PROVING TEST OF ANALYSIS METHOD ON NONLINEAR RESPONSE OF CYLINDRICAL STORAGE TANK UNDER SEVERE EARTHQUAKES

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SUMMARY

With the view of establishing adequate measures for ensuring security against severe earthquake of LNG storage tanks installed above ground in thermal power stations, and of verifying the applicability of FEM analysis to the nonlinear behavior of such tanks under strong seismic force, dynamic tests were conducted on model tanks mounted on shaking table. Preliminary tests on side slipping were performed on small scale models of stout steel and pliable aluminum 2 m in diameter and 2.5 m high, which proved the tank to be appreciably more susceptible to side slipping when filled to 1.6 m from bottom than when only filled to 1.0 m. Anchor strapping of wall bottom to supporting frame proved effective not only to restrain uplifting but also side slipping. Comparison of the results of FEM analysis with test data substantiated the applicability of FEM analysis to nonlinear tank behavior. Subsequent tests on large models 8 m diameter 4 m high models covered “elephant foot bulging” of tank wall, as well as side slipping.

INTRODUCTION

The importance of ensuring the continuity of power supply under conditions of seismic disturbance was brought into evidence on the occasion of the Southern Hyogo Prefecture Earthquake, 1995. This experience led the Ministry of International Trade and Industry to establish a committee chaired by Emer. Prof. H. Shibata of the University of Tokyo gathering specia1its and representatives from electrical uti1ity companies and plantmanufacturers, to initiate a project named Seismic Proving Test of Equipment and Structures in Thermal Conventional Power Plant (SPT), to be performed in the period in the 1996-2000 covering a series of surveys and experiments for proving the resistance of thermal power plant installations to severe earthquake (see Fig.1). The thermal power equipment selected as subject were LNG storage tanks installed above ground (equipment comprising tank proper nozzle connections between tank and piping, and foundations for tank and piping), together with boilers.

Of the above selected equipment, the present report concerns work on above-ground LNG storage tank, covering shaking table tests on large tank model to prove the resistance of such tanks to earthquake, and to verify the applicability of FEM analysis for estimating the nonlinear response of tank body to severe seismic force.
Nonlinear behavior considered in the study comprised lateral slip and the particular deformation of tank wall known to occur under severe seismic load known as “elephant-foot bulging.
Before proceeding to the large tank model test, preliminary shaking table tests were conducted on two small-scale models, to assemble data on lateral slip to serve in planning the large model tests and for verifying the adequacy of the analytical procedure.[3,6]
Moreover, at the 12WCEE, three reports[1,2,5], together with the present contribution, are being presented covering the studies performed under the SPT Committee.

