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RELATIVELY LONG-PERIOD GROUND MOTIONS OBTAINED BY MENDING OF SATURATED RECORDS OF A LOW-MAGNIFICATION SEISMOGRAPH

Shigeru Noda[1], Saburo SHIMADA[2] and Takaharu YOSHIDA[3]

[1]Department of Social Systems Engineering, Faculty of Engineering,
Tottori University, Tottori-city, Tottori, Japan
[2]Earthquake Engineering Section, Technical Research Institute,
Maeda Corporation, Nerima-ku, Tokyo, Japan
[3]Sendai Branch, Maeda Corporation, Sendai-city, Miyagi, Japan

SUMMARY

In this study, considering that valuable information concerning the aseismic design of structures is hidden in saturated records, a more reasonable method to mend the saturated ones of a low-magnification seismograph of Japan Meteorological Agency (JMA) is proposed. The results obtained indicate that; (1) The mending method is able to mend a saturated seismogram prepared by response analysis with a low percent error; (2) For the saturated seismogram obtained from a shaking table test, the mended seismogram and velocity response spectra are congruent with those calculated from the motion of the shaking table.

INTRODUCTION

Continuing progress in civil engineering methodology has made possible the design and construction of increasing number of complex large-scale structures with long natural periods of vibration, such as high-rise buildings, long-span suspension bridges, cable-stayed bridges, large storage tanks, etc. However, in spite of the fact that these structures can easily be induced into resonant conditions when subjected to relatively long-period ground motions, no clear-cut method has yet been established for calculating the response spectra of such ground motions. Recently, to investigate engineering characteristics of relatively long-period ground motions, quantitative works have been done by using low-magnification seismograms including the Japan Meteorological Agency's (JMA) records, but these studies hardly included strong ground motions.

On the other hand, the authors (Ref.1) have attempted to mend the interrupted parts of the JMA's low-magnification seismogram recorded at the Niigata Weather Bureau Station during the Nihonkai-chubu earthquake of 1983 by the rough method. It was shown that the velocity response spectrum value with 0.1 % damping for periods of about 10 sec was 200 kine, and that this value roughly matched observed sloshing heights in oil storage tanks in Niigata. Also, Morioka (Ref.2) has mended the off-scaled Ewing strong-motion seismogram recorded at Hongo in Tokyo during the great Kwanto earthquake of 1923, and has shown that the undamped velocity response value for periods of about 13 sec was 300 kine. From these facts, it is found that valuable information concerning the aseismic design of structures with long natural periods of vibration is hidden in such saturated records.

In this paper, a more reasonable method to mend saturated records of the JMA's low-magnification seismograph is proposed.

SEISMOGRAPH CHARACTERISTICS AND DYNAMIC MODEL ON RESPONSE ANALYSIS

The JMA's low-magnification seismograph, which has a magnification factor of one unit, is a kind of mechanical displacement seismometer (Photo 1). On the horizontal component, it has a pendulum weighting 6 kg, a natural period of 5.95 sec, and a damping ratio of 0.55. It is good for recording relatively long-period ground motions because of its relatively long natural period. A pair of stoppers are located on both sides of the pendulum to prevent damage when the seismograph is subjected to strong ground motions. The maximum displacement amplitude to be recorded is usually set at $\pm$ 3 cm by the stopper. A piece of oxhide acting as a shock absorber is located on the weight-striking part of the stoppers.

For the purpose of reproduction of the JMA's saturated seismograms, the dynamic model shown in Fig.1 is adopted, that is, the pendulum is represented by a single-degree-of-freedom system having mass m, spring constant k_1, and damping coefficient c_1, and a pair of stoppers represented by spring k_2 and damper c_2. The equations of motion are given as follows;

$$\left.\begin{array}{ll} m(\ddot{x}+\ddot{y})+c_1\dot{x}+k_1x=0 & ;\ x\leqslant s\ \text{(condition 1)} \\ m(\ddot{x}+\ddot{y})+(c_1+c_2)\dot{x}+k_1x+k_2(x-\frac{x}{|x|}s)=0 & ;\ x>s\ \text{(condition 2)} \end{array}\right\} \qquad (1)$$

where x is relative response displacement of the mass, s is the maximum displacement amplitude to be recorded, and $\ddot{y}$ is the ground acceleration. Numerical integration of these equations is carried out by Nigam-Jenning's method. The values of the time increment for conditions 1 and 2 in Eq.(1) are adopted as 0.1 sec and 0.001 sec, respectively.

