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Dynamic Behavior of Large Suspended Facilities in Large Enclosures

by

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ABSTRACT

Recent large enclosures were designed to be more adaptable and multi purpose. This requires large suspended facilities hung under the large roof structures. In this study, in order to examine the safety of such large suspended facilities, simple two dimensional calculation and three dimensional large displacement simulations were carried out and discussed.

1.Introduction

In the emergency of Great Hanshin Earthquake large enclosures, such as public gymnasiums and public halls, were converted to temporary refuge spaces and very well functioned. On the other hand, in many large span spaces damage to suspended ceilings or suspended facilities spoiled safety of the inner space. Most of them could not opened to public in spite of strong needs of neighbors. Although dynamic behavior of structures itself has been well investigated very few researches have been done on that of non-structural elements attached to or suspended from the structures. Since suspended ceilings cover wide area hung high above the people and suspended facilities are becoming heavier and heavier, it is extremely important to grasp the seismic performance of them, particularly for large span structures.

Recent large enclosures are becoming more multi purpose and high adaptability of interior space is strongly required. As the result facilities inside the enclosures are becoming heavier. General structural parameters of recent large enclosures are shown in Table 1.

At the design stage such large suspended facilities are regarded as the mass particles attached to the roof structures. Their dynamic behavior as suspended objects is rarely considered. Suspended facilities are usually hung by flexible cables that do not resist against compression stress. They may jump under strong vertical exitation and strong impact may attack the suspending cables and roof structures.

In this paper, we investigate the dynamic behavior of roof-suspended facilities systems by means of numerical analysis.

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2. Damage of suspended facilities in the Great Hanshin Earthquake

In the disaster of the Great Hanshin Earthquake 1995., while few structural damage was observed in large span structures, their interior suspended ceilings or suspended facilities were damaged (fig.1). Large suspended facilities, such as huge speaker clusters or acoustic boards, were fallen (fig.2 and 3). In the case of the speaker cluster in fig.2, it is reported that a cast iron gear in the winch box was broken under heavy vertical excitation. The cluster was released and fallen freely. Cables might have been subjected to large stress as several times much as the design load.

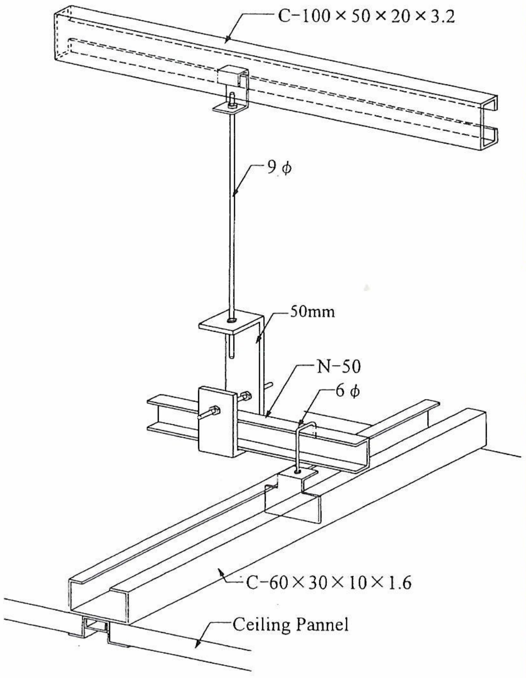


fig.1 Suspended Ceilings

fig.2 Fallen speaker clusters

fig.3 Fallen acoustic boards

3. Horizontal behavior of frame-suspended facility structural system as a two particle system

Basic horizontal behavior of frame-suspended facility systems are investigated as two particle models. The model is indicated in fig.4, in which the suspended facility is modeled as a simple pendulum. Natural frequency of the frame, f_1, and of the suspended facility, f_2, can be given by

$$f_1^2=k_1/m_1 \ , f_2^2=g/l \qquad (1)$$

where k_1, m_1, m_2, g and l are the shear stiffness of the frame, lumped mass for the frame, lumped mass for the suspended facility, gravity acceleration and the length of the hanging cable, respectively.

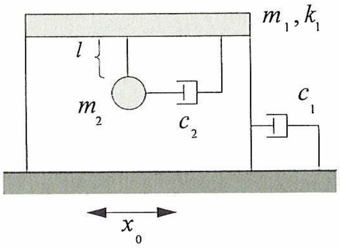


fig.4 Two particle models

Following three cases were considered;

Case 1: No dumping for the frame and the suspended facility,

Case 2: 2% dumping for the frame and no dumping for the suspended facility,

and

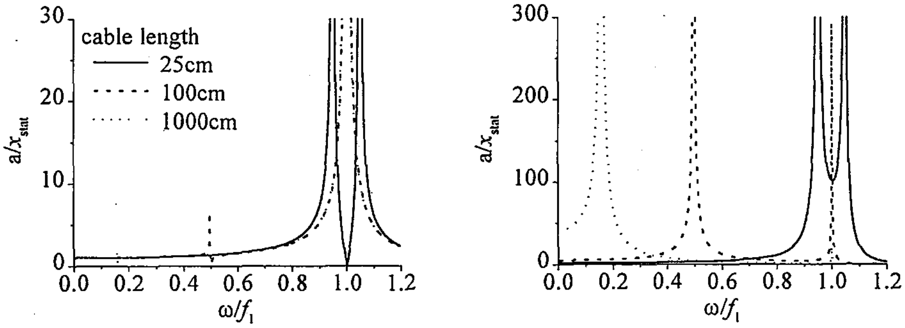
Case 3: 2% dumping for the frame and various dumping for the suspended facility.

