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Settlement of Oil Storage Tank During Liquefaction by Centrifuge Study

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ABSTRACT

The settlement of the oil storage tank during liquefaction on site, is the most serious problem for the engineers and company owners. Several liquefaction-resistant methods for the oil tank site are presented. In this paper, one of these methods which constrain the soil under the oil tank by a sheet pile wall is used. Some series of model tests using centrifuge facility are carried out to evaluate the liquefaction-resistant method from a settlement point of view. The effects of the closed type of a sheet pile wall, the open type of a sheet pile wall and mass of an oil tank are tested, respectively. The results show that the settlements of the oil tank depend on the mass of the oil tank, and on the type of sheet pile wall, and also show that the closed type wall is more useful against liquefaction than the open type wall.

INTRODUCTION

In these few decades, many oil storage tanks were damaged in Japan by several big earthquakes due to liquefaction. In Japan, many tanks have been constructed under unavoidable circumstances such as rapid development, or the soft ground condition, etc. Once an oil tank is damaged, the companies get large economic damages and are discredited with the public. Hence, developing certain countermeasures for the oil tank against liquefaction, has become an important task.

Following conditions are needed for the liquefaction-resistant methods.

i) Economical method.
ii) Reliability of the countermeasures (investment and effect).
iii) Applicability to the existed oil tanks (for the newly built oil tanks, many methods can be adopted).

Against above mentioned conditions, the sheet pile wall method is chosen as a typical countermeasure and evaluated by the centrifuge test equipment. In these cases, using centrifuge test has some merits. One of the merits of using it is to keep the similarity law. Another important merit is to keep the earth pressure conditions similar to that exists in the real ground.

The purposes of the studies are ; i) to evaluate the sheet pile wall method through the centrifuge model tests ; ii) to evaluate the effect of the methods against the settlement by means of comparing closed type wall models and open type ones.

LIQUEFACTION-RESISTANT METHOD

The sheet pile wall method is easily applicable for already built oil tanks. The layout of the method is shown in Fig.1. The sheet pile wall makes the ground under the tank to be constrained to prevent large

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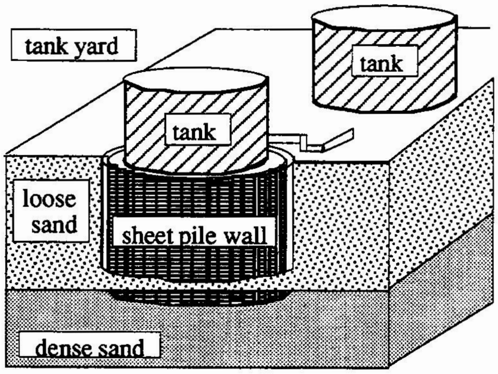


Fig.1 sheet pile wall method for oil storage tank

Table 1. law of similarity (Kutter,B.L.,1992)

Quantity	Symbol	Units	Scale
Length	L	L	n^{-1}
Volume	v	L^3	n^3
Mass	M	M	n^3
Gravity	g	LT^{-2}	n
Force	F	MLT^{-2}	n^2
Stress	σ	$ML^{-1}T^{-2}$	1
Moduli	E	$ML^{-1}T^{-2}$	1
Strength	s	$ML^{-1}T^{-2}$	1
Acceleration	a	LT^{2}	n
Time (Dynamic)	$t_{dyn.}$	T	n^{-1}
Frequency	f	T^{-1}	n
Time (Diffusion)	t_{dif}	T	n^{-1} or n^{-2}

settlements by liquefaction inside the area of the wall. By this method, following effects were expected.

i) to keep the liquefaction potential low and to reduce the settlements.
ii) to reduce the differential settlements of the oil tank, even if the liquefaction occurs.
iii) to transfer the stresses of the oil tank to deeper layers by the sheet pile wall beneath the oil tank.

In this study, a model tank size was restricted by the centrifuge facility, so that the prototype tank was 150 kl class one.

