A VELOCITY TYPE STRONG MOTION SEISMOGRAPH WITH WIDE FREQUENCY AND DYNAMIC RANGE

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SUMMARY

As the upper boundaries of particle velocities of several strong earthquakemotions are almost constant over a wide frequency range, the author developed a velocity type strong motion seismograph with the dynamic range from 100 to 0.01 kines over the period range from 0.05 to 50 seconds. The main part of this seismometer is composed of two fan shaped pendulums coupled by thin piano wires, so that the forces of non-oscillating directions are eliminated. As the whole system of the coupled pendulums is immersed in high viscous silicon oil, it has enough strength to resist against destructive earthquakes.

INTRODUCTION

Long period components in strong earthquake motions have been a topic of keen attentions because the natural periods of the modern large buildings and civil engineering structures have become gradually longer, and because the recent studies on the earthquake source mechanism have shown that long period seismic waves are generated in the case of large earthquakes. Accordingly, a number of investigations have been carried out for finding out long period components of waves in the time history of ground displacements, which might be obtained by integrating the acceleration seismograms, but the results of integration are not always reliable, particularly for the earthquake motions with long duration time. On the other hand, so-called displacement seismographs have often been off-scale for large earthquakes. It may therefore be said that we do not yet know accurately what is the destructive earthquake motion.

ON THE MAXIMUM VALUES OF THE STRONG EARTHQUAKE MOTIONS

Many records of the strong earthquake motions obtained by various seismographs are collected and the amplitudes and the corresponding periods of remarkable waves in these seismograms are plotted in Fig.1 (Muramatu(1976)). Accordingly, the ground motions plotted in Fig.1 indicate the upper boundaries of the strong earthquake motions in time domain. Since the almost ground motions plotted here are obtained from accelerograms and their integrations, it is difficult to recognize long period components longer than about 5 seconds even if they were contained. The long period ground motions at Tokyo in Fig.1 are estimated from the Ewing's seismogram shown in Fig.2 considering the characteristics of the instrument after Nasu(1971). We can see in Fig.1 that the maximum particle velocities are almost constant for wide range of periods from 0.1 to 20 seconds and the values are about 20-30 kines, exepting the strong motions at Pacoima dam and at Parkfield.

On the other hand, it is shown theoretically that the large earthquake fault generates the longer period body waves corresponding to the rise time of the fault dislocation which becomes several ten seconds for some large earthquakes. Brune(1970) indicates further that there is a limited value of the particle velocity on a fault surface and the maximum value is about 100

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kines and the corresponding acceleration is 2g for 0.1 seconds.

DESIGN OF A VELOCITY TYPE STRONG MOTION SEISMOMETER

Fig.1 suggests us that a velocity type seismometer is suitable to observe the strong motions of large earthquakes. The period range is desiable to cover from 0.1 seconds or shorter to 20 seconds or longer. Basic requirment for the design of the velocity seismometer is to have a large dynamic range with high fidelity because the records of weak motions which occur frequently are also significant in the research of strong earthquake motions.

The author has therefore designed a velocity type strong motion seismometer to fulfill the requirment in the following items:

1) The sensitivity is flat over the period range from 0.05 to 50 seconds and the dynamic range covers from 100 to 0.01 kines.
2) The dynamic characteristics of the pendulum are not affected by the forces of non-oscillating directions.
3) It has enough strength to resist against the ground motion of 1g.
4) The size is to be small.

Improved Matuzawa's coupled pendulum system. Matuzawa(1938) had devised a coupled pendulum system as shown in Fig.3 which was composed of two fan-shaped pendulums combined by thin belts. One is suspending,another is inverted. Some authors had been already proposed various coupled pendulum systems in order to eliminate the forces of non-oscillating directions in the case of large ground motions, but Matuzawa's system has the following merits for our purposes; 1) it can avoid solid friction because the pendulums are beared by springs only and 2) in principle, there is no expansion and shrinking of the belts by the deflection of the pendulums when the belts are tangential to the fan-shaped surfaces of the pendulums. In spite of large advantage in the Matuzawa's pendulum system, the fatal defect was seen in the unstableness of the system. As it seemed that the instability is caused by the self-weight of the inverted pendulum, the author improved the status in placing the coupled two pendulums in a same horizontal level as shown in Fig.4.

