VIBRATION TESTS FOR SCALE MODELS OF CYLINDRICAL COAL STORAGE SILO

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SYNOPSIS

For the purpose of evaluating the seismic response of coal storage silos, the authors have carried out forced vibration tests on small-scale model silos resting on a shaking table. Also, the dynamic behaviour of the model silos has been simulated by a computer program and a satisfactory agreement between the test results and the numerical method has been obtained.

INTRODUCTION

Recently use of large-scale silo systems for coal storage has attracted the attention of the Electric power industry in Japan, because silos provide convenient storage space and prevent the spread of coal dust.

In previous research studies on seismic design of tall cylindrical silos, Chandrasekaran (Ref.1) and Shibata (Ref.2) have discussed the effective live load of fill under dynamic conditions. However, very few studies have been reported concerning flat cylindrical silos of diameter to height ratio approximately unity, such as the coal storage silo.

For the purpose of evaluating the seismic response of coal storage silos, the authors have carried out small-scale tests on a shaking table. The fundamental relationships between prototype and models have been carefully controlled.

This paper presents results of these tests, especially the graphical representation of the response due to coupled vibrating behaviour of the fill and the container, and also offers preliminary numerical analysis on the dynamic response of the model silo.

TEST STRUCTURE AND INSTRUMENTATION

Test Models

The four cylindrical model silos used in the present investigation were made of PVC (Polyvinylchloride Resin) or STEEL and were of dimensions as shown in Table 1 (Ref.3). Fig. 1 shows the outlines of the model test silos. Each test silo was secured

Table I. Dimensions of Models

Model	D (cm)	H (cm)	t (mm)	λ	Material
PVC I	150	160	5	25	Polyvinyl-chloride Resin
PVC II	85	90	2	44	
PVC III			4		
STEEL	150	160	0.8	25	Steel

D ; Inner Diameter t ; Shell Thickness
H ; Height λ ; Scale Factor

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to the shaking table with bolts passing through the bottom plate. The top ends of the silos were stiffened with ring plate. Any initial out-of-roundness at the top was less than 2 % of the diameter.

Each model test silo was intended to simulate a 38 m diameter 40 m high prototype silo. The important aspect of the experiment was to study the coupled vibrating behaviour of the fill and the container. The similarity between the distorted model and prototype was carefully chosen as shown in Table 2 (Ref.4). For cylindrical containers the similarity for membrane stress was considered, not the bending stress.

Filled Coal

The coal specimen was selected from material passing a 5 mm sieve and was weighed. Table 3 shows the physical properties of the coal.

The coal was slowly poured into the silo resting on the shaking table and oscillating at a sinusoidal wave of 300 gal acceleration amplitude. The height of fill was about 95 % of the silo height and the average bulk density of the fill was calculated to be in the order of 0.90 gr/cm³.

Input Waves

The shaking table was excited in two ways;

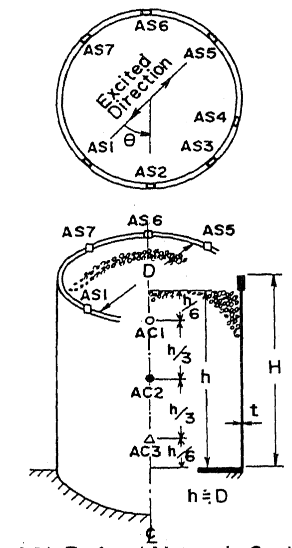
(1) Stationary sinusoidal wave mode at an acceleration amplitude of 10 - 200 gals and frequency of 5 - 45 Hz ,

(2) Earthquake wave mode at a higher acceleration amplitude of 200 - 300 gals to simulate EL CENTRO 1940-NS (EL wave) and HACHINOHE 1968-EW(Ha wave).

For the seismic waves, the time scale was scaled down by $\lambda^{3/4}$ to maintain similitude (refer to Table 2).