The natural period of the frame is set as 1.0 sec. Mass of the suspended facility, m_2, is set 0.01 of the mass of the frame, m_1, i.e. $m_2/m_1=0.01$.

Resonance curves for various cable lengths are shown in figs.5-9. Hanging cable length 25cm is for 1.0sec natural period equalized to that of the frame.

The abscissas are non-dimensioned by f_1 and the ordinates are non-dimensioned by x_{stat}, the static displacement of the frame.

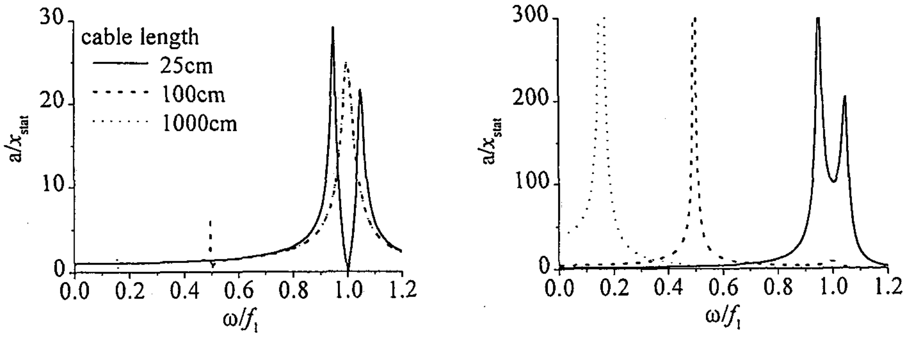
In general the frame and the suspended facility less interact as the hanging cable length becomes longer. When the natural frequency of the suspended facility coincides that of the frame the sympathetic vibration is observed. However if dumping is provided to the suspended facility this phenomenon can be controlled. When the length of hanging cable is 25cm, where natural periods of two systems are the same, fig.7, the suspended facility can act as tuned mass dumper. Though this



(a) Frame

(b) Suspended Facility

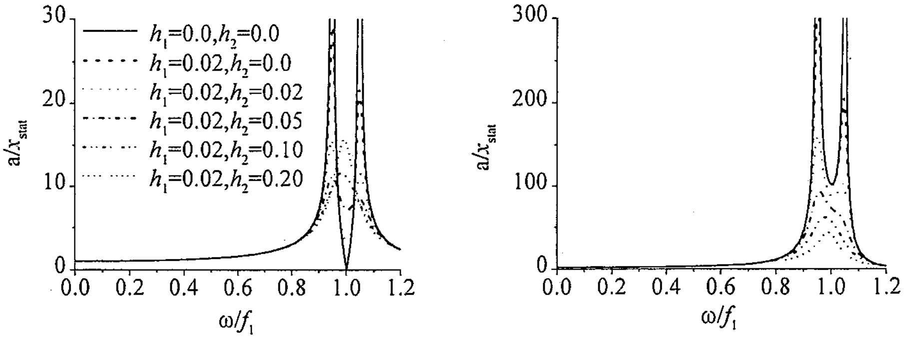
fig.5 Resonance Curve for Case 1(m_2/m_1=0.01)



(a) Frame

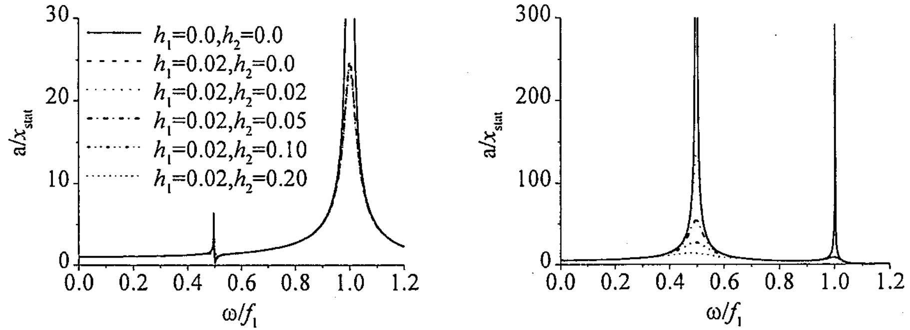
(b) Suspended Facility

fig.6 Resonance Curve for Case 2(m_2/m_1=0.01)