MENDING METHOD

Observing the behavior of the mass m before and after a collision against the stopper, it collides with the velocity v_1 and rebounds with v_2 (Fig.2). Assuming that duration time of a collision, ΔTc, is very short in comparison with ground motion periods treated in this study, the ground motion during the collision may be ignored, and it may be assumed that the mass rebounds back from the stopper with velocity $v_2=-ev_1$ simultaneously with the collision (Ref.3); e is the coefficient of restitution. Under these conditions, a mended seismogram, x(t), can be represented by the following equation in terms of the saturated one, x'(t).

$$\begin{aligned} x(t_0+\tau) &= x'(t_0+\tau)+(v_1-v_2)\exp(-h_1\omega\tau)\sin(\omega_d\tau)/\omega_d \\ &= x'(t_0+\tau)+(1+e)v_1\exp(-h_1\omega\tau)\sin(\omega_d\tau)/\omega_d \end{aligned} \qquad (2)$$

where t is the time, t_0 is the time at a collision, $\tau=t-t_0$, $\omega(=\sqrt{k_1/m})$ is the natural circular frequency of the seismograph, h_1 is the damping ratio of the seismograph, and $\omega_d=\omega\sqrt{1-h_1^2}$. The second term in Eq.(2) represents free vibration which depends on the intitial velocity (v_1-v_2).

MENDING ERROR OF THIS METHOD FOR THEORETICAL SEISMOGRAMS

Applying this method to saturated seismograms prepared by numerical analysis, the difference between a mended seismogram and a theoretical one is investigated. In this chapter, the values of k_2 and c_2 are adopted as 100 kg/cm and 0.1427 kg.sec/cm refering to measured values. For the collision and rebound velocities, those obtained by response analysis are used.

Investigation for a-half-cycle sinusoidal ground motions, with periods of 4 to 14 sec and amplitudes of 3 to 30 cm, were carried out. Mending errors for maximum response displacement are summed up in Fig.3. From Fig.3, it is clear that the error is very small, that is, most absolute values are less than 2 % and even the maximum value is about only 5 %. It was certified that the duration time of collision, $\Delta T_c = 0.0248$ sec, which was about half of the fundamental period in condition 2 ($\bar{T} = 2\pi\sqrt{m/(k_1+k_2)} = 0.0492$ sec), was very short in comparison with the ground motion periods of interest.

The result for an earthquake motion is shown in Fig.4; (a) is the nonsaturated seismogram, (b) is the saturated one, (c) is the quantity to be mended, and (d) is the mended one. The period chracteristics of (a) and (b) are practically the same, but the wave-form of (b) differs exceedingly from (a). It is difficult to imagine that (a) is the original form of (b). However, the difference between (a) and (d), which was mended by this method, is invisible to the naked eye.

From the above, it is not much to say that the validity of this mending method was demonstrated on analysis.

MENDING OF PRACTICAL SEISMOGRAMS WITH SATURATIONS

Using the JMA's saturated seismograms obtained from a shaking table test with the differential transformer-type displacement meter, the applicability of this mending method to a practical record was investigated with the following results.

When a practical seismogram is mended, collision and rebound velocities must be evaluated from the record. Some care has been taken to digitize the recorded waves before and after the interrupted parts of the seismogram which should be mended. Fig.5 shows three points (a, b and c) of the digitized data before and after a collision against the stopper. In Fig.5, Δx is the displacement increment during a time increment Δt_1 or Δt_2. Δt_1 is given by $e\Delta t/(1+e)$, and Δt_2 by $\Delta t/(1+e)$. Coefficient of restitution e is assumed as 0.8 refering to measured value. In this paper, collision velocity v_1 is evaluated by $v_1=\Delta x/\Delta t_1$, and rebound velocity by $v_2=-\Delta x/\Delta t_2$.

Fig.6 shows the results for a sinusoidal excitation with a period of 10 sec and a displacement amplitude of 14 cm. The seismogram (a) has two saturated parts at the positive side and one at the negative side for each cycle. Observing the mended seismogram (b), it is found that peak levels are different, in spite of steadily sinusoidal excitation. Observing the saturated seismogram (a), it is found that there are many parts where the wave-form is distored. Consequently, the seismogram (c) including the correction for instrumental characteristics, also has different peak levels. Comparing with the amplitude of the sinusoidal excitation, those are generally small, and maximum value of the mending error for displacement amplitude is about 16 %.

