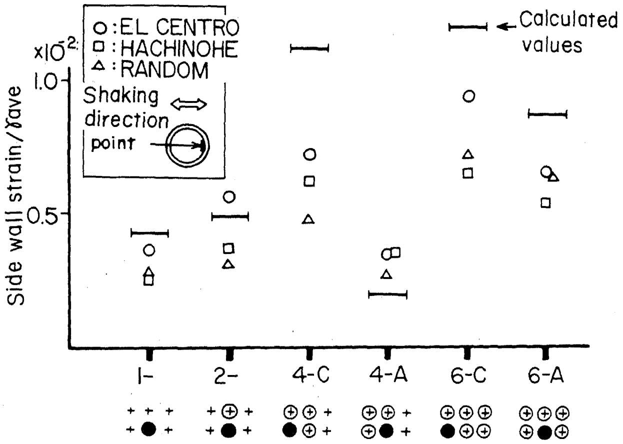


Fig. 8 Comparison of Strains of Tank Side Wall: Calculated vs. Experimental

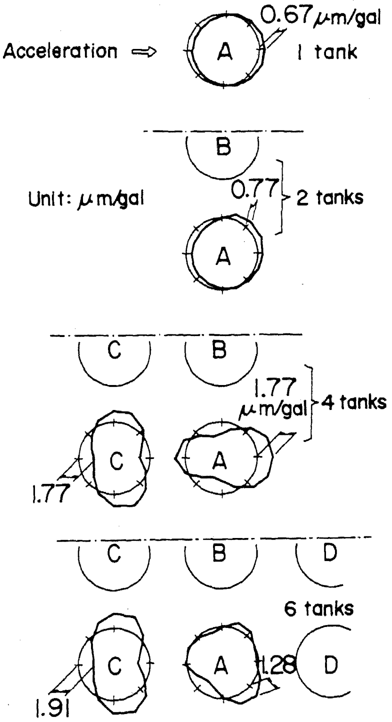


Fig. 9 Calculated Distributions of Radial Deflections

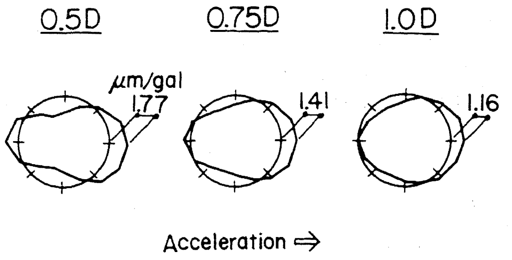


Fig. 10 Influence of Distance Between Tanks on Deflection Modes (4-Tanks Case)

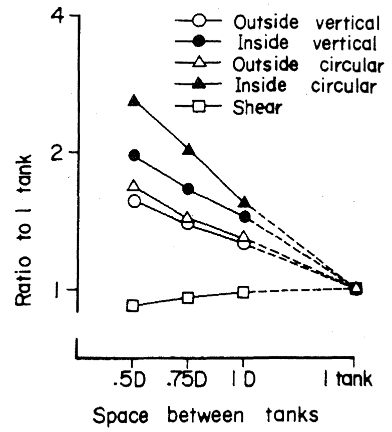
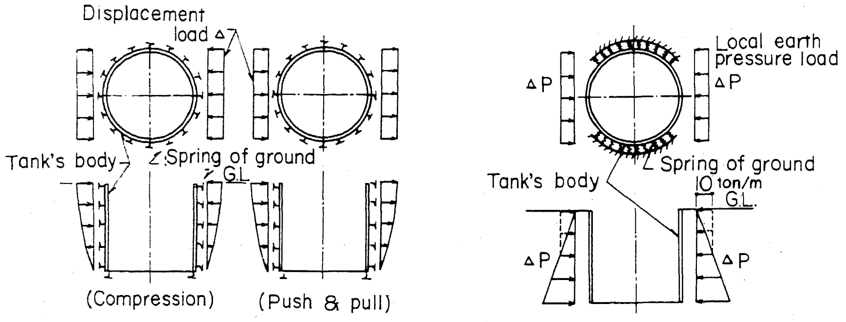


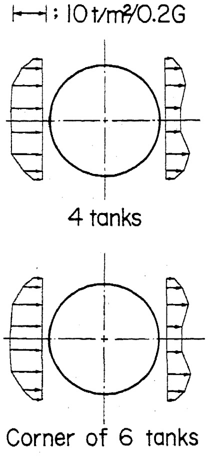
Fig. 11 Max. Strains vs. Distance



Seismic displacement method

Seismic earth pressure method

Fig. 12 Existing Earthquake-Resistant Design Methods



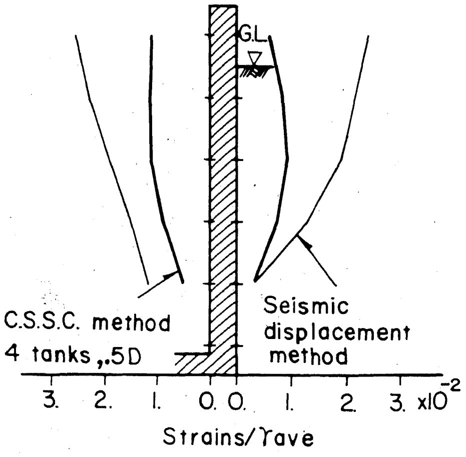


Fig. 13 Seismic Earth Pressure Obtained by C.S.S.C.M.

Fig. 14 Comparison of Vertical Distributions of Strain: S.D.M. vs. C.S.S.C.M.