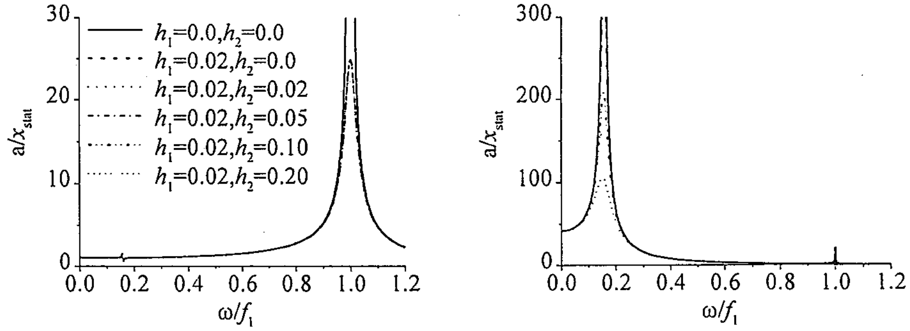
(a) Frame (b) Suspended Facility

fig.7 Resonance Curve for Case 3(cable length=25cm,m_2/m_1=0.01)



(a) Frame (b) Suspended Facility

fig.8 Resonance Curve for Case3(cable length=100cm,m_2/m_1=0.01)



(a) Frame (b) Suspended Facility

fig.9 Resonance Curve for Case3(cable length=1000cm,m_2/m_1=0.01)

dumping effect becomes weaker as the dumping ratio of the suspended facility becomes higher the band where this dumping effect observed becomes wider. When the length of hanging cable is 100cm, in fig.8, change of the dumping ratio of the suspended facility do not so much affect the response of the frame. When the length of hanging cable is 1000cm, in fig.9, two systems do not affect each other at all.

As far as for the horizontal dynamic behavior, when the length of hanging cable is long enough it is sufficient to regard the suspended facilities as the particles which are attached to the frame. However when the natural period of the frame is longer, e.g. being equipped ground isolating system, the suspended facility with longer hanging cable can also cause sympathetic vibration.

4. Three dimensional analysis of roof-suspended facility structural system as a two particle system

In order to grasp the three-dimensional dynamic response of the roof-suspended facility system, a geometrically nonlinear program was developed and simulations in large displacement range were carried out. The roof-suspended facility structural model is shown in fig.10. The rise-span ratio of the roof is 0.2 and the lumped mass of the suspended facility is 0.01 of that of the roof. The natural period of the roof structure in the horizontal direction was set to be 1.0 sec. while natural period in the vertical direction became 1.8 sec. Properties of the roof members are shown in Table 2. Spiral rope of 1m long is assumed to be employed for the hanging cable.

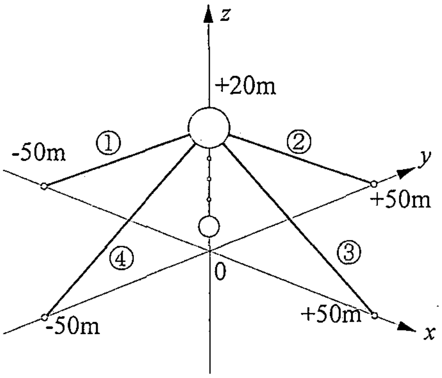


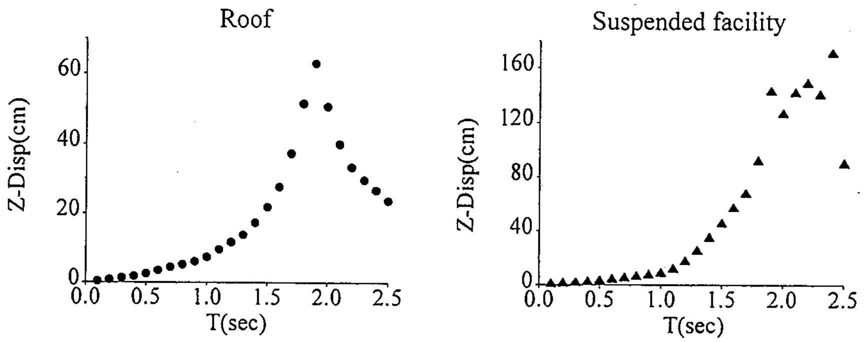
fig.10 The roof-suspended facility structural model

Table.2 Properties of roof members

Steel	Sectional area(cm^2)	59.914
	Young's modulus(kgf/cm^2)	2100000
Cable	Sectional area(cm^2)	1.17
	Young's modulus(kgf/cm^2)	1600000
	Cable length(cm)	100
Lamped Mass	Roof (ton)	1000
	Suspended facility(ton)	10

