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SEISMIC RESPONSE OF CONCRETE STAVE SILOS WITH STRUCTURAL DISCONTINUITY

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SUMMARY

This paper describes the earthquake response behavior of a silo structure, called "concrete stave silo," with structural discontinuity. A 1/8-scale stave silo model filled with or without a stored material has been tested for the dynamic behavior under sinusoidal and simulated earthquake excitations. Another shaking table tests on a cylindrical shell model with no discontinuity have also been conducted for investigating the effect of the structural discontinuity. These experimental results reveal the effects of a stored material and of the structural discontinuity on the hysteretic restoring force characteristics and nonlinear seismic response behavior of concrete stave silos.

INTRODUCTION

Concrete stave silos are segmental silo structures which are cylindrically assembled from precast concrete blocks called "staves" and held together by exterior pretensioned steel hoops. These stave silos have widely been utilized in the U.S.A. and Canada as industrial and agricultural storage structures for various materials such as coal, grain and silage (Refs. 1,2). In recent years large stave silos have been constructed even in seismic regions since they are more economical and reasonable as compared with other types of silos. However, there are few researches on their dynamic behavior and seismic safety.

The purpose of this study was to clarify the seismic response behavior of stave silos with such structural discontinuity through a series of shaking table tests. The effects of a stored material and of the joint of staves on their dynamic behavior are also investigated.

SHAKING TABLE TESTS

Stave Silo Model In order that the behavior of prototypes may be simulated by model tests, similitude requirements must be satisfied (Ref. 3). Scale factors for model design applied in the present shaking table tests are shown in Table 1. A 1/8-scale model of an actual stave silo was designed on the basis of the scale factors. This 0.8 m x 2.0 m stave silo model was cylindrically constructed from 650 mortary blocks (15.2 cm x 5.0 cm x 2.0 cm) and 32 steel hoops (4 mm in diameter) on a 2.5 m x 2.5 m shaking table. "Rice" of 540 kgf was used as a stored material. The detailed dimensions and configuration of the stave silo model are shown in Fig. 1.

Cylindrical Shell Model To compare with the dynamic behavior of continuous structures and to examine the effect of the joint of staves, a mortary cylindrical shell model was also designed. This shell model was almost the same dimensions as the stave silo model and was similarly tightened with steel hoops, as shown in Fig. 2. Therefore, the structural difference of the two models is only with or without the structural discontinuity.

Experimental Procedure Sinusoidal and simulated earthquake shaking tests were performed for the empty and full states of each model, respectively. The table accelerations used in the simulated earthquake shaking tests were derived from the accelerograms of the 1968 Tokachi-oki and the 1973 Nemurohanto-oki earthquakes, but were speeded up by the time scale factor of 8. The peak table accelerations were gradually increased from 0.1g up to approximately 1.1g. Several types of instrumentation were used to measure accelerations, strains of staves and hoops, and lateral pressures. The gage locations are shown in Figs. 1,2 with simplified symbols. In this paper, the acceleration response behavior at the top (A1) of each model is discussed below.

EXPERIMENTAL RESULTS

Sinusoidal Shaking Tests The sinusoidal shaking tests were conducted in an attempt to clarify the effects of a stored material and of the joint of staves on the lowest natural frequencies and mode shapes of stave silos. Fig. 3 shows the acceleration resonance curves at the top of the stave silo model for the empty and full states. As can be seen from Fig. 3, the effect of filling a stored material gradually reduces the fundamental resonant frequency of the stave silo model. In addition, no oval mode shapes were induced for the full state of the stave silo model in the range of exciting frequency up to 50 Hz.

Fig. 4 shows a comparison of the fundamental resonant frequencies between the stave silo model and the cylindrical shell model. It can be seen from this comparison that the resonant frequencies of the stave silo model are remarkably lower than those of the shell model for both the empty and full states. The experimental results suggest that the effect of the joint of staves may produce the considerable degradation of stiffness of stave silos.

Simulated Earthquake Shaking Tests As described above, two kinds of table accelerations were used in the simulated earthquake shaking tests. A time history of those table accelerations, derived from the 1973 Nemurohanto-oki earthquake, is shown in Fig. 5. Also, shown in Fig. 5 are typical time histories of the acceleration responses at the top of the stave silo model to the Nemurohanto-oki earthquake excitations.