Measurement

The response accelerations of the fill in the direction of excitation were measured by three accelerometers (AC 1 - 3) placed in the fill along its center axis at various depths. The response accelerations of the silo wall in radial direction were measured by seven accelerometers (AS 1 - 7) mounted on the top rim of the test silos. For a particular case study (Fig. 6), in order to



AC1~3 ; Accel.Meters in Coal
AS1~7 ; Accel.Meters at the Top of the Silo

Fig.1 Outline of Silo Models and Location of Meters

Table 2. Similarity of Scale Cylindrical Silo Model

Quantity	Scale (Prototype / Model)
Length	λ
Displacement	$\lambda^{\frac{3}{2}}$
Strain	$\lambda^{\frac{1}{2}}$
Acceleration	1
Time	$\lambda^{\frac{3}{4}}$
$E \cdot t / \rho$	$\lambda^{\frac{3}{2}}$

E ; Modulus of Elasticity
t ; Shell Thickness
ρ ; Mass Density

Table 3. Physical Properties of Coal

Item		Measuring Value	Remark
Density of Coal Particle		1.45	apply JIS A1202
Bulk Density	Max.	1.008	Moisture Content ≒ 0 %
	Min.	0.758	
Moisture Content		10.75 %	apply A1203
Angle of Internal Friction		39.6°	Triaxial Compression Test
Cohesion		0.07 kg/cm²	
Friction Coefficient	against PVC	0.240	Direct Shear Test
	against Steel	0.226	
Relationship of Shear Modulus-Shear Strain Amplitude		Fig. 12	Cyclic Triaxial Test
Relationship of Damping Ratio-Shear Strain Amplitude		Fig. 13	

measure the surface acceleration behaviour of the silos, eight accelerometers were mounted on two opposite generatrices of the cylindrical surface of the steel test silo.

Positions of the accelerometers mounted on the test silos are shown in Fig. 1. The setting up for the tests is shown in Fig. 2 .

TEST RESULTS

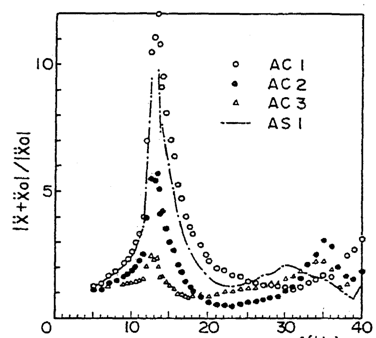
Stationary Sinusoidal Wave Tests

Test data were analyzed by a Fourier Analyser, as shown in Fig. 2. Table 4 shows the resonance frequencies of the test models and the corresponding frequencies modified by the similarity factor.

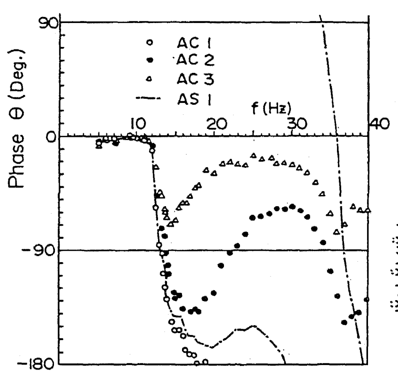
Fig. 3 shows the typical resonance curves of PVC I at table acceleration amplitude $|\ddot{x}_o|$ = 30 gal. The acceleration amplification value (i.e. the ordinate of Fig. 3(a)) is the ratio of response acceleration amplitude and excitation acceleration amplitude.

(1) Fill behaviour

Fig. 4(a) and (b) indicate the resonance curves respectively of PVC II and STEEL expressed as function of table acceleration parameters.



(a) Relationships between Accel. Amp. and Freq.



(b) Relationships between Phase Differences and Freq.