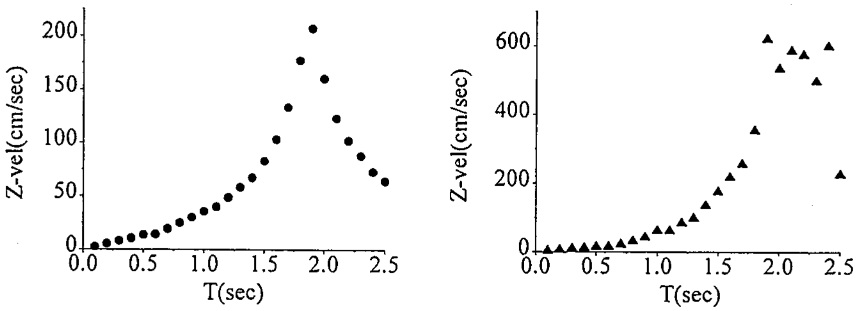
Sinusoidal seismic excitation with 180gal maximum acceleration was applied in horizontal and vertical directions simultaneously. Fig.11 shows response spectra of the model. In fig.11(h) high cable tension area can be observed, which is indicated by a circle. This high cable tension can be due to jumping motion of the suspended facility.
Time history of the response under sinusoidal input with period 1.9 sec. is shown in figs.12 and 13. In fig.12(e) strong spike response can be seen just after the points where cable tension becomes zero. This is due to the slackening of the cable. This spike is repetitive since the facility jumps again after the first spike. The magnitude of the stress reaches about ten times of the static response at the maximum.

Secondly the real seismic load, the JMA Kobe record, was applied. Although the Kobe wave was comparatively strong excitation anything particular response, such as jumping of suspended facility, was not observed (fig. 14).