Although the duration time of a collision ΔT_c (Fig.2) was very short, it was found that the ground motion during the collision should be not ignored from a shaking table test. In order to improve the accuracy of mended seismogram, correction coefficient β which should be multiplied by the initial velocity (v_1-v_2) was calculated, so that the amplitude of mended and instrumentally corrected seismogram is equal to record amplitude obtained by strong motion seismometer of displacement-type. β is plotted against v_1 in Fig.7. β increases monotonically and is described by the straight line, $\beta=0.14v_1+1.27$ (v_1; cm/sec). Under this condition, a mended seismogram can be represented by linear combination of the saturated one and free vibration which depends on the initial velocity $(1+e)\beta v_1$.

Fig.8 shows the result of mending for an earthquake excitation; (a) is the JMA's seismogram with 18 saturation parts, (b) is the mended one, (c) is instrumentally corrected seismogram, and (d) is the motion of shaking table recorded by displacement meter. Observing the mended and instrumentally corrected seismogram (c) over comparing with (d), it is found that (c) and (d) match very well for the most part.

Solid line in Fig.9 shows velocity response spectrum with 2 % damping calculated from the motion of shaking table; and that from the mended seismogram (c) in Fig.8(c), but that including the correction for instrumental characteristics, is represented by a broken line. Although both spectra for periods around 5 sec differ somehow, in generall, they are congruent for the period range from 4 to 15 sec. Besides, comparing with the spectrum from the nonmended seismogram with instrumental correction, represented by dotted line in Fig.9, it is clear that the spectrum can be improved by using this mending method.

JMA's records at Niigata with saturations obtained during the Nihonkai-chubu earthquake of 1983 were mended by the proposed method. The tapered band pass filter (2 to 20 sec) was used in the calculations. Result of analysis is shown in Fig.10; (a) is saturated seismograms, and (b) is mended and instrumentally corrected seismograms. In order to examine the accuracy of seismograms mended by this method, two-dimensional velocity response spectra S_v with 0.1 % damping are compared with ones (symbol o) calculated backward from the observed sloshing heights in large tanks (Ref.4) as shown in Fig.11; solid line indicate the value by this method, and broken line by the rough method (Ref.1). The correspondence of the S_v by this method and S_v deduced from the recorded sloshing heights is fairly, improved in comparison with S_v by the rough method. Consequently, mended displacement seismograms are found to give much higher response spectra than design values for long-period (5 to 15 sec) structures(Ref.1).

CONCLUSIONS

Major results of this study may be summarized as follows.

1) The mending method proposed in this paper is able to mend a saturated seismogram prepared by response analysis with a low percent error.
2) For the saturated seismogram obtained from a shaking table test, the mended seismogram and the velocity response spectrum with 2 % damping is generally congruent with those calculated from the motion of the shaking table.
3) It must be noted that accuracy of this mending method is directly influenced by digitization error for the original record.

ACKNOWLEDGEMENTS

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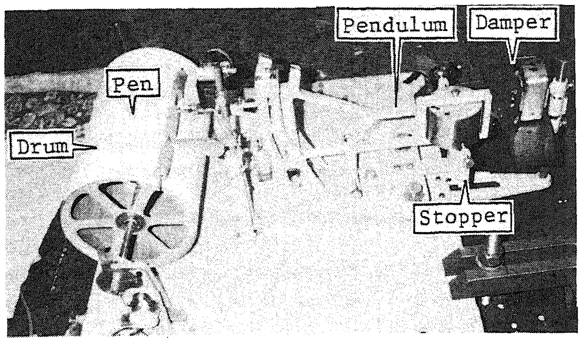