Fig.3 Resonance Curves (PVC I , $|\ddot{X}o|$=30 gal)

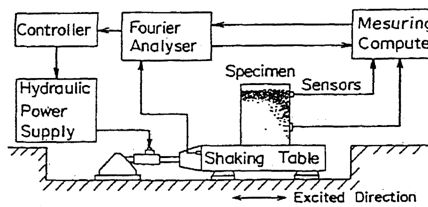
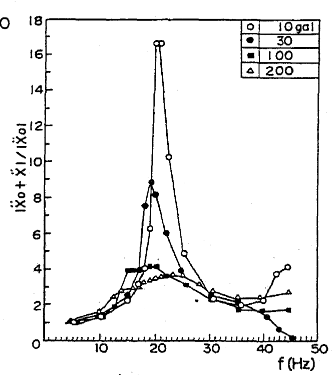


Fig. 2 Measuring and Analyzing System

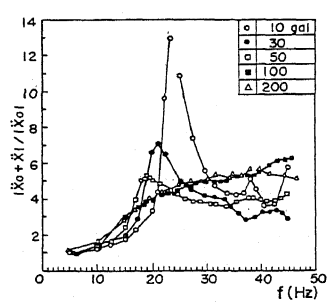
Table 4. Resonance Frequency

		Resonance Frequency f_I (Hz)	$f_I/\lambda^{\frac{3}{4}}$ (Hz)
PVC	I	13.5	1.2
	II	20.5	1.2
	III	22.4	1.3
STEEL		23.0	2.0

PVC I ; $|\ddot{X}o|$ = 30 gal
PVC II , III , STEEL ; $|\ddot{X}o|$= 10 gal



(a) PVC II



(b) STEEL

Fig.4 Resonance Curves (Accelerometer − ACI)

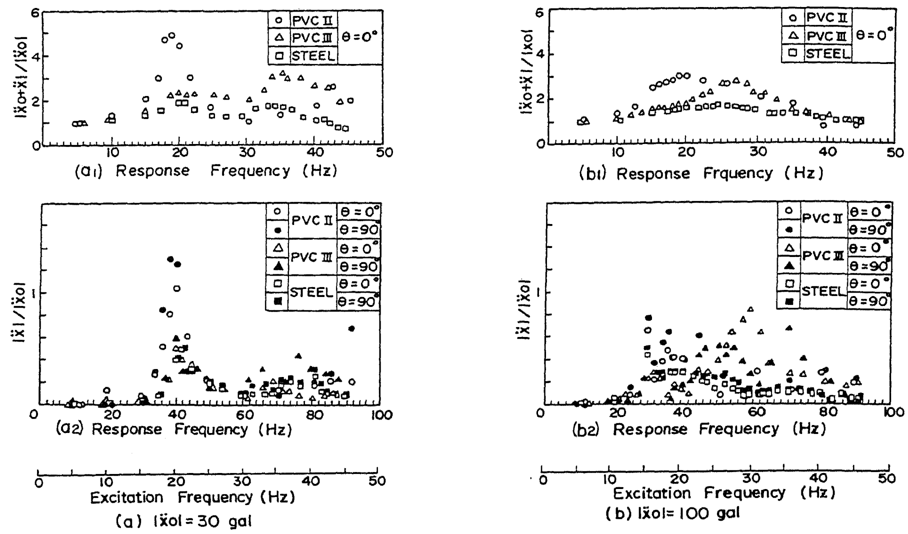


Fig.5 Resonance Curves ($\theta=0^\circ$;Average of AS1 and AS5, $\theta=90^\circ$; Average of AS3 and AS7)

In Fig. 4, it is noticeable that with progressive increase of the table acceleration amplitude, the upper accelerometer in the coal fill registers a decrease in the peak acceleration amplification values of the fill as well as a shift of the peak values toward lower frequency range. The same trend was observed in the readings of the middle and the lower accelerometer in the fill.

(2) Vessel behaviour

Fig. 5(a) and (b) show the resonance acceleration amplitudes observed at the top of the silos corresponding to table acceleration amplitudes of 30 gal and 100 gal respectively, excited at various frequencies.