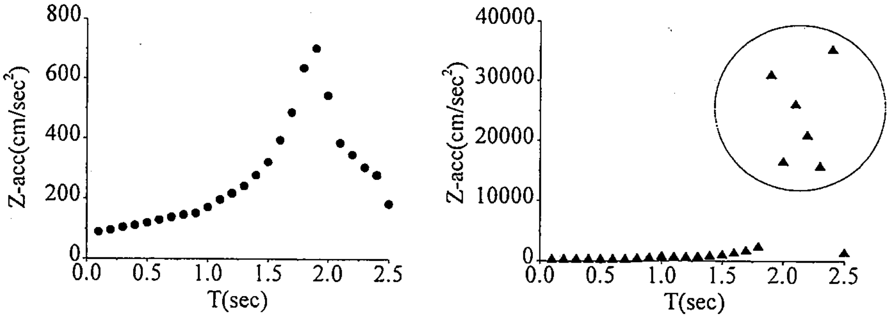
(a) Z-displacement

(b) Z-displacement



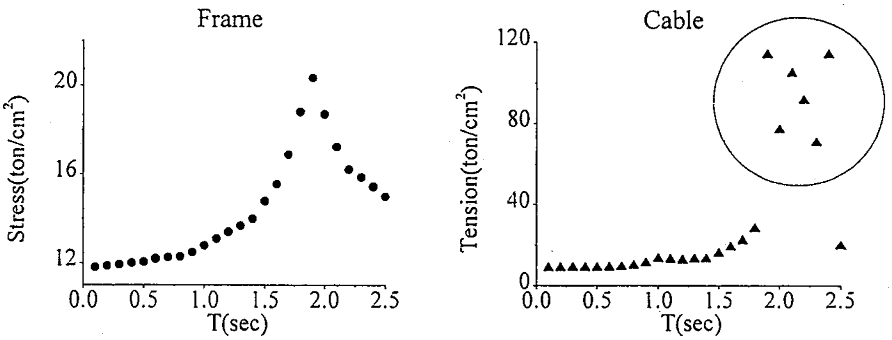
(c) Z-velocity

(d) Z-velocity



(e) Z-accelaration

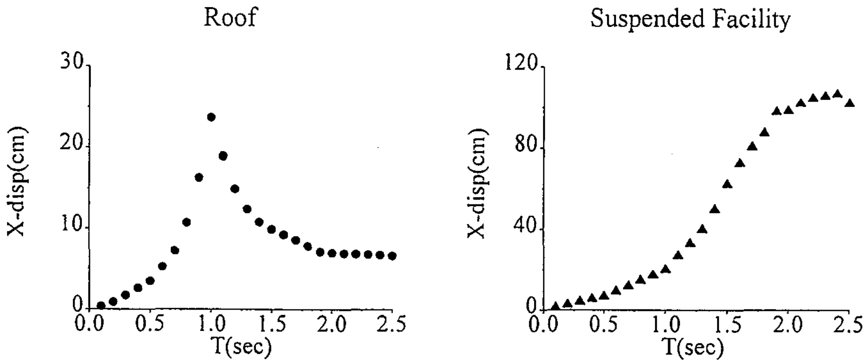
(f) Z-accelaration



(g) Stress of Frame

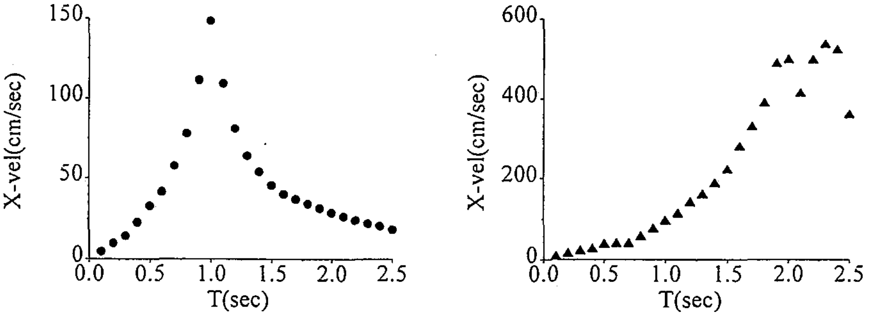
(h) Tension of Cable

fig.11 Response Spectra 180gal cable length=1m (1)



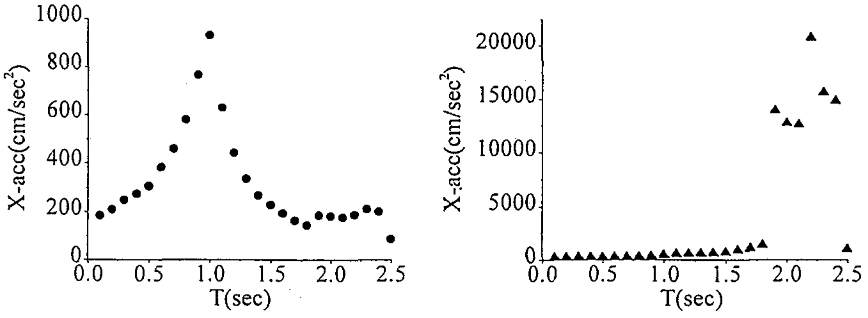
(j)X-displacemet

(j)X-displacemet



(k)X-velocity

(l)X-velocity



(m)X-acceleration

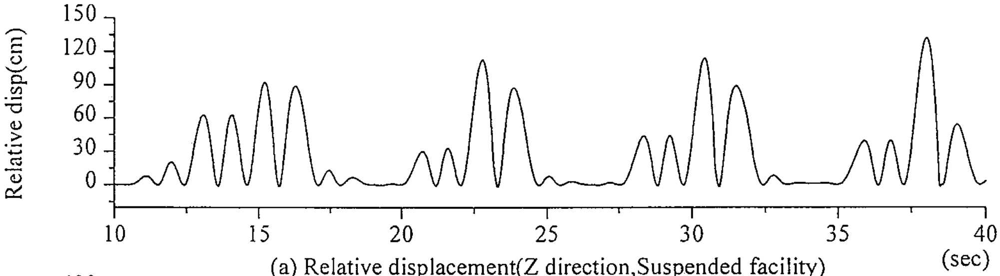
(n)X-acceleration

fig.11 Response Spectra 180gal cable length=1m (2)

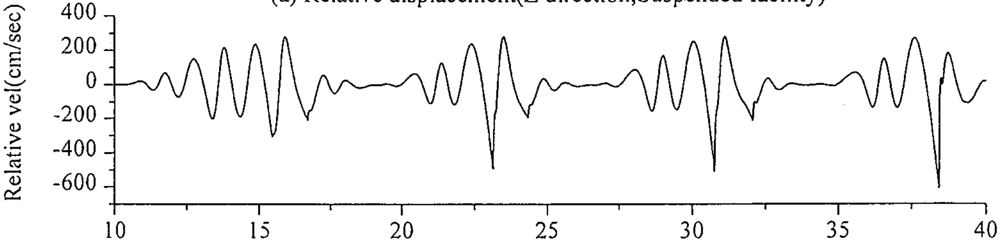
A shock wave in a short period and strong acceleration, 10g, was also applied (fig.15). Under this excitation the hanging cable was slackened and the jumping of the facility was observed.

5.Conclusive remark

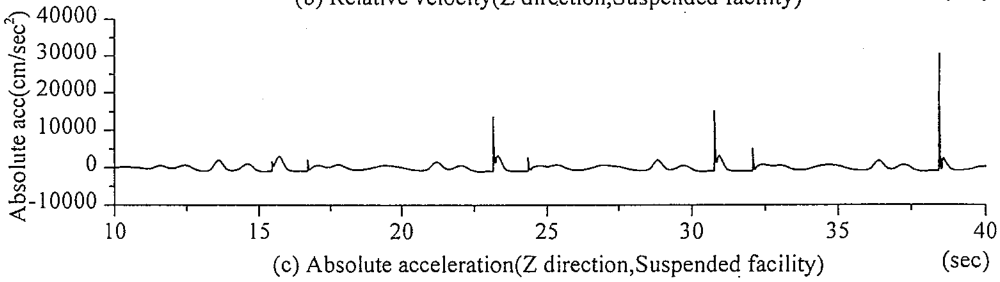
For horizontal responses when the length of the hanging cable is long enough it is sufficient to regard the suspended facility as the weight attached to the roof. However when the cable length is not long enough interaction between the suspended facility and the building frame appears. Especially when the natural period of the both system coincide mass damper effect of the suspended facility to the frame is noticeable.