The equation of motion of the pendulum system in Fig.4 are as follows: For the left pendulum

$$I\ddot{\theta} = -K\theta - R\dot{\theta} + m\ddot{x}b\cos\theta + m\ddot{y}b\sin\theta - Aa, \quad (1)$$

where A is the tension in the belts. It is noticed that when $\ddot{y}$ is zero, A is zero. For the right pendulum

$$I\ddot{\theta} = -k\theta - R\dot{\theta} + m\ddot{x}b\cos\theta - m\ddot{y}b\sin\theta + Aa. \quad (2)$$

Eliminating A from Eqs.(1) and (2), y-component forces vanish simultaneously and we have

$$I\ddot{\theta} = -k\theta - R\dot{\theta} + m\ddot{x}b\cos\theta \quad (3)$$

In the case when there is an inclination φ to the direction x, the equation of motion is

$$I\ddot{\theta} = -k\theta - R\dot{\theta} + m(\ddot{x} + g\sin\varphi)b\cos\theta \quad (4)$$

In static state, that is $\dot{\theta} = \ddot{\theta} = \ddot{x} = 0$ in Eq.(4), and when $\theta^2 \ll 1$, we have the following equilibrium equation

$$k\theta = mbg\sin\varphi \quad (5)$$

The design of the horizontal component seismometer of the coupled pendulum system is shown in Fig.5. In this design piano wire are used as the coupling belts and cross springs are used for the falcrums. The improved coupled pendulum system is better than the Matuzawa's in the dynamical stability. The vertical component seismometer of the coupled pendulum system is shown in Fig.6. As the equations of motion are similar to those for the horizontal seismometer, we omit them.

Measurement of the relative displacement. The relative displacement of the pendulum is transformed into electric voltage by using a magnesensor or a differential transformer. The latter is better than the former because the latter is not affected by the external magnetic field.

TEST

Free oscillation test. An example of the free oscillation record is shown in Fig.7 and from it the value of solid friction or its equvalent force is determined smaller than 0.0001 gals. Therefore, our velocity seismometer can detect a weak motion of 0.001 kines for the period of 50 seconds.

Damping oil. When silicon oil with viscosity of 30,000 c stokes (or 10,000 c stokes) is used for damping, the damping constant,h, becomes about 120 (or 40) times of the critical. Then the deflection of the pendulum is about 1 mm (or 3 mm) for 100 kines of ground motion and eddy does not occur and the force proportional to second power of the relative velocity of pendulum can be neglected.

Test by means of a large shaking table. The set of three components of the velocity seismometer is fixed on a large shaking table and the sensitivity and the effects of the force of non-oscillating directions are examined. Out-put voltages from three components by a large vibration test on one direction are shown in Fig.8 and in Table 1. As the shaking table, particularly the vertical shaking table may generate the vibration of other components, it may be thought that the effects of the force of non-oscillating direction are smaller than several percents even for the in-put over 1g.

The sensitivity curves are shown in Fig.9.

Table 1. The largest effects of the forces of non-oscillating directions obtained from Fig.8. e_{H1} etc is the output voltage of each component.