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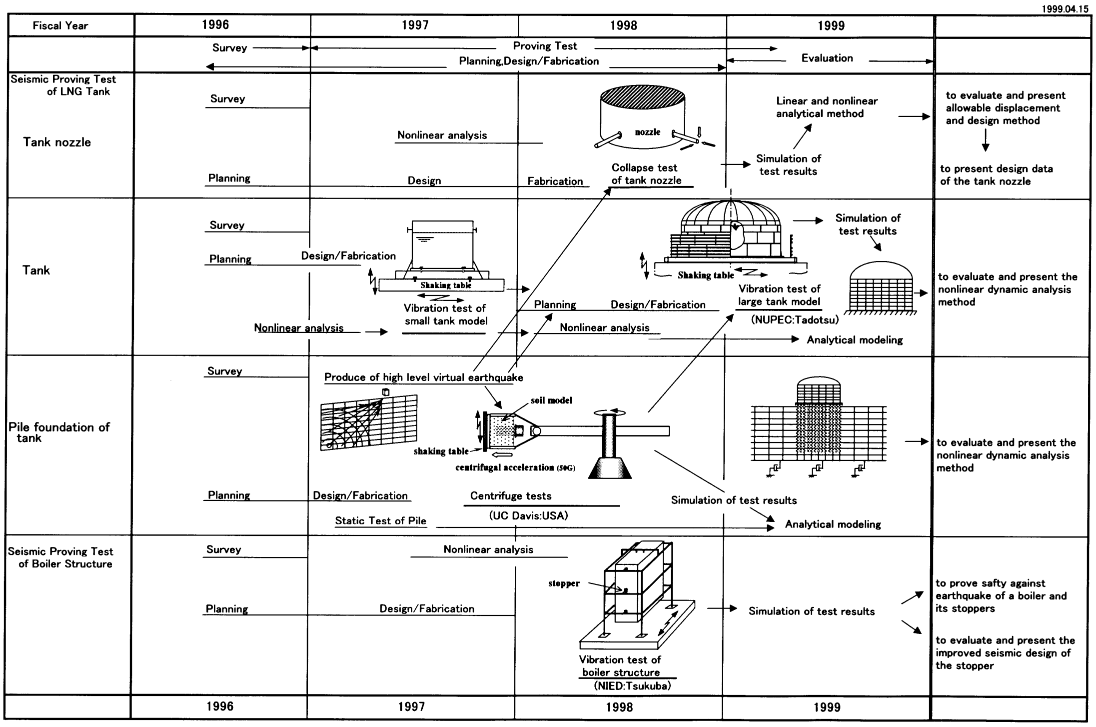

Fig.1 : Seismic Proving Test on Equipment and Structures of Conventional Thermal Power Plants(SPT)

PRELIMINARY STUDY ON NONLINEAR RESPONSE OF LNG TANKS

Liquefied natural gas(LNG) tanks installed above ground in Japanese thermal power stations generally take a form such as illustrated in Fig. 2, comprising an inner vessel containing the liquid and an external wall supporting the thermal heat insulation. The bottom of the inner vessel is fixed by anchor straps to the foundation slab concrete, to prevent angular uplifting of bottom plate with the overturning moment of seismic force.
These tanks are of capacity ranging from 25,000 m^3 to 120,000 m^3, among which those of 80,000 m^3 constitute the largest number. Since 1981, the tanks have been designed to withstand a maximum seismic acceleration of 3 m/s^2 at ground level, in conformity with the Recommended Practice for LNG Aboveground Storage laid down by the Japan Gas Association.

In the present study, a preliminary examination was made of the nonlinear behaviourin yielding modeof structures under high-acceleration seismic excitation.
In the first place, calculations were performed applying the finite element method to derive the stresses generated in different parts of the inner tank according to the modified seismic coefficient method as prescribed in the above-mentioned Recommended Practice. The results are shown in Fig.3 for the case of a 80,000 m^3 tank of JIS SL9N590base metal of 600 MPa yield stresswith inner tank measuring 59.5 m in diameter, and filled to 28.8 m liquid level. The “stress ratio” constituting the abscissa of Fig. 3, is the measured stress expressed in terms of its ratio to the allowable stress prescribed in elastic design Practice. When the stress ratio exceeds unity the member enters the nonlinear domain of yielding. The lines in Fig. 3 that rise beyond unity at relatively low acceleration are (a)hoop stress of shell plate (which causes elephant-foot bulging), (b)axial stress of shell plate, (c)anchor strap yielding and (d)side slipping. The aspects of such nonlinear behavior are schematized in Fig. 4.

Among the above factors, side slipping and elephant-foot bulging were taken up for the verification tests on shaking table on using large model. In large model testing however, simultaneous treatment of multiple parameters is difficult, and for this reason preliminary tests were conducted on two reduced-scale models which were subjected mainly to tests on side slipping.