Photo 1 JMA's low-magnification seismograph

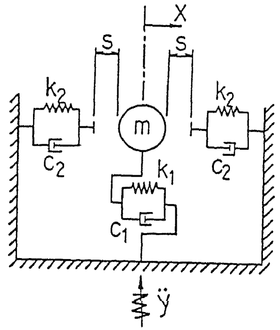


Fig.1 Dynamic model of the JMA's seismograph

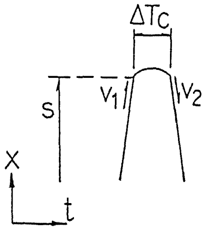


Fig.2 General mass behavior at a collision against the stopper

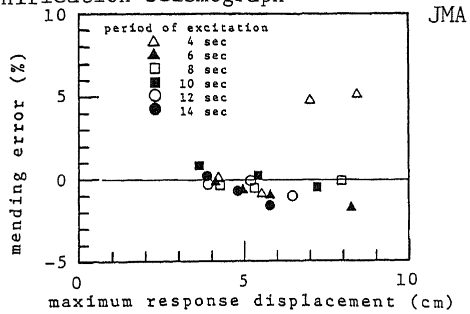


Fig.3 Mending errors for calculated response of the dynamic model of the JMA's seismograph subjected to a-half-cycle sinusoidal excitations

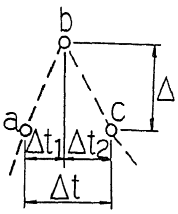
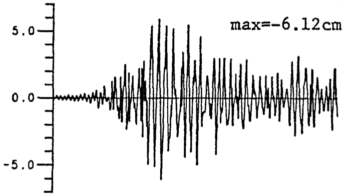
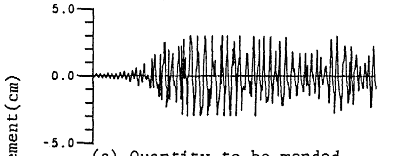


Fig.5 Digitization of the saturated parts of wave

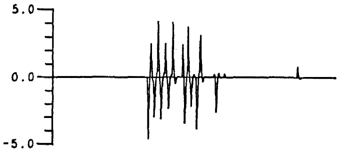
(a) Response without saturations



(b) Response with saturations



(c) Quantity to be mended



(d) Mended response

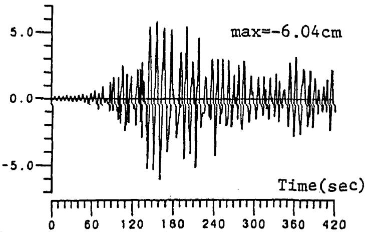
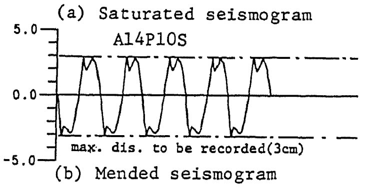
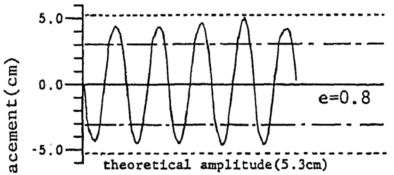


Fig.4 Mending of calculated response of the JMA's seismograph subjected to an earthquake excitation

(a) Saturated seismogram



(b) Mended seismogram



(c) Instrumentally corrected seismogram

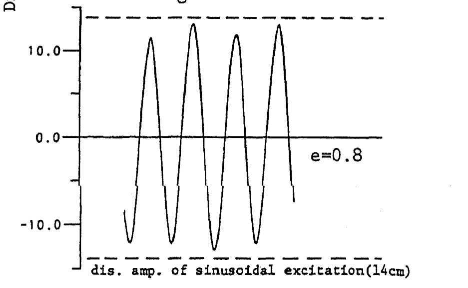


Fig.6 Mending of the JMA's seismogram subjected to a sinusoidal excitation with a period of 10 sec and a displacement amplitude of 14 cm

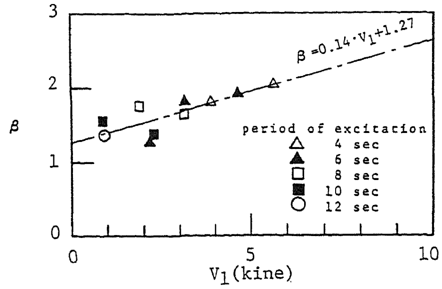


Fig.7 Relation between the correction coeffcient β and the collision velocity v_1