V-direction shaking ;	$e_{H1}/e_V = 0.08$,	$e_{H2}/e_V = 0.08$
H1-direction shaking;	$e_{H2}/e_{H1} = 0.005$,	$e_V/e_{H1} = 0.02$
H2-direction shaking;	$e_{H1}/e_{H2} = 0.015$,	$e_V/e_{H2} = 0.006$

TEMPERATURE COMPENSATING CIRCUIT

Sensitivity of velocity seismometer depends on the viscosity of damping oil which changes with room temperature. Therefore, we connect a temperature compensating circuit with a thermister to the output of the seismometer. Fig.10 shows the temperature dependences of the viscosity of the silicon oil, the resistance of a thermister and the resistance of a compound thermister, respectively. When the compound thermister shown in Fig.10 is used in the feed-back circuit of an operational amplifier which is connected to the output of the transformer, the output voltage of the amplifier becomes independent on temperature. The external appearance of a set of three component seismometers with the temperature compensating circuit is shown in Fig.11.

RECORDING SYSTEM

The velocity seismometer developed here is a kind of tranceducer. We have further developed a recording system which is called SAMTAC-14V where the three component particle velocities of ground motion and the time cord of crystal clock are recorded by digitalized signal in a cassette tape with a delay time of 10 seconds. The crystal clock is automatically corrected by the time signal from NHK(Nippon Hoso Kyokai). AGC(automatic Gain Control) changes 1 kine range to 100 kines range. Start level is variable. Strength of the apparatus of SAMTAC-14V is tested by a large shaking table. The external appearance is shown in Fig.12.

SOME SEISMOGRAMS OBTAINED BY THE VELOCITY SEISMOGRAPH

Fig.13 shows the seismograms of the Near Izu-Oshima earthquake, Jan. 14, 1978, observed by the velocity type strong motion seismograph at Shibaura in Tokyo and that by a strain meter at Haneda in Tokyo obtained by J. Tamura(1978). We can see that the velocity seismogram bears resambrance to the strain seismogram in long period waves. Fig.14 shows the seismograms obtained at two observation points in Shizuoka Prefecture simultaneously. Comparing these seismograms, we can see that the initial motions of P-waves and S-waves are corresponding well and that the later waves express the vibrational characteristics at each site.

COMPARISON ON THE RECORDING RANGES WITH OTHER SEISMOGRAPHS

The recording ranges of some seismographs which are used widely nowadays are shown in Fig.15. The thick lines indicate the ground motions corresponding to the full scale of these seismographs are all 30 mm. The range of thin closed line denoted by A indicates the earthquake motions shown in Fig.1. We can understand that the earthquake motions of which the periods are longer than several seconds are all scaled out in the record of so-called displacement seismographs and they are buried in the shorter motions in the record of so-called acceleration seismographs. Oblique lines indicate the ground motions corresponding to the Japanese seismic intensity scale. Broken line indicates the lower limit to be recorded by VS-100 which is the high sensitive range of the velocity type strong motion seismograph. By the way, the recording ranges of some highest sensitive seismographs are shown.

CONCLUSION

Many records of the strong earthquake motions indicate that the upper boundaries of particle velocities are almost constant for wide period range from 0.1 to 20 seconds and the values are almost 20-30 kines. Accordingly, it may be thought that a velocity type seismometer is suitable to observe the strong earthquake motion. By the way, weak motions which occur frequently are also valuable to study the properties of earthquake motions. Therefore, the author developed a velocity type strong motion seismograph which can record the earthquake motions from 100 to 0.01 kines with high fidelity over the periods from 0.05 to 50 seconds.

The main part of this seismograph is a coupled pendulum system which had been designed by Matuzawa(1938) and improved by the author here. The whole system of the coupled pendulums is immersed in high viscous silicon oil and the relative displacement of the pendulum is transformed into voltage. The dependence of sensitivity on temperature is compensated by an electric circuit with a compound thermister.

The velocity type strong motion seismograph reported here already recorded several felt earthquakes satisfactorily and we can expect further that it will also record successfully the destructive earthquake motions caused by a large earthquake, if it occurs.