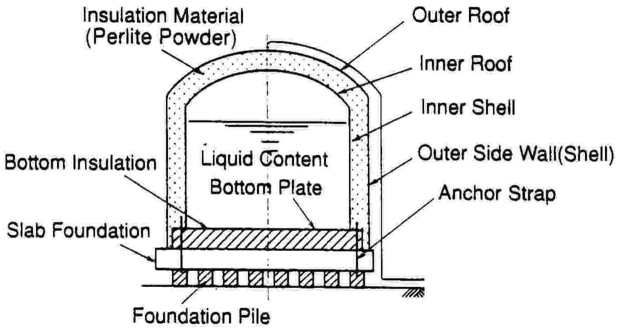

Fig.2: Flat-bottomed Cylindrical Storage Tank for LNG

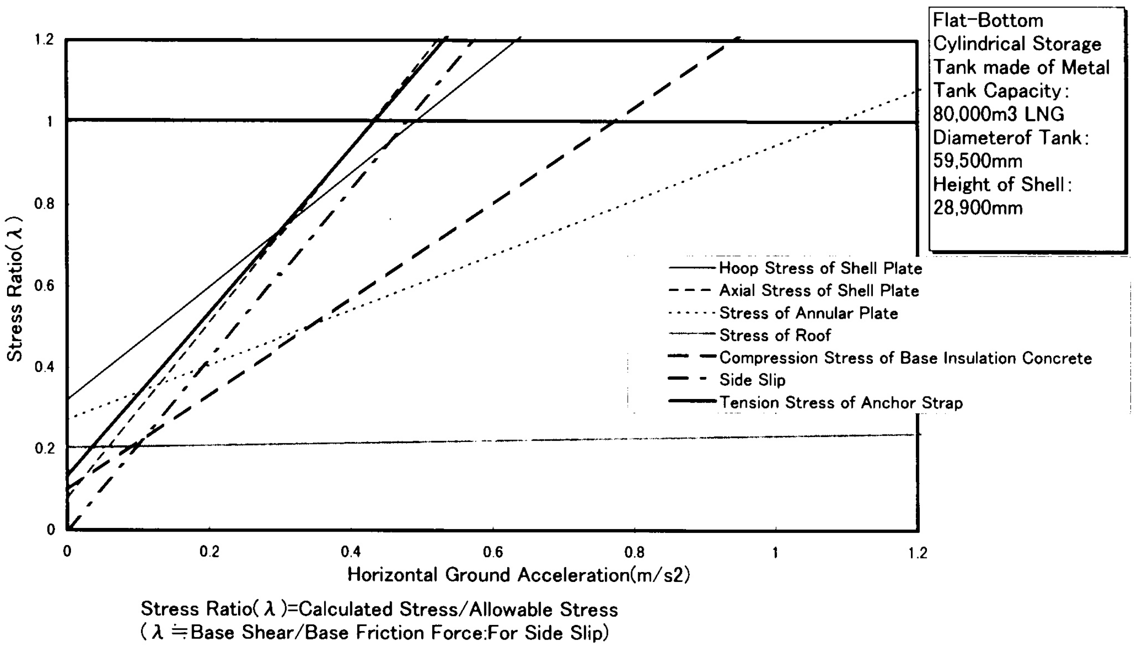

Fig.3: Relationship between Ground Acceleration and Stress ratio of Storage Tank

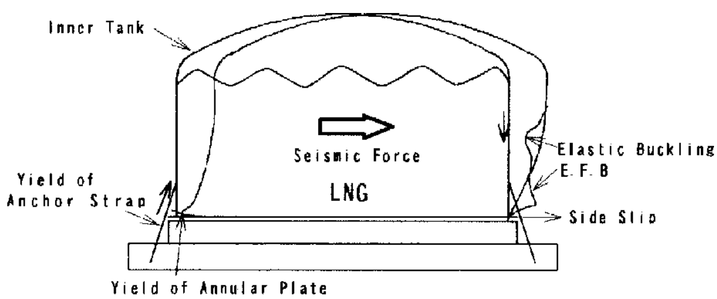

Fig.4: Typical Nonlinear Behavior of Flat-bottomed Cylindrical Tank due to Severe Earthquake