CENTRIFUGAL APPROACH

Law of similarity

The scaling relationships have been presented by several researchers (for example, Schofield, A.N., 1981 ; Tan, T., S., 1985). Reduction of length by the model factor $1/n$ meant area and mass reductions, and an increase of acceleration by a model factor n would give identical stress at homologous points in the model and the prototype as shown in Table 1 (Kutter, B.L., 1992). The law of similarity requirement in case of dynamic tests, were also shown in Table 1. In dynamic problems it is important that the acceleration of the model increases in the same proportion as the centrifugal acceleration. Dynamic events occur n times faster in the model than in the prototype. The liquefaction of permeable soils may result in simultaneous dynamic generation of pore pressures and dissipation of pore pressure, which is governed by diffusion. Concerning to the pore fluids, the authors were sure that liquefaction model tests under n G field, satisfy the similarity law using silicon oil with viscosity $\nu = n$ cSt. In the other words, the permeability k in n G field corresponds to that of 1 G field (Sakemi, *et al.*, 1995).

Centrifuge facility and the sample preparation

The centrifuge test facility owned by Taisei Corporation Technical Research Center was used in this study. The liquefaction tests were performed by using a circular laminar box type container (ϕ : 400 mm, H=264 mm, 20 mm laminar rings are layered with 2 mm roller bearings each other). The container is made from aluminium. When the centrifugal acceleration reaches a certain value, the swinging platform is fixed on the outer frame of the arm by oil jacks. Some specifications and a general view of the centrifugal facility , is shown in Table 2 and Fig. 2, respectively. For the ground model material, the Sengenyama sand produced in Chiba prefecture in Japan was used. The sand was sieved using 4.75 mm

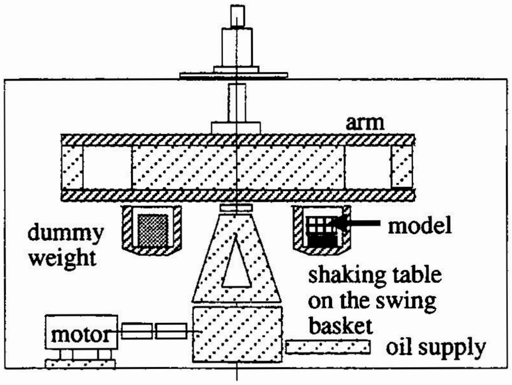


Fig.2 General view of the centrifuge facility

Table 2 the specification of the centrifugal facility include shaking table

effective radius	(m)	2.65
max. size of container	(mm)	L1,000×B900 ×H1,000
max. revolution	(r.p.m.)	260
max. acceleration	(G)	static : 200 dynamic : 50
max. payload	(kg)	s : 400 ; d : 180
max. capacity	(G-ton)	80
main motor	(KW)	300
frequency	(Hz)	30 - 300
max. displacement	(mm)	±2.0
max. channel	(ch.s)	32