The variations of acceleration response factors during earthquakes with peak table accelerations are shown in Fig. 6. The response factor here represents the ratio of maximum response value to peak table acceleration. For both the empty and full states of the stave silo model, it is found that the acceleration response factors decreased gradually as the peak table accelerations were increased. The experimental results may demostrate that the earthquake response behavior of stave silos is significantly nonlinear when filled not only with but also without a stored material. Compared with these results, the seismic behavior of the shell model was still in the linear range of responses within the same intensity of excitation as the stave silo model.

Fig. 7 presents the power spectra of acceleration responses of the stave silo model to earthquake excitations at a few levels of peak table accelerations. As can be seen from Fig. 7, the predominate frequencies were reduced as the peak table accelerations were increased. These experimental results may also indicate the nonlinear seismic behavior of stave silos.

Restoring force-displacement curves during earthquake responses of both the stave silo model and the shell model are shown in Fig. 8. These curves were obtained by the following procedure (Ref. 4): the equation of motion for a SDOF system excited by an earthquake can be expressed as

$$F(\dot{x}, x) = -M[\ddot{x} + \ddot{z}] \quad (1)$$

in which $F(\dot{x},x)$ represents nonlinear restoring force as a function of relative velocity $\dot{x}$ and displacement x; M is mass; $\ddot{z}$ is ground acceleration. Based on this equation (1), a hysteretic curve can be obtained by plotting the measured absolute acceleration vs. the calculated relative displacement of a structure. It can be found from Fig. 8 that the restoring force-displacement curves for the full state of the stave silo model show a softening spring type of remarkable hysteretic characteristics. It is also revealed that the joint of staves itself produce a type of hysteretic characteristics for the empty state of the stave silo model at a high intensity of excitation.

CONCLUSIONS

Based on the experimental results described above, the following conclusions can be drawn:

1. The presence of a stored material remarkably reduces the fundamental resonant frequency of the stave silo model. The effect of joint of staves produces the degradation of stiffness, so that the resonant frequencies of the stave silo model are considerably lower than those of the shell model.

2. The hysteretic restoring force characteristics of stave silos during earthquakes may be caused by not only the effect of a stored material but of the structural discontinuity itself.

3. For the stave silo model, the acceleration response factors decreased gradually and the predominate frequencies were reduced as the peak table accelerations were increased. It is possible to interpret such nonlinear seismic response behavior of stave silos from a softening spring type of the hysteretic characteristics.

REFERENCES

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Table 1 Scale Factors for Stave Silo Model

Scaling Parameters		Scale Factors
Length	L_r	$L_r = 1/8$
Mass Density	ρ_r	Prototype Material
Modulus of Elasticity	E_r	$\rho_r=1,\ E_r=1$
Stress	σ_r	$E_r = 1$
Strain	ε_r	1
Force	F_r	$E_r L_r^{2} = L_r^{2}$
Time	t_r	$(E/\rho)_r^{-1/2} L_r = L_r$
Frequency	ω_r	$(E/\rho)_r^{1/2} L_r^{-1} = L_r^{-1}$
Displacement	δ_r	L_r
Velocity	v_r	$(E/\rho)_r^{1/2} = 1$
Gravitational Acceleration	g_r	neglected
Acceleration	a_r	$(E/\rho)_r L_r^{-1} = L_r^{-1}$