REDUCED-SCALE MODEL TANK TEST ON SIDE SLIPPING

Testing equipment

The models subjected to test were one each of aluminum and steel, both measuring 2 m in diameter and 2.5 m high (see Fig. 5). The aluminum tank had both side wall and bottom plate made of pliant 2 mm-thick plating, to realize side slipping under the effect of mutual interaction between liquid content and tank shell. The steel tank, on the other hand was made of stout 9 mm thick plating, for observing rigid tank shell behaviour. Both tanks had their wall bottom tied to the supporting frame by 16 anchor straps (9 mm diameter stainless steel rods), to prevent rocking uplift, similarly to actual tank. The test runs were conducted with the tank filled to 1.0 m and to 1.6 m from bottom.

The model tanks were mounted on the shaking floor (faced with pearlite concrete) of a 35-tf three-dimensional facility of Ishikawajima-Harima Heavy Industries Co., Ltd.

Sensor Arrangement

The items measured were (a)displacement, (b)strain, (c)acceleration, (d)dynamic liquid pressure, and (e)exciting force. The number of measuring points counted 83 on the aluminum and 59 on the steel tank. Representative measuring points are indicated in Fig. 6 for the case of aluminum tank.

Preliminary Friction Test

Among the measured values to be inputted for comparison with the results of side slip analysis, that of friction coefficient needed to be determined independently, and to this end a static hauling experiment was conducted using both steel and aluminum tanks. Filled respectively to 1.0 m and to 1.6 m from bottom, the tank was statically hauled, with load cell mounted between hauling rope and tank for measuring the maximum force imparted at the instant of slip initiation. The friction coefficient was derived as the measured force divided by the aggregate weight of tank body and filled water.

Excitation waves

The shaking table was excited (a) in single horizontal direction and (b) simultaneously in horizontal and vertical directions, in wave pattern simulating the seismic waves recorded at Kobe Maritime Meteorological Observatory on the Southern Hyogo prefecture Earthquake, 1995. The excitation wave pattern is reproduced in Fig. 7 in time history form. The waves imparted to model had their time scale compressed alternatively to 1/5 and to 1/10 of actually recorded value. The excitation level was varied in steps from 3.00 to 7.00 and to 12.00 m/s^2.

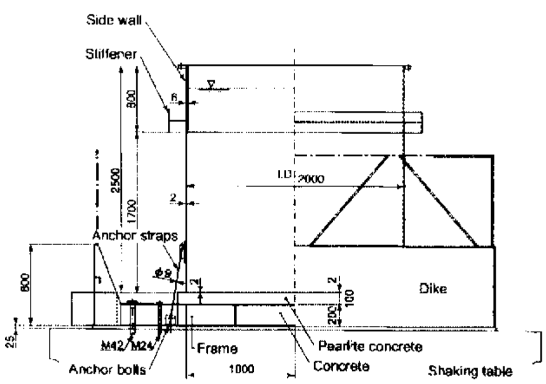

Fig.5: Slide Slip Test Aluminum Tank

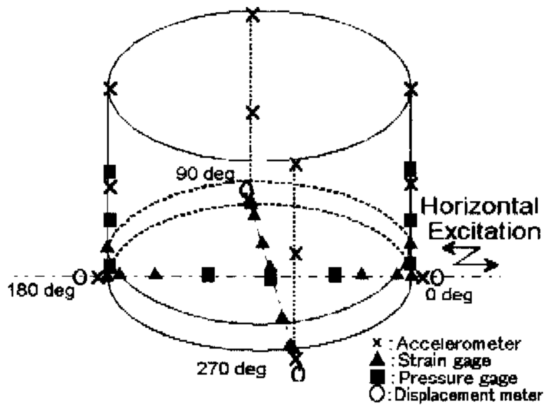

Fig.6: Sensor Arrangements on Side Slip Test Model

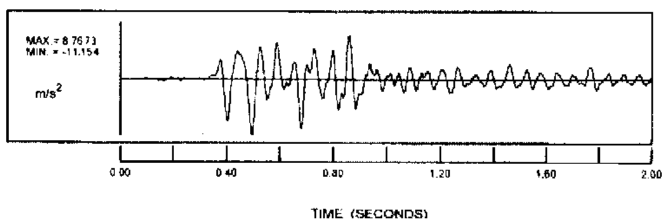

Fig.7: Time History of Input Acceleration Wave

RESULTS OBTAINED FROM SMALL MODEL TESTS

Preliminary Friction Test

The static hauling test proved the friction coefficient to be 0.71 for the steel tank and 0.70 for the aluminum tank.