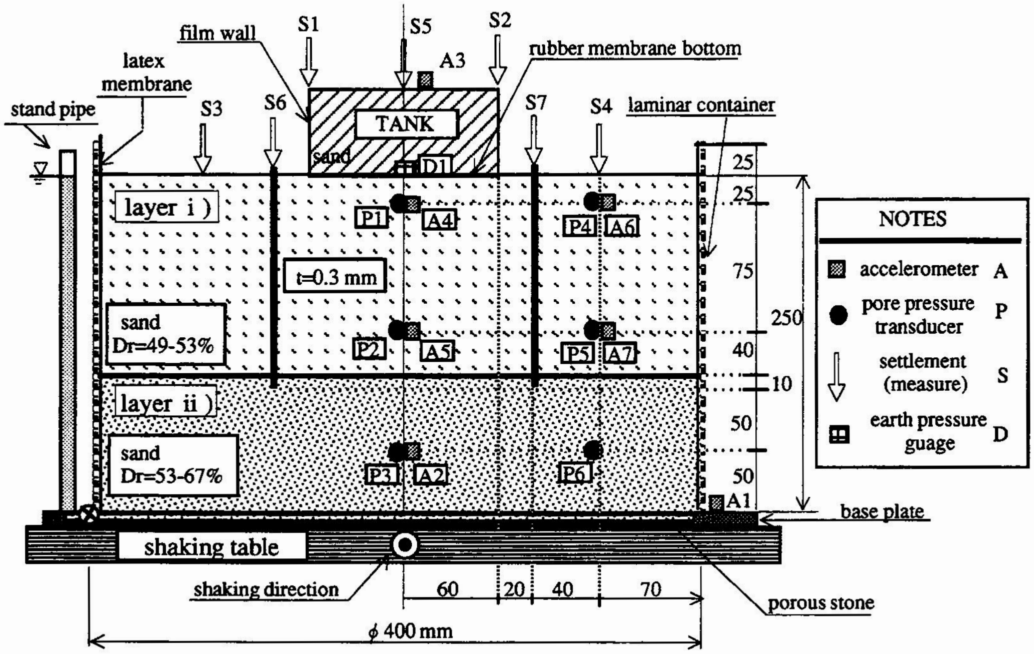


Fig.3 layout of the model container with tank and sheet pile wall sieve, and dried over 48 hours. The physical property of the Sengenyama sand is shown in Table 3. Silicon oil (Shin-Etsu Chemical Co.) was used as a pore fluid. The viscosity of the silicone oil, ν , is 50 cSt, and the specific gravity, ρ , is 0.960, respectively. The model ground depth is 25 cm. Before making the model ground, the sand and the silicon oil, are measured every 5 cm depth of the layer to provide desirable relative density. The sand was poured into the laminar container by a silicon oil pluviation to a depth of 5 cm each. The free falling height were fixed. During the sample preparation, the instrumentation buried within the sand was installed at the proper orientation and location. Figure 3 shows sketches of the model container on the shaking table. This figure includes a model of an oil storage tank with a sheet pile wall.

Table 3 physical properties of the Sengenyama sand

specific gravity	unit	2.683
max. grain size	(mm)	4.75
mean grain size	(mm)	0.26
fine gravel content	(%)	0.8
coars sand contents	(%)	18.4
fine sand content	(%)	75.2
silt content	(%)	5.6
min. dry density	(g/cm^3)	1.320
max. dry density	(g/cm^3)	1.680

Table 5. specifications of transducers

transducer	dimensions (mm)	mass (grams)	model
accelerometer	6 mm square	0.7	A6H-50G T_o = 1 kHz
pore pressure transducer	8 mm diameter 6 mm hight	1.2	P306A-5kgf/cm^2 T_o = 24 kHz
earth pressure transducer	8 mm diameter 18 mm hight	2.0	P306A-5kgf/cm^2 T_o = 24 kHz

all transducers produced by S.S.K.Co.,Tokyo, Japan

Table 4. test conditions

Case No.	Relative Density at 1 G (%)	Relative Density at 50 G (%)	Tank Load (ton-f/m^2)*$^)$	Input Level (Gal)*$^)$	Comments
R-1	i) 53 / ii) 80	———	———	15	ground Model
S-1	i) 53 / ii) 80	i) 53 / ii) 80	3.76	——	sheet pile wall
S-2	i) 53 / ii) 80	i) 54 / ii) 80	13.27	——	sheet pile wall
D-1	i) 49 / ii) 80	i) 53 / ii) 80	2.21	180	no sheet pile wall
D-2	i) 53 / ii) 80	i) 63 / ii) 80	2.21	230	sheet pile wall
D-3	i) 53 / ii) 80	i) 65 / ii) 80	3.98	230	sheet pile wall
D-4	i) 53 / ii) 80	i) 67 / ii) 80	2.21	240	no sheet pile wall
D-5	i) 53 / ii) 80	i) 67 / ii) 80	———	400	ground Model
D-6	i) 49 / ii) 80	i) 56 / ii) 80	13.27	200	sheet pile wall
D-7	i) 53 / ii) 80	i) 67 / ii) 80	2.21	230	partial sheet pile wall
D-8	i) 53 / ii) 80	i) 66 / ii) 80	13.27	225	partial sheet pile wall
D-9	i) 56 / ii) 80	i) 67 / ii) 80	11.00	195	no sheet pile wall

Case No.; R : resonant test, S : static test, D : dynamic test *$^)$: Prototype scale, Peak-Peak acceleration
Relative density ; i): upper sand layer , ii) : lower sand layer (compacted),

Test conditions

Table 4 shows the series of the test cases. Static tests were performed in order to investigate the strain of sheet pile wall caused by the tank load. In the other hand, dynamic tests were carried out in order to investigate the behavior of the tank-ground model during liquefaction. Especially, in the dynamic cases, the differences of the settlements, the rises of the pore pressure, and the accelerations of the ground were investigated for each load levels. Before dynamic tests, the resonant frequency test were performed. The resonant frequency (f) of the typical model is 85 Hz - 90 Hz under the centrifugal gravity of 50 G.