The observed behaviour indicates that the resonance acceleration pattern induced at the top of the silos follows a compound acceleration amplitude curve composed of; (a) an acceleration amplitude mode that follows the same frequency as the table excitation frequency (refer to Fig. 5a1 and 5b1), and (b) an acceleration amplitude mode that follows a frequency twice that of the table excitation frequency (refer to Fig. 5a2 and 5b2). This was concluded by analyzing the compound curve with a Fourier Analyser. This observed phenomenon was most pronounced as the excitation frequency approached the first resonance frequency.

Fig. 6 shows the typical acceleration amplitude modes developed in the excited direction in the test steel silo for a table acceleration of 10 gal vibrating at the first resonance frequency and the second resonance frequency.

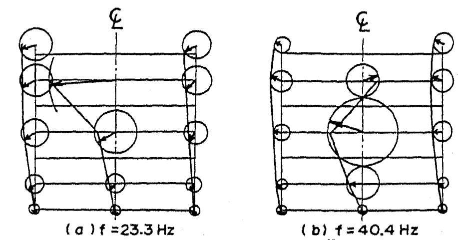


Fig.6 Resonance Modes(STEEL,|Ẍo|=10gal)

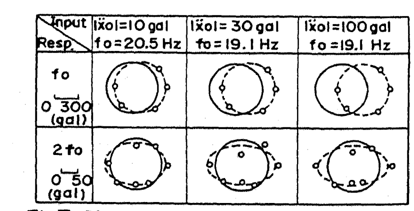


Fig.7 Circumferential Modes of Top Rim Accel. (PVC II)

Fig.7 shows the radial acceleration amplitude mode at the top rim of the PVC II test silo.

The Fig. 5 - 7 show that; (a) as with the fill, there is also a progressive reduction in the peak acceleration amplification values of the vessel as the table acceleration amplitude increases; (b) the response acceleration wave at the top rim has a component acceleration of a frequency twice as high as the resonance frequency which probably accounts for the slight elliptical deformation of the ring plate; and (c) at the first resonance frequency the test silo and the coal fill vibrate with the first mode shape, but at the second resonance frequency, the coal only vibrates with the second mode shape.

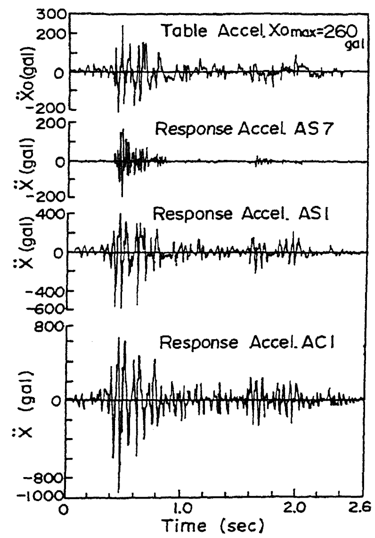


Fig. 8 Typical Response Records
(PVC II, Ha wave)

Seismic Wave Tests

The data obtained from each accelerometer can be studied in the form of a time history plot. The table acceleration record and the response acceleration records of PVC II (typical for all test silos) are shown in Fig. 8. The time axis is scaled down by the factor $\lambda^{3/4}$ (refer to Table 2) to maintain similitude. An inspection of these waves shows that the time of occurrence of the maximum response acceleration for all measured points on the vessel and in the fill coincide with the time of the maximum table acceleration.

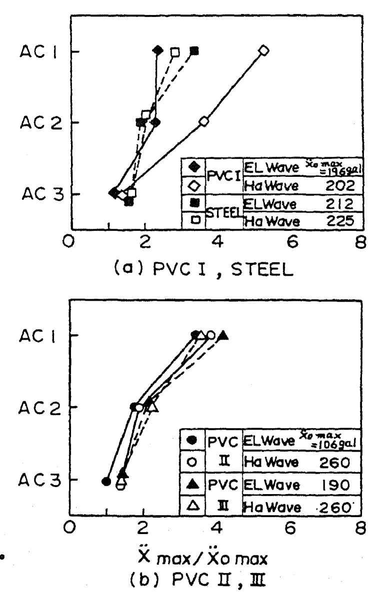


Fig. 10 Ratios of Max. Response Accel. to Max. Table Accel. (Coal)