Side Slip Test on Steel Tank

The relation between input excitation and side slippage is indicated in Fig. 8 for the runs on steel tank filled to 1.0 m and to 1.6 m from bottom. It is seen that the twice as large amount of maximum slippage was recorded with tank filled to 1.6 m compared with the case of 1.0 m filling. This can be ascribed to the 30% increase in effective liquid weight raising the inertial force—that induces the side slip—relative to friction force—that restrains the same movement.

The cases of anchor strap installed and removed are compared in Fig. 9. Without anchor strap, maximum slippage is raised by a factor of 2. The additional restraint against slipping can be ascribed to the tension applied to anchor strap generating a countervailing pressure exerted at the opposite side of tank bottom, thus adding to the friction against slip. The presence of anchor strap is thus seen not only to restrain rocking uplift but also affords the additional benefit of diminishing the side slippage.

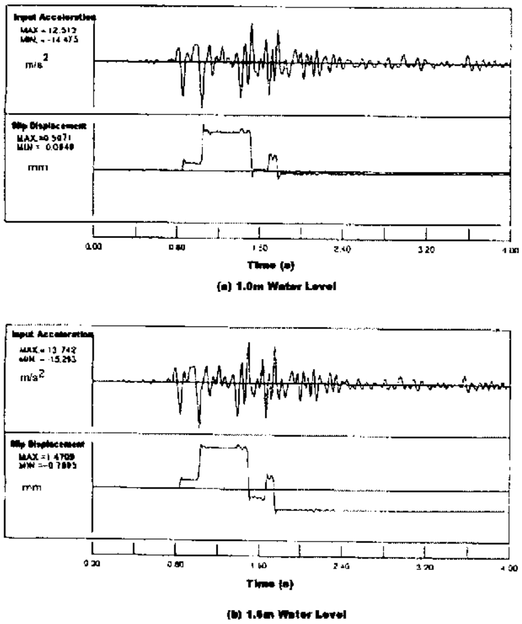

Fig.8: Side Slippage of Steel Tank by excitation

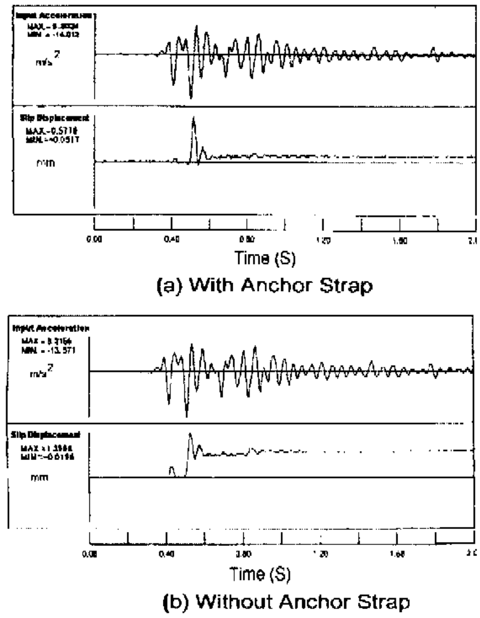

Fig.9: Side Slippage of Steel Tank by excitation

Side Slip Test on Aluminum Tank

As in the case of steel tank, the aluminum tank (Fig. 10) recorded twice as large a maximum slippage with tank filled to 1.6 m as when filled to 1.0 m. Cases of anchor strap present and absent are compared in Fig. 10 in terms of slippage pattern and uplift. Residual slippage is nil with anchor strap present, but amounts to 0.05 mm without it. Without anchor strap, inertial force can be considered to have been amplified with the rocking motion generated by the excitation.