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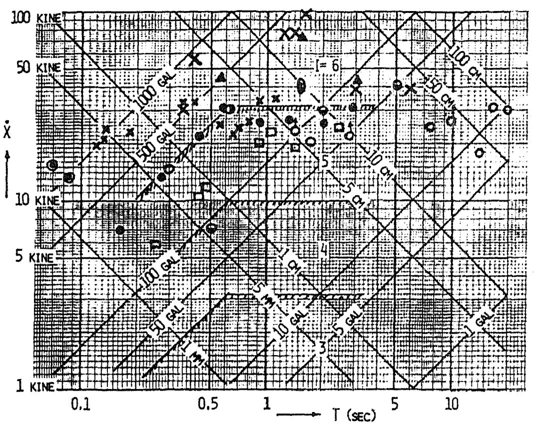

Fig.1 Upper boundaries of the strong earthquake ground motions recorded until now.

		I=6*	M=8.0
◉ Nagoya	(1891,10,28)	I=6*	M=8.0
○ Tokyo	(1923, 9, 1)	6	7.9
Niigata	(1964, 6,16)	5	7.5
◑ Matsushiro	(1965, 5,28)	5	4.9
□ Hachinohe	(1968, 5,16)	5	7.9
● El Centro	(1940, 5,18)	(6)	6.9
▲ Parkfield	(1966, 6,27)	(6)	5.6
X Pacoima Dam	(1971, 2, 9)	6	6.6
x Gazli,USSR	(1976, 5,17)	6	7.3
Bucharest	(1977, 3, 5)	6	7.2

* Japanese seismic intensity scale

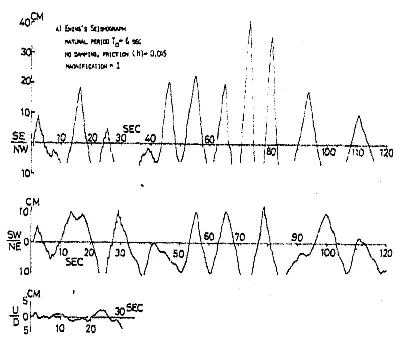

Fig.2 Ewing's seismogram of the Kanto earthquake,1923, at Tokyo University. The original is a disk record. Characteristics of the seismograph; natural period=6.0 sec, no damper, friction(equivalent h =0.045), magnification=1, length of the pendulum=51 cm, weight of the pendulum=25 kg(after Nasu(1971)).

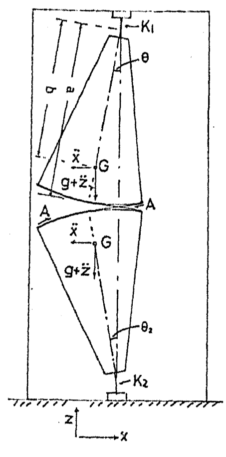

Fig.3 Matuzawa's coupled pendulum system and its principle.

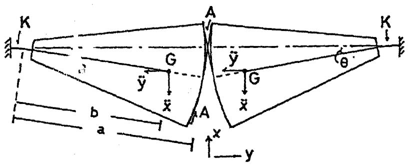

Fig.6 Structure of the vertical component seismometer and its behaviour.

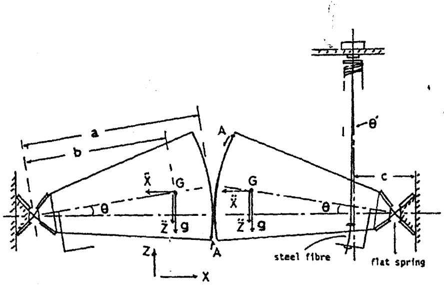

Fig.4 Improved coupled pendulum system of a horizontal seismometer and its behaviour(a ground plane).