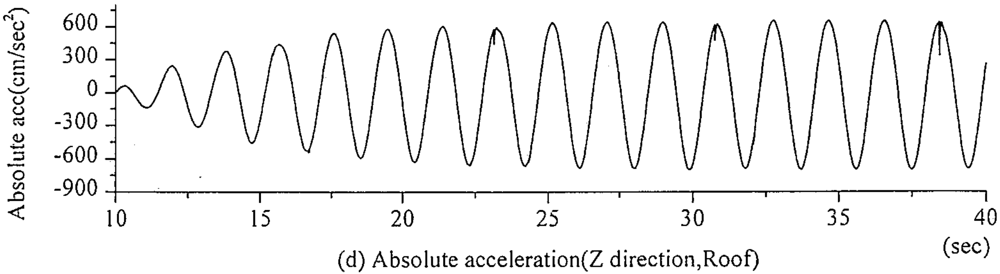
(a) Relative displacement(Z direction,Suspended facility)



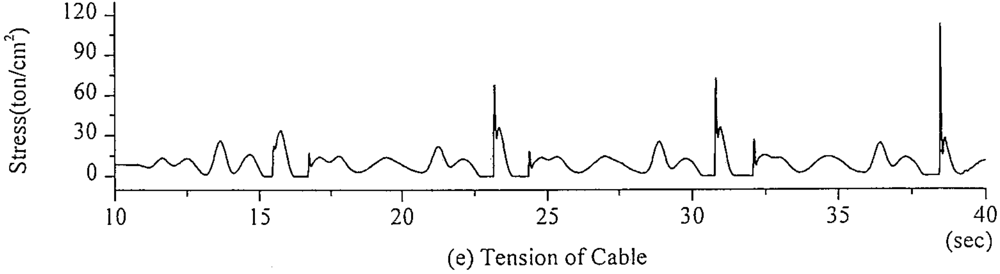
(b) Relative velocity(Z direction,Suspended facility)



(c) Absolute acceleration(Z direction,Suspended facility)

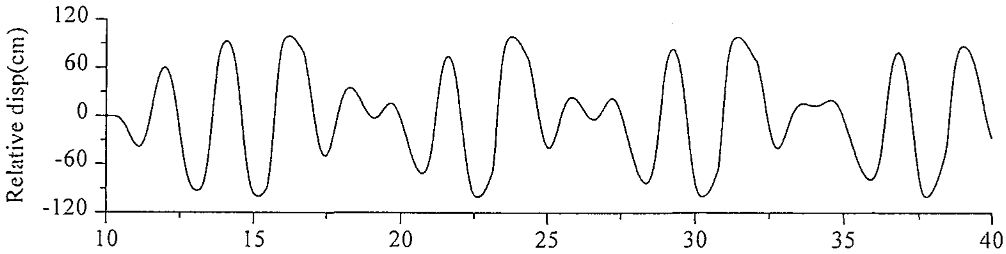


(d) Absolute acceleration(Z direction,Roof)

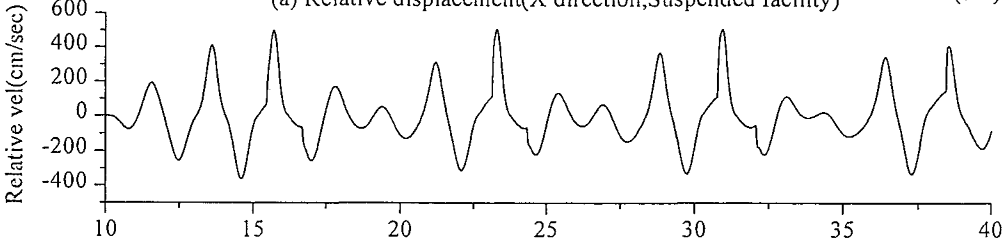


(e) Tension of Cable

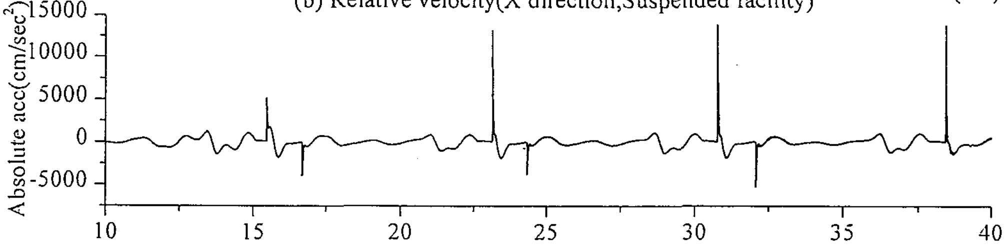
fig.12 Time history of response under sinusoidal input with period 1.9 sec