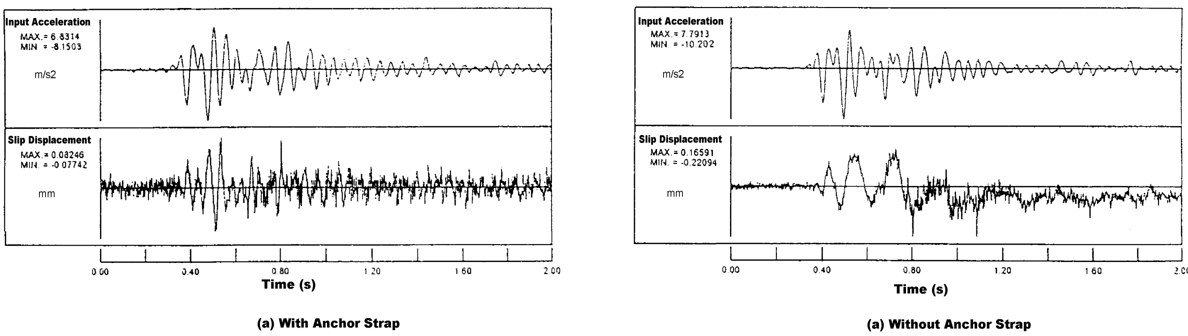

Fig.10: Results of Side Slip Test on Aluminum Tank —Effect of anchor strap presence (time scale compressed to 1/10 from that for actual tank)

Comparison with Results of FEM Analysis

Side slip

For evaluation of side slippage, the method indicated in JEAG [4] has been adopted for the value of acceleration at slip initiation. This method takes account of (a) the horizontal inertial force of tank, (b)the friction resistance exerted by the weight of tank body and contained liquid, and (c)the friction resistance exerted by tank bottom on foundation surface as counterforce of strap restraint. The comparison was made for the case of steel tank filled to 1.6 m from bottom. The results are shown in Fig. 11, where the evaluated acceleration at which slip is expected to be initiated is indicated by the vertical broken line. "slip initiation" is defined as the point where the tank is dislocated by at least 0.1 mm. Fairly good agreement is seen between analyzed and measured results.

Comparison with results from FEM analysis was performed adopting the model illustrated in Fig. 12. The analysis was conducted using the ANSYS code, with account taken of (a)geometrical nonlinearity, (b)contact between tank bottom and foundation surface, and (c) friction. Shown in Fig. 13 are the results of comparison for the case of aluminum tank filled to 1.0 m from bottom and subjected simultaneously to 12.00 m/s^2 horizontal and 5.0 m/s^2 vertical acceleration. Good agreement is seen between analysis and measurement.

Partial slip

In Fig. 13, the horizontal dislocation is seen to be greater at the 90 side of wall bottom than at center. The explanation of this behavior is that the horizontal inertia force of tank and liquid, restrained by the friction between tank bottom and supporting frame, creates larger shear force acting on the side wall at the 90 and 270 sides corresponding to sinusoidal distribution of shear stress of thin cylindrical shell. This results in deformation by shear of bottom plate causing the slippage at these sides to be greater than at bottom center. This slip displacement difference is termed partial slip.