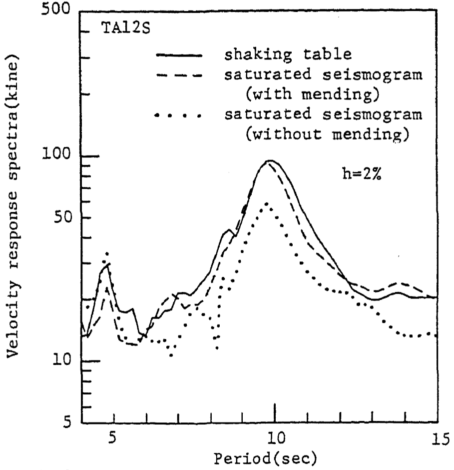
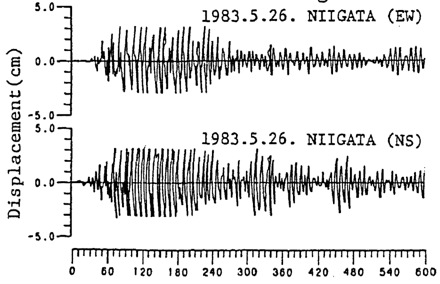
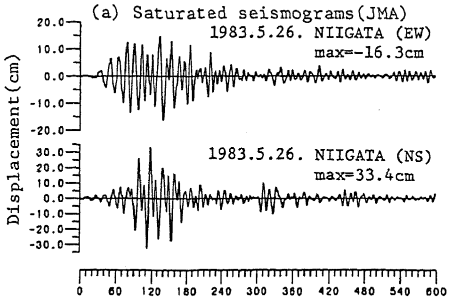


Fig.9 Comparison of velocity response spectra (h=2 %) calculated from the motion of the shaking table and the JMA's saturated seismogram



(a) Saturated seismograms(JMA)



(b) Instrumentally corrected seismograms

Fig.10 Mending of JMA's seismograms at Niigata recorded during the Nihonkai-chubu earthquake of 1983

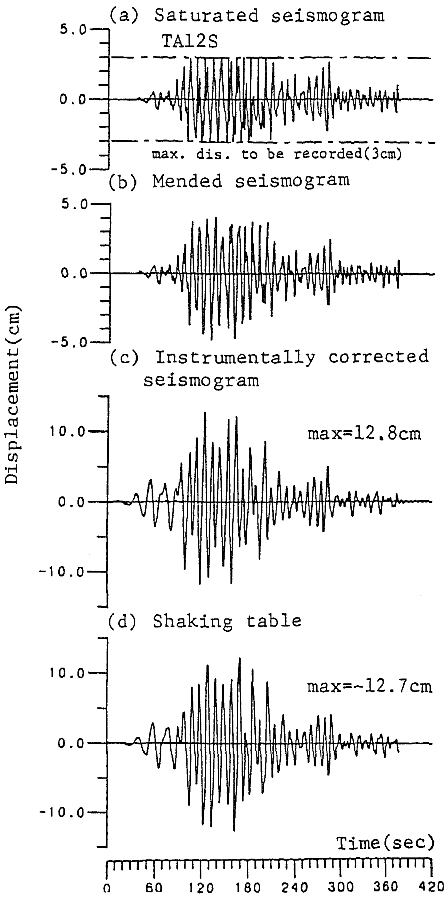


Fig.8 Mending of the JMA's seismogram subjected to an earthquake excitation

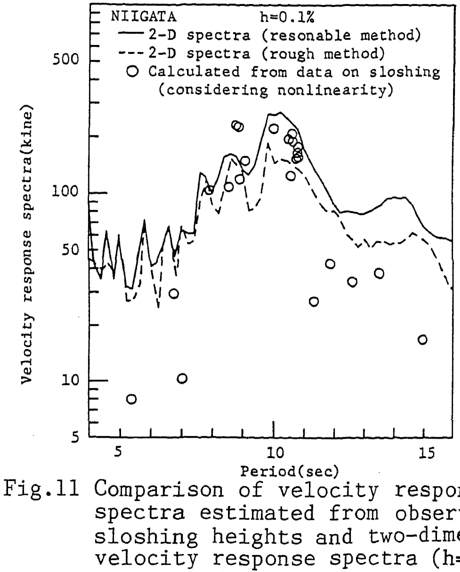


Fig.11 Comparison of velocity response spectra estimated from observed sloshing heights and two-dimensional velocity response spectra (h=0.1 %) obtained from seismograms shown in Fig.10