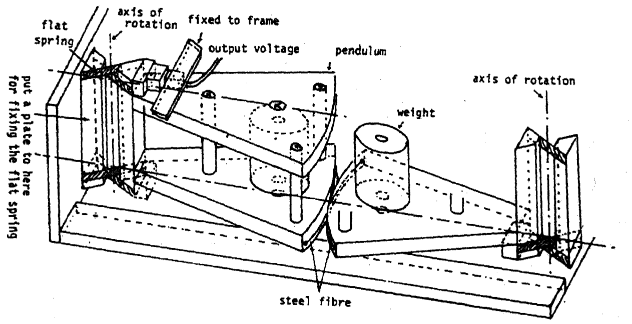

Fig.5 Illustration of the structure of the horizontal component seismometer

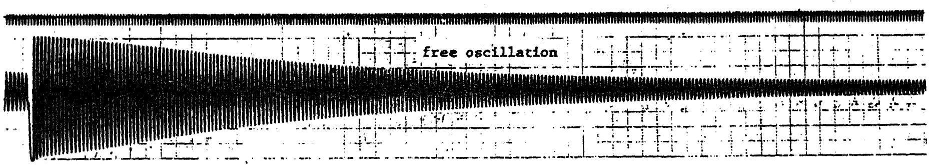

Fig.7 An example of free oscillation of the coupled pendulum system.

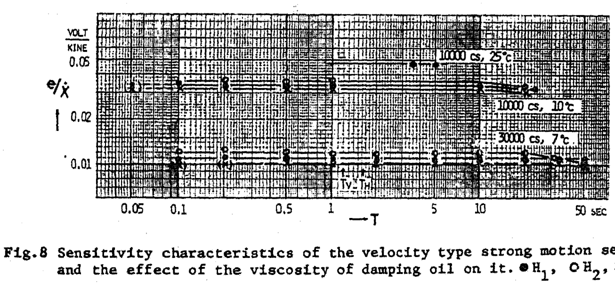

Fig.8 Sensitivity characteristics of the velocity type strong motion seismometer and the effect of the viscosity of damping oil on it. ●H_1, ○H_2, ×V.

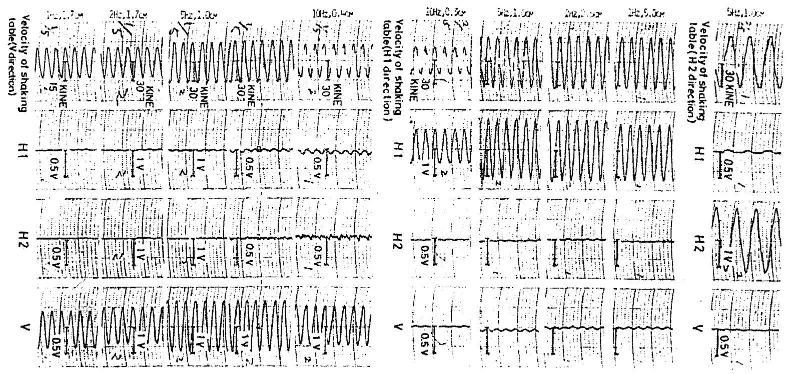

Fig.9 Effects of the non-oscillating direction forces. Simultaneous records of the shaking table and three component seismometers.

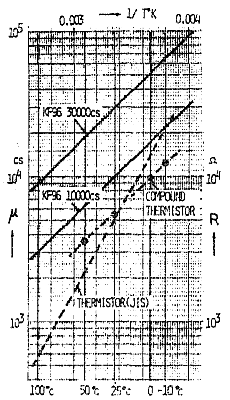

Fig.10 Effects of temperature on the viscosity of silicon oil and on the resistance of some thermister. real line; viscosity of silicon oil. broken line; resistance of thermister. chain line; resistance of compound thermister.

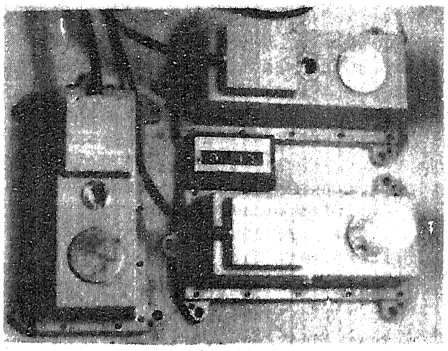

Fig.11 Exterior appearance of a set of three components or the velocity type strong motion seismometer.