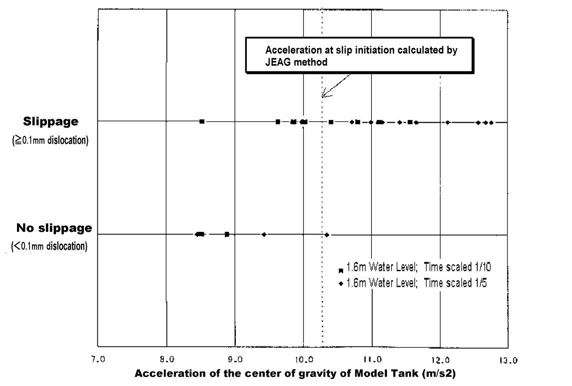

Fig.11: Comparison of Test Results with Calculation Using JEAG Method for Acceleration at slip initiation (Steel Tank)

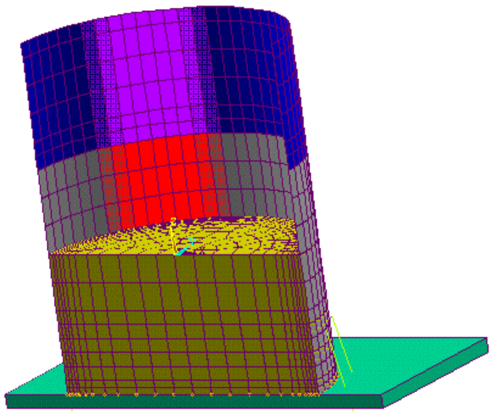

Fig.12: FEM Analysis Model

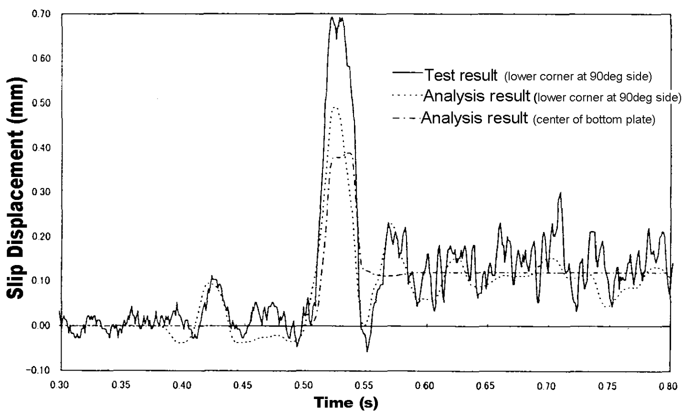

Fig.13: Comparison of Test Results with Analysis by FEM for Sip Displacement

LARGE SCALE MODEL TANK TESTS

Objectives

To verify the results obtained on the small scale model tests, further tests were conducted on a model of size closer to actual tank. The items of test were :-

- Verifying the earthquake resistant property of LNG storage tanks installed above ground
- Verifying applicability of the FEM analysis for nonlinear behavior of storage tanks under severe earthquake.

The factors considered for the nonlinear behavior of LNG above-ground storage tanks were, side slippage and elephant-foot bulging.

Test Model

The large model tank subjected to test is illustrated in Fig. 14. It is a steel tank of 1/8 scale, and measures 8 m in diameter and 3.89 m side wall in height. The side wall is 4.5 mm thick, and the bottom plate 4.5 mm thick in the peripheral zone and 20 mm thick at center. The reason for the thick central part is that the tank bottom had to be bolted to the shaking table for preventing slippage in the elephant-foot bulging test. To prevent rocking uplift, the wall bottom is fixed to the foundation slab concrete by 28 anchor straps (30 mm diameter stainless steel rods). In these tests on large model, the testing conditions were further approached to those on actual tank by installing the anchor straps initially tensioned. No runs were performed with anchor straps left unfixed, as it as the case with small model tests. The tank was filled to 3.872 m from bottom. The above model assembly was set on the 1,000 tf shaking table (world's largest) of the Tadotsu Engineering Laboratory of the Nuclear Power Engineering Corporation. The shaking table has a mounting frame of concrete faced with pearlite concrete.

The side slip tests were performed with the model tank laid on the table without fixing. For the elephant-foot bulge test, the tank bottom was bolted to the table, as already mentioned.

Sensor Arrangement

The items measured were (a)displacement, (b)strain, (c)acceleration, (d)dynamic liquid pressure and (e)exciting force. The measuring points amount in all to around 300.