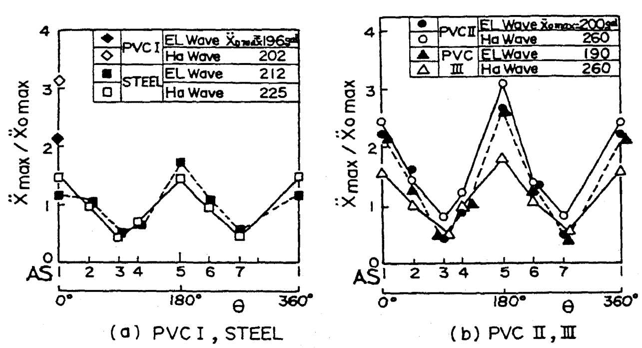


Fig. 9 Ratios of Max. Response Accel. to Max. Table Accel. (Vessel)

As with the stationary sinusoidal wave tests, the results for the seismic wave tests were also analyzed by Fourier Analyser. Fourier analyses show that AS1, AS5 (vessel accelerometers $\theta=0°$, $180°$) and AC1 (fill accelerometer $\theta=0°$) have peak Fourier amplitudes at the frequency near the first resonance frequency of the coupled system, but AS3, AS7 (vessel accelerometers $\theta=90°$, $270°$) have a peak Fourier amplitude near at a frequency which is approximately twice that of the first resonance frequency of the system - similar to what was observed during stationary sinusoidal wave tests.

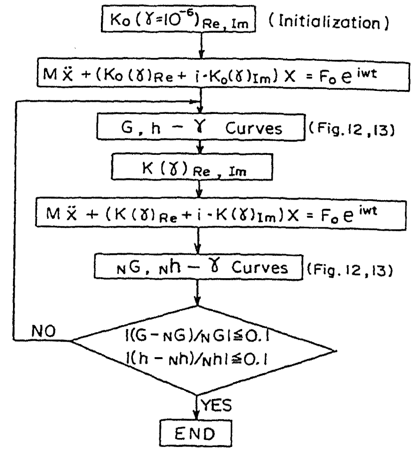
Fig. 9 shows the ratios of the maximum accelerations at various points at the top of model silos and that of the table for simulated seismic wave tests (El Centro and Hachinohe wave).

Fig. 10 shows the ratios of the maximum accelerations at various points on the center axis of the coal fill and that of the table for the same seismic wave test conditions.

NUMERICAL ANALYSES

The axisymmetric finite element program (Ref.5) used for the mathematical interpretation of the results of the model tests has been developed by the authors. The flow diagram used in the program is shown in Fig. 11.

The model silo wall has been simulated to conical shell element and the coal fill has been simulated to axisymmetric solid element (Ref.6). The numerical results of dynamic response of the coal fill have been obtained by "Equivalent linear analysis" (Ref.7), in which the strain dependency of dynamic properties of coal has been taken into account. The strain dependency and the dynamic properties of coal used in the numerical analysis were obtained by cyclic triaxial tests and are shown in Fig. 12 and 13.