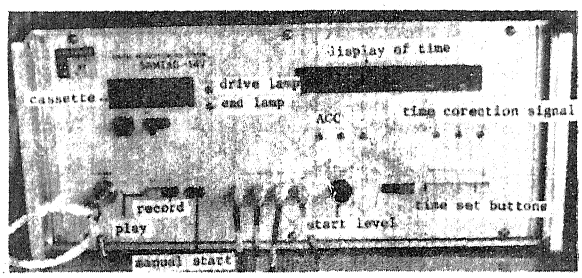

Fig.12 Recording apparatus of the velocity type strong motion seismograph, SAMTAC-14V.

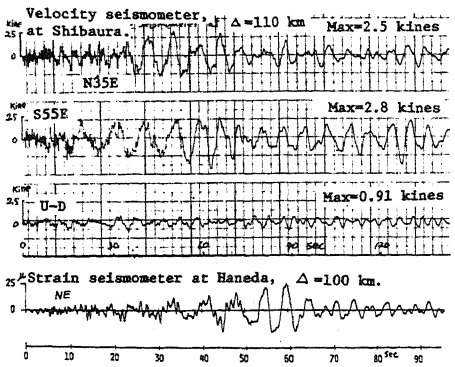

Fig.13 Seismograms of the Near Izu-Oshima earthquake, Jan.14, 1978, M=7.0, h=0,

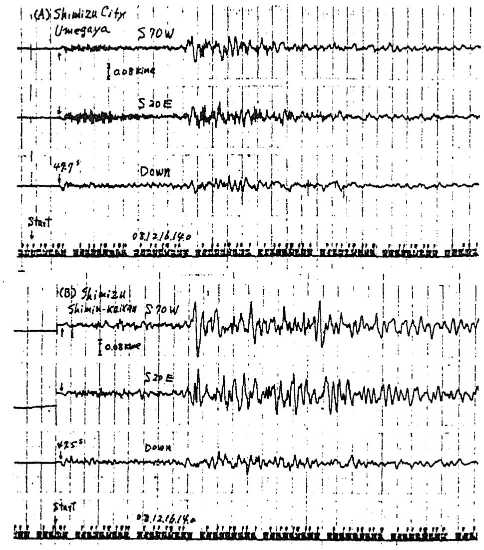

Fig.14 Seismograms of the S.off Chiba Prefecture, Aug,12, 1979, M=5.7, h=50 km. Δ ≒200 km

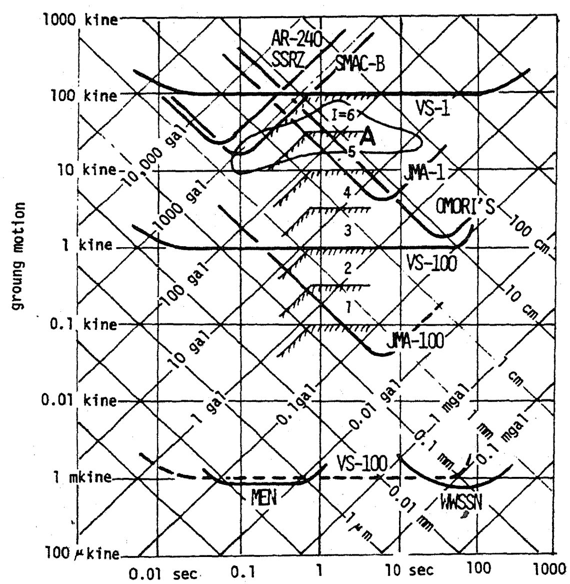

Fig.15 Recording ranges of various seismographs which are widely used nowadays. It is assumed that the values of full-scale of their records are all 30 mm. Thick lines; the earthquake motions corresponding to full-scale of each seismograph. Closed line denoted by A; the earthquake motions shown in Fig.1. Oblique lines; Japanese seismic intensity scale. Broken line; lower limit of ground motions to be recorded by VS-100.