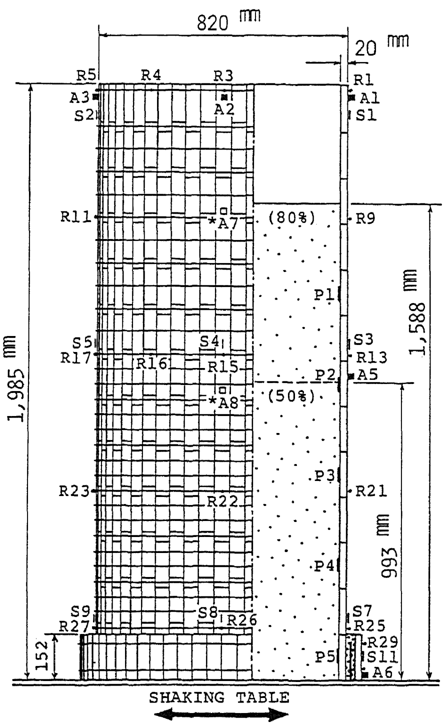

Fig. 1 1/8-scale Model of a Stave Silo

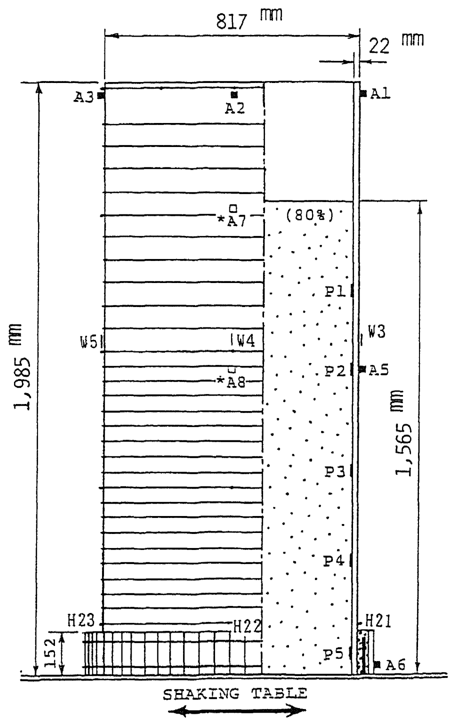

Fig. 2 Cylindrical Shell Model Tightened with Steel Hoops

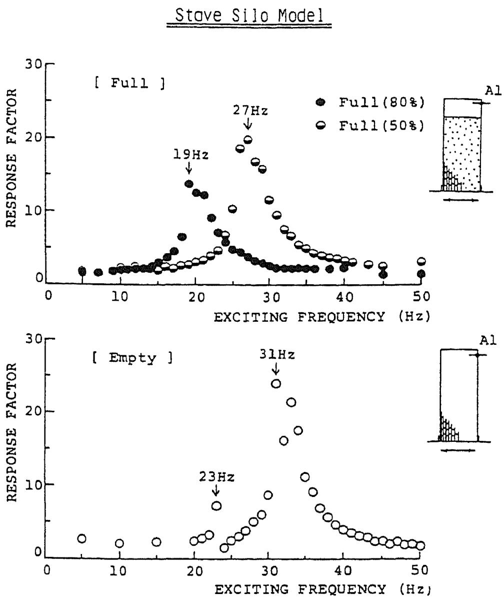

Fig. 3 Effect of a Stored Material on Resonant Frequencies of Stave Silo Model

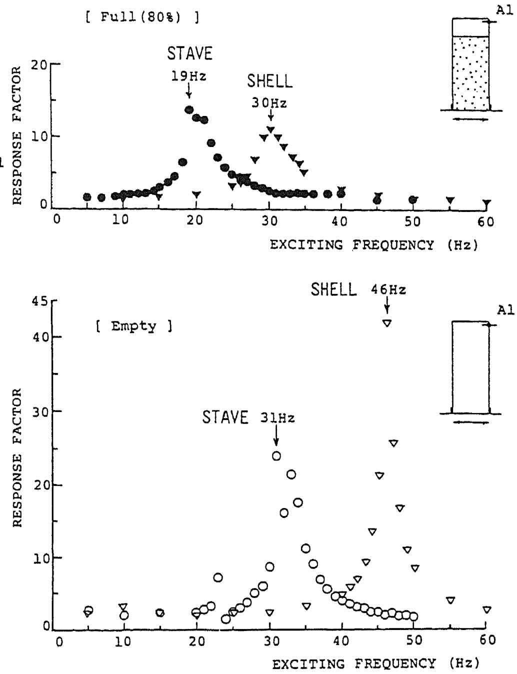

Fig. 4 Comparison of Acceleration Resonance Curves between Stave Silo Model and Cylindrical Shell Model

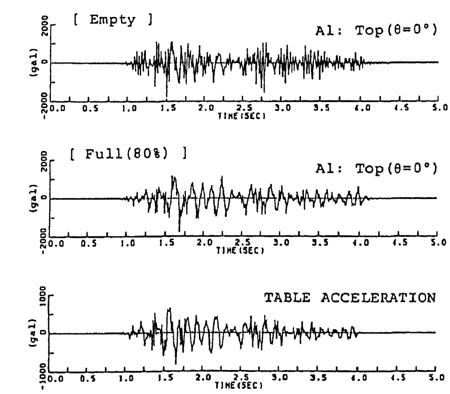

Fig. 5 Time Histories of a Shaking Table Motion and Typical Responses at the Top of Stave Silo Model