Loading

The mounted model tank was shaken simultaneously in horizontal and vertical directions in artificial seismic wave pattern. The pattern applied was devised alternatively for verifying security against seismic excitation, and for determining the limiting excitation. The former wave pattern for side slip test is shown in Fig. 15.

Law of similitude

Different laws of similitude were applied for the side slip and elephant-foot bulge tests. With side slip, the dominant factor is the friction between tank bottom and supporting table, and for this reason the acceleration of gravity was adopted as basis for similitude; with elephant-foot bulge, the similitude law was sought in letting model and actual tank share in common the ratio between elastic and inertia forces (Chauchy's number). The actual values adopted for the two laws of similitude are given in Table 1.

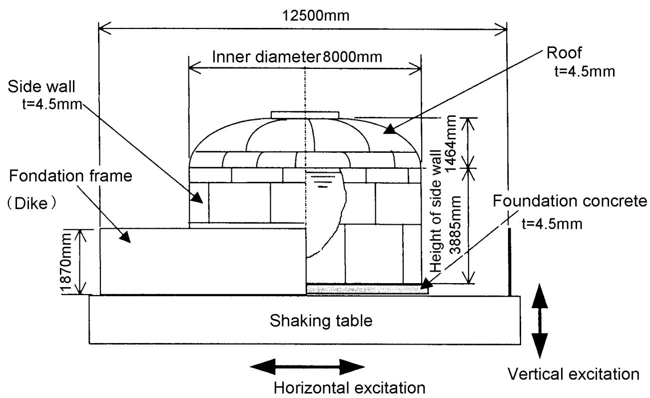

Fig.14: Large Model Tank Used for Test

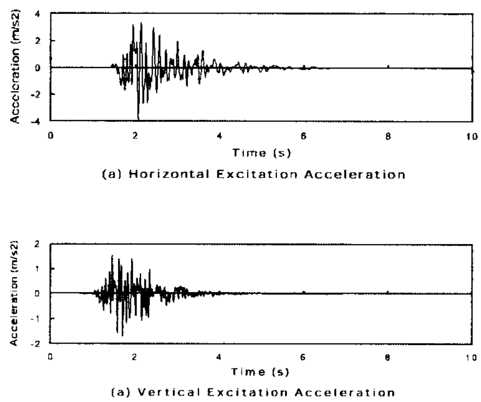

Fig.15: Excitation wave for side slip Test

Table 1: Values Adopted for Law of Similitude

Similitude		Actual Tank / Test Tank
Side Slip	N_t (time)	5.49
	N_r (acceleration)	1/1.0
	N_{iy}(Input acceleration)	N_r^{-1}
EFB	N_t (time)	5.49
	N_y (acceleration)	1/4.0
	N_{iy}(Input acceleration)	$4.0\times N_r^{-1}$

N_r: Ratio of response between actual and model tanks.

CONCLUSIONS

The applicability of FEM analysis to the nonlinear side slipping behavior under strong seismic force of LNG storage tanks installed above ground was verified through a series of model tests on shaking table. Preliminary tests on small model furnished information on:
The relation to side slippage brought by differences in level of liquid filling the tank and by the presence or absence of anchor strap.
Applicability of analysis by FEM analysis to nonlinear side slpping tank behavior.

Subsequent tests on large models of 1/8 actual size covered “elephant foot bulging” of tank wall ,as well as side slipping.

ACKNOWLEDGEMNTS

The present series of tests have been planned, and are being pursued, under the Committee of Seismic Proving Test of Equipment and Structures in Thermal Conventional Power Plant (SPT), established in the Japan Power Engineering and Inspection Corporation, with a commission from the Ministry of International Trade and Industry. Unreserved guidance and invaluable advice has been accorded in the course of planning and implementation of the work by the Committee Chairman, Emeritus Professor H. Shibata of the University of Tokyo , and members of the Committee, to whom grateful acknowledgment is due.

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