G : Secant Shear Modulus
h : Damping Ratio
γ : Shear Strain Amplitude

Fig. 11 Flow Diagram of Numerical Analysis

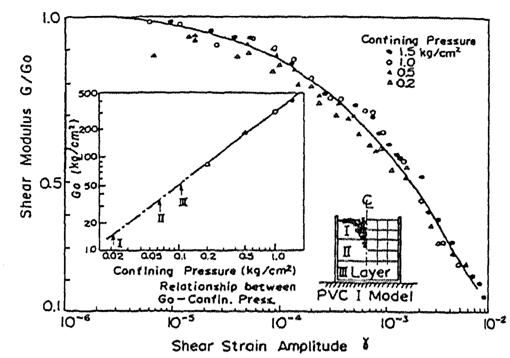


Fig.12 Relationship between G/Go − γ

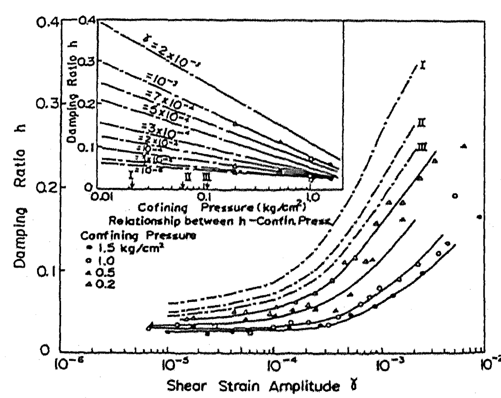


Fig.13 Relationship between h−γ

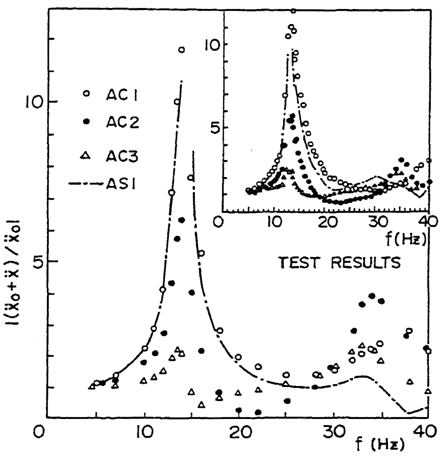


Fig.14 Frequency Response (PVC I, |ẍo|=30gal)

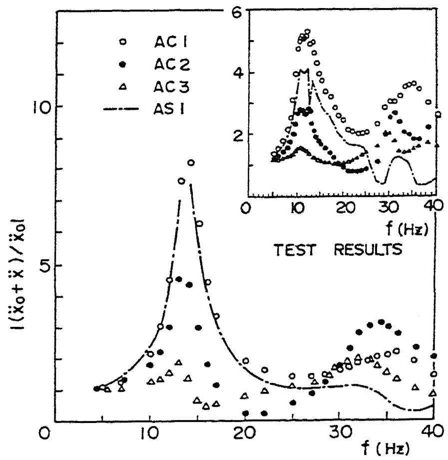


Fig.15 Frequency Response (PVC I, |ẍo|=100gal)

Numerical analysis for PVC I test silo was conducted on the mathematical model for excitation acceleration amplitudes of 30 gal and 100 gal. For excitation acceleration amplitude of 30 gal, good agreement was obtained between the theoretical and the test results with respect to the resonance frequency as well as to peak response acceleration amplitudes, as shown in Fig. 14. The tendency of shift of the peak response acceleration amplitudes toward lower frequency under increasing excitation acceleration amplitudes was confirmed by the numerical analysis. For the 100 gal excitation acceleration amplitudes, however, the agreement of the response acceleration was not quite as keen, as shown in Fig. 15.

CONCLUSIONS

From the results of the investigation, the following conclusions may be drawn:

1. For a given H/D ratio the measured resonance frequencies of the models corrected by the similarity factor resemble to each other comparatively well for a certain range of membrane stiffnesses. The effect of membrane stiffness on resonance frequency appears to be relatively small.
2. With increase in excitation (table) acceleration amplitude the peak acceleration amplification values of contained material (coal) decrease and the decreased peak values shift towards lower frequency, which can also be interpreted by numerical analysis in terms of shear modulus and damping ratio of fill material expressed as a function of strain.
3. The silos and the contained material (coal) vibrate in the first mode shape at the first resonance frequency. But at the second resonance frequency the fill only vibrate in the second mode shape.
4. At first resonance frequency there is tendency of the top rim to suffer an elliptical deformation induced by a component acceleration of frequency twice that of the resonance frequency. The origin of the component acceleration probably can be attributed to the dynamic pressure of the contained material (coal).

5. For excitation acceleration amplitude of higher order (such as under seismic acceleration), the maximum response occurs almost at the same time as the maximum excitation (table) acceleration. The highest amplification of the component frequencies also occurs at the first resonance frequency.

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