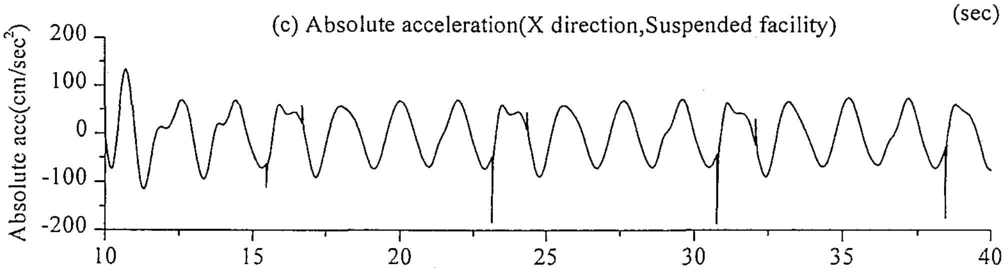
(a) Relative displacement(X direction,Suspended facility)



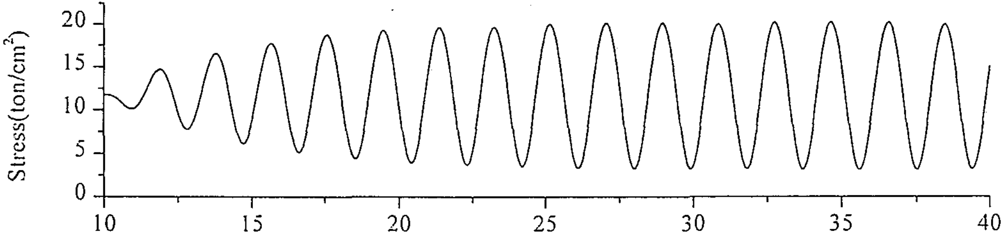
(b) Relative velocity(X direction,Suspended facility)



(c) Absolute acceleration(X direction,Suspended facility)

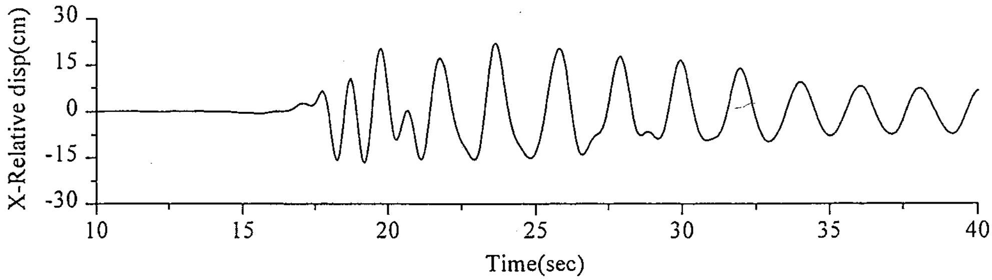


(d) Absolute acceleration(X direction,Roof)

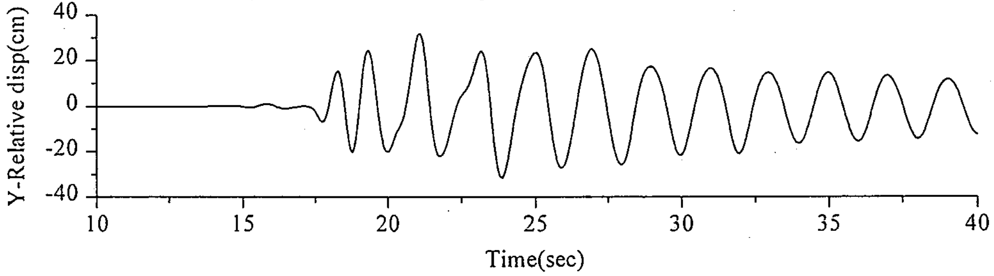


(e) Pressure of Frames

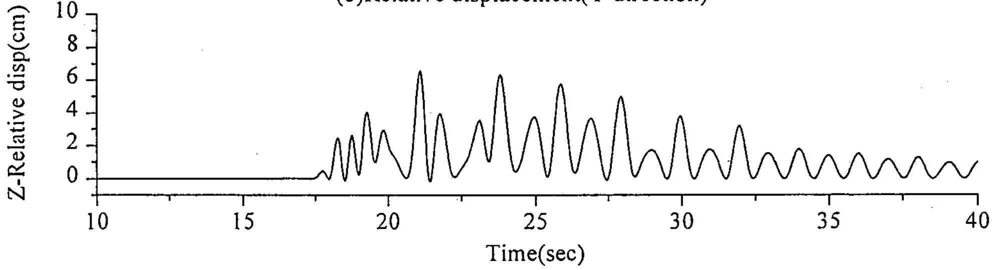
fig.13 Time history of response under sinusoidal input with period 1.9 sec