Test procedures

Before the centrifuge test was started, the model was left in the laboratory for 24 hours. Pre-centrifuge loading were performed before the shaking test to create specific model condition and to check the settlements caused by the consolidation of sand. The centrifuge platforms were accelerated up in steps of 5 G, 10 G, 20 G, 30 G, 40 G, and 50 G, and keep 30 minutes under 50 G, then deaccelerated down at the same steps. After stopped the centrifuge, settlements were carefully measured by hand. After that the test started by accelerated the model at the same step as during centrifugal acceleration of 50 G. After a centrifugal acceleration of 50G, shaking test was started. The centrifugal acceleration was maintained for 5 minutes after the shaking to allow for the dissipation of excess pore pressure.

Specifications of transducers

A brief description of the instrumentation used to measure the acceleration, the pore pressure and the earth pressure within the model in each tests is presented (shown in Table 5).

TEST RESULTS

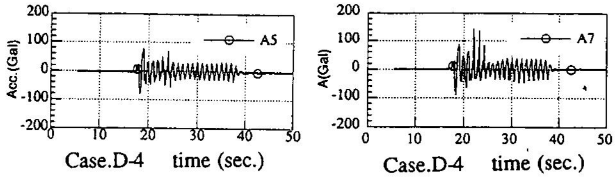
Recorded accelerations

Figure 4 shows the typical response acceleration waves (A5, A7) in the ground during the test (Case.D-1, D-4, D-7, D-6, D-8, D-9). The peak horizontal acceleration is significantly reduced after liquefaction of the loose sand layer. The response accelerations, A5 and A7, of Case.D-1,D-4, and D-7 were reduced after liquefaction. The response accelerations, A5, of Case.D-6,D-8, and D-9 were not reduced. In these cases, this means that there were not liquefied below the tank. In the case of D-9, the response acceleration A7, which was installed 6 cm (in prototype scale : 3 m) apart from the tank edge, and as same depth as A5 (in prototype scale : -5 m), is not liquefied. When the tank load is 2.21 ton-f/m^2, most of the accelerometers show that accelerations are reduced. When the tank load is about 13 ton-f/m^2, in particularly, Case.D-6 and D-8 that have sheet pile wall, the response acceleration, A7, show liquefaction, even though the acceleration, A5, shows liquefaction did not occurred. But in the case of D-9, A5 and A7 were not so much liquefied. It is considerable that the effects of the tank load is heavily depend on the existence of the sheet pile wall when the tank load is larger. In the other hand, the sheet pile wall can transfer the stresses derived from the tank load to deeper layer, but not spread around the ground.

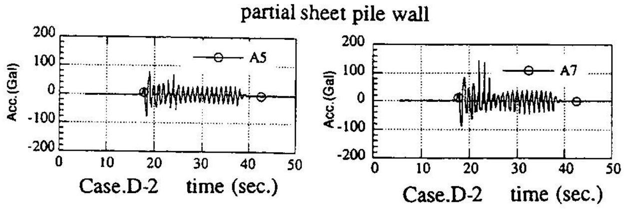
Recorded excess pore pressure

Figures 5, 6 and 7 show the excess pore pressure recorded in the tests, Case.D-2,D-4,D-7 respectively. They were normalized to σ_{v0}' to obtain excess pore pressure ratios r_u. Figures show that the sand layer liquefied during the shaking, with dissipation starting near the end of shaking. In the case of D-2 with sheet pile wall, the excess pore pressure ratio is not so high. The maximum excess pore pressure ratio is about 0.8. While, in the case of D-4 with no sheet pile wall, the maximum excess pore pressure ratio is about 1.0. This means that the liquefaction occurred at the point. In the case of D-7, with partial sheet pile wall, it shows the intermediate pattern of the cases, D-2 and D-4. Sheet pile wall tank load = 2.21 ton-f/m^2