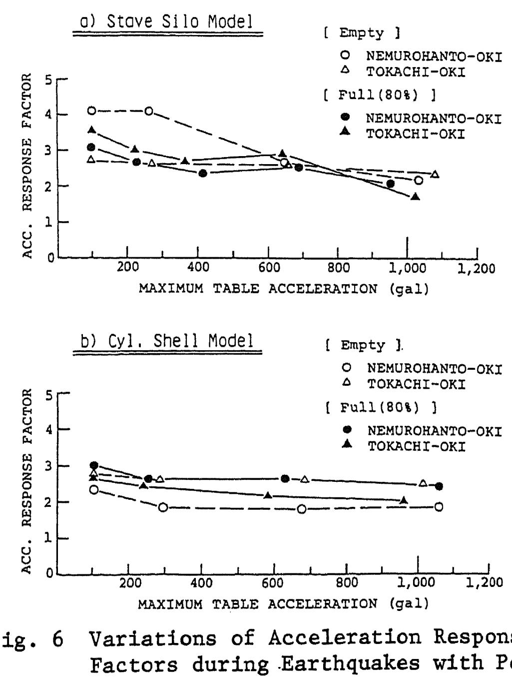

Fig. 6 Variations of Acceleration Response Factors during Earthquakes with Peak Table Acceleration

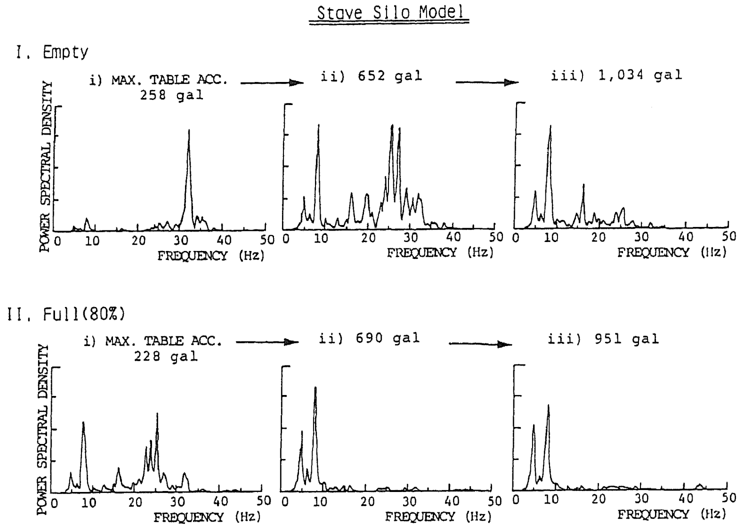

Fig. 7 Change in Predominate Frequency of Earthquake Responses of Stave Silo Model with Peak Table Acceleration

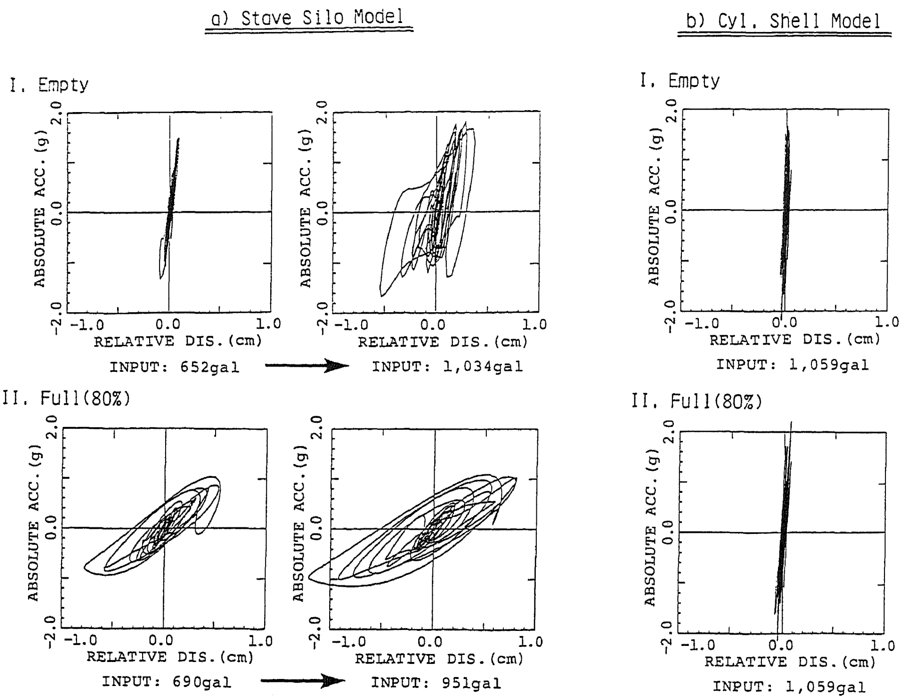

Fig. 8 Comparison of Restoring Force-Displacement Curves during Earthquake Responses