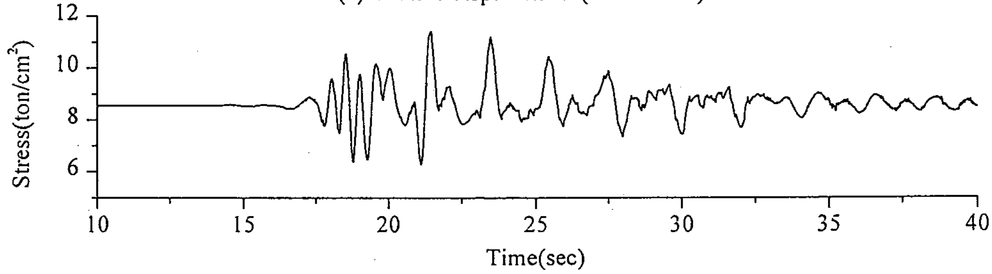
(a)Relative displacement(X direction)



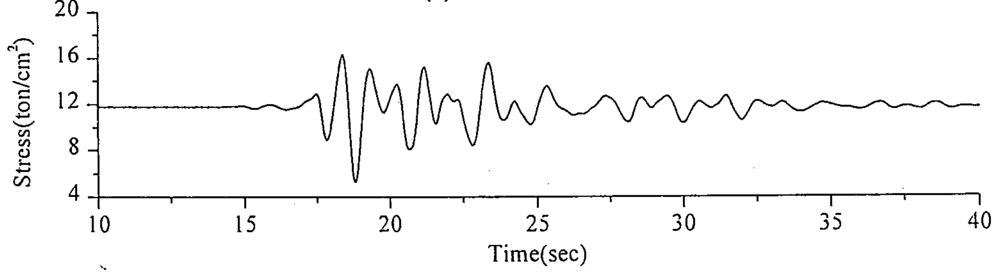
(b)Relative displacement(Y direction)



(c)Relative displacement(Z direction)

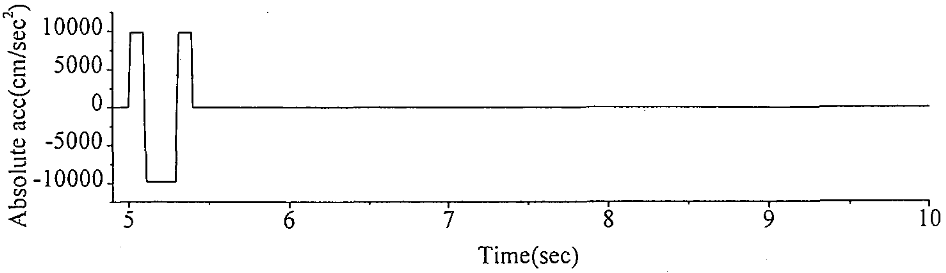


(d)Tension of Cable

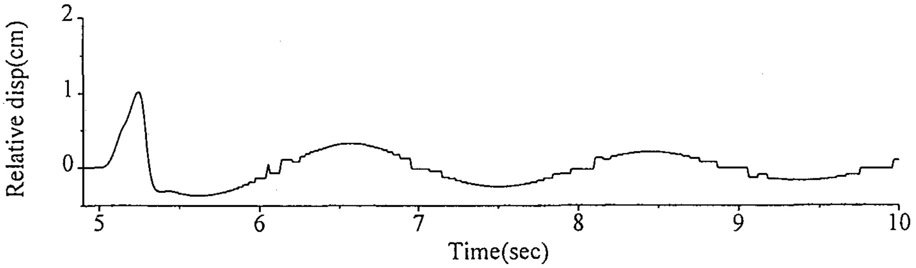


(e)Pressure of Frames

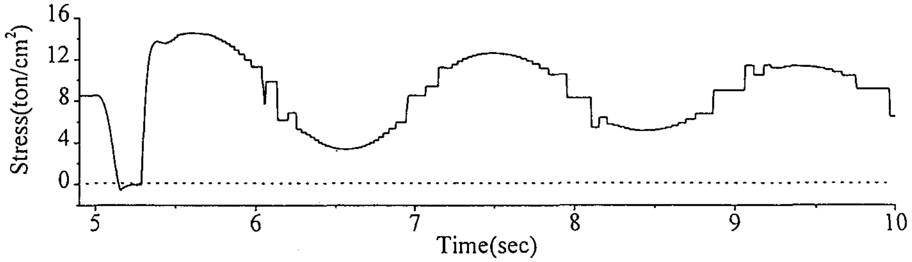
fig.14 Time history of the response under the Kobe wave



(a) Input shock wave



(b) Relative displacement(cm)



(c) Tension of Cable

fig.15 Time history of the response under a shock wave

Three dimensional large displacement analyses, in which cable slackening can be simulated, were carried out for a roof-suspended facility system. As the result of the simulations, it was found that when the vertical excitation period coincides the vertical natural period of the roof structure, the suspended facility may jump and strong tension stress can occur in the hanging cable.