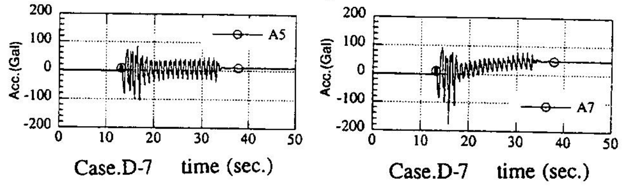
sheet pile wall



partial sheet pile wall

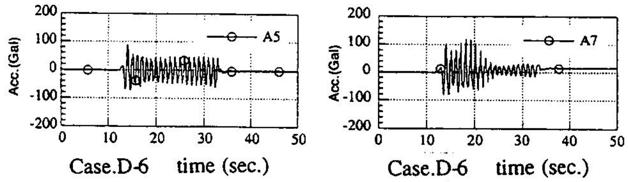


no sheet pile wall

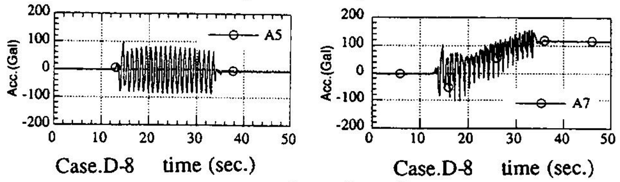


tank load = 11-13 ton-f/m^2

sheet pile wall



partial sheet pile wall



no sheet pile wall

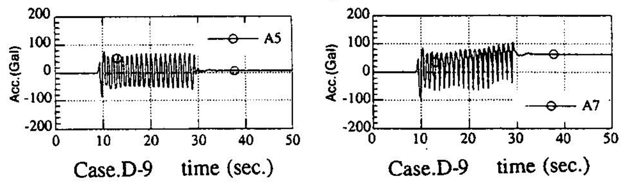


Fig.4 the typical acceleration waves (Case.D-1, D-6)

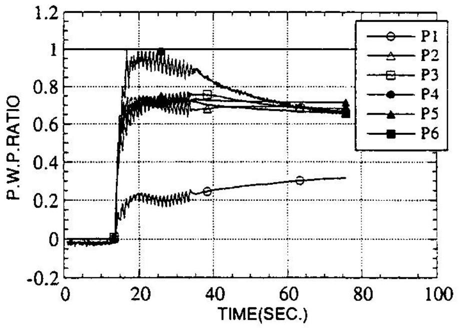


Fig.5 excess pore fluid ratio (Case.D-4)
no sheet pile wall

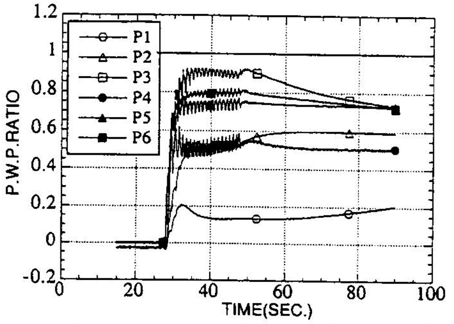


Fig.6 excess pore fluid ratio (Case.D-7)
partial sheet pile wall

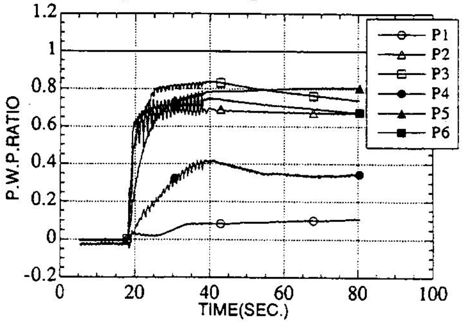


Fig.7 excess pore fluid ratio (Case.D-2)
sheet pile wall

is slightly efficient in case that The tank load is small such as 2.21 ton-f/m^2 at the point of view of excess pore pressure ratios.

Vertical settlement

Measured data from pre-centrifuge ground model indicated that the settlements of the ground surface after centrifugal 50 G loading were 10 cm - 25 cm in prototype scale. While in case of the tank-ground model ,which tank load is 2.2 t/m^2, the settlement of the tank was 30 cm in prototype scale. Figure 8 shows the vertical settlements of the tank and ground surface, after shaking. Figures 8a),8b),8c) show the settlement data of models with no sheet pile wall (Case.D-1, Case.D-4, Case.D-9), with sheet pile wall (case.D-2, Case.D-3, Case.D-6), and with partial sheet pile wall (Case.D-7, Case.D-8), respectively. The difference among the results shown in Fig.7 is due to the effect of the tank load, and heavily depend on the existence of walls. Notes that the settlement in Fig.7b) is the smallest.

Strain generated on the sheet pile wall

Strains generated on the sheet pile wall were measured during centrifugal loading, and during shaking. The Young's modulus of the model sheet pile wall , E_m, is 1.2×10^6 kg/cm^2. The model sheet pile wall was made of copper film with 0.3 mm thickness. When the tank load is 2.2 t/m^2, the maximum value of the strain generated on the sheet pile wall is 60 micro-strain. This means that the stress generated on the sheet pile wall is 70 kgf/cm^2 (tension) under 50 G. In the other hand, that of during shaking is 60 kgf/cm^2 (tension) under 50 G. The maximum stress was measured at the bottom sheet pile wall. Figure 9 shows the typical strain measured in the case of D-2 , and shows its input acceleration.

CONCLUSIONS

The results of the study show the following tendencies of tank model during liquefaction.

i) It is cleared that the levels of settlements depend on the tank load, and heavily depend on the existents of the sheet pile wall.

ii) In the real oil tank yard, it is found that the settlement of the ground around the tank is caused by the liquefaction during some earthquakes in Japan (For example,K.H.K.Report, 1994). The settlement data from this study is similar to the settlement of real earthquake damages.

iii) The sheet pile wall method is very useful to prevent settlement of the tank, includes differential settlement, when liquefaction occurs. It is important to note that, in case of partial wall, there were not enough effect to prevent settlement during liquefaction.

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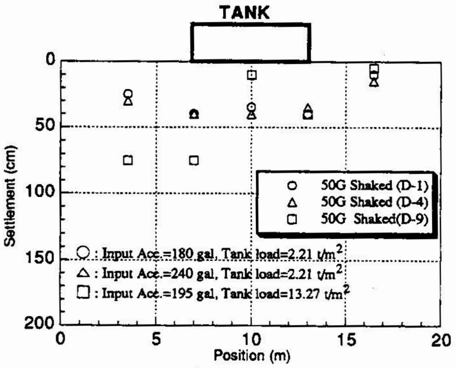
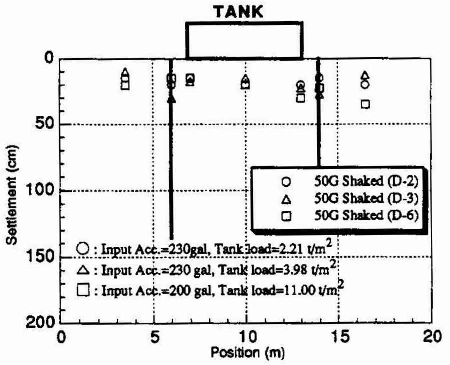
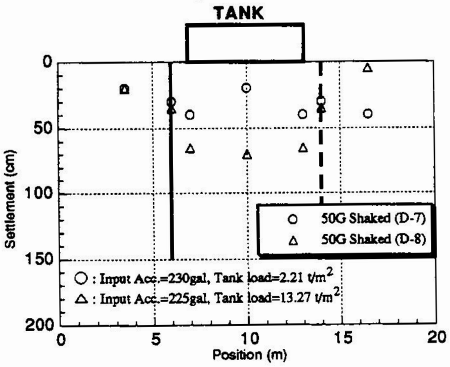


a) no sheet pile wall

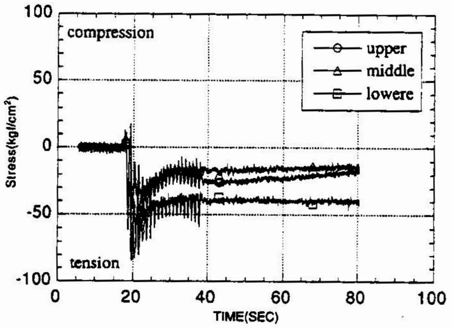


b) sheet pile wall

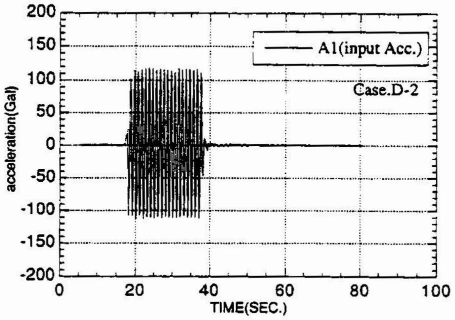


c) partial sheet pile wall

Fig.8 Settlement of the tank and the ground in the tests



a) stresses on the sheet pile wall



b) input acceleration (Case.D-2)

Fig.9 Stresses od the sheet pele wall and input acceleration (Case.D-2)