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A research of base isolation system by the enforcement construction

M.Takayama & H.Tada
Fukuoka University, Japan

A.Wada
Tokyo Institute of Technology, Japan

ABSTRACT: A base isolated building emphasizing seismometry was constructed at CHIBA Prefecture YACHIYO City in order to confirm the actual behavior of a base isolation system during an earthquake. The building is a 2-story reinforced concrete structure and has six rubber bearings between the base mat and first floor. In this paper, vibration test, seismometry and dynamic response analysis on this building are described.

1. Introduction

Since 1979 we have been repeatedly performing model experiments using a vibrating table and simulations by numerical analysis as a part of our research into base isolation systems. This research was aimed at the development of a system which effectively resists the long period seismic waves peculiar to our country. Simultaneously, the development of an actual size base isolator for use in a building was begun, with a satisfactory product being finally obtained in 1981.

In experiments and research into the dynamic behavior of a building structure, verification using scale models was considered to be inadequate, and thus became absolutely necessary to perform full-scale experiments. In line with this thinking, we obtained special permission to construct an actual size housing structure where experiments to could be performed to obtain the necessary engineering data. Yachiyo City in Chiba Prefecture was selected as the location for this structure because of the relatively frequent occurrence of earthquakes, and with the most important aim of confirming the validity of this system through observation during an actual earthquake.

The main items of examination at this building were as follows:

(1) Vibration characteristics of the building (microtremors, forced vibration, free vibration)

(2) Abstraction of problems through specific construction and acquisition of construction know-how.

(3) Relatively long-term seismic observation using a strong motion seismograph.

(4) Habitability test (effect due to strong wind, etc., necessity of stabilizing devices and quantification thereof)

Items (1) and (2) above were performed between November 1982 and the end of January 1983, and the habitability test (4) between August 1983 and March 1985. The observation of item (3) above is still in progress. This report describes the results of vibration experiments of item (1) above and earthquake motion wave forms observed up to the present, as well as performing numerical analysis from the following viewpoints and the results thereof:

(a) How closely the numerical calculation represents the actual phenomena, and how strict the modeling should be to obtain satisfactory analysis results?

(b) Define a simple model useful for design.

(c) Confirm the effectiveness of the base isolation system using dynamic analysis.

(d) Examine the condition of the superstructure and interior.

2. Building outline

The building is fully equipped with the facilities found in a conventional housing development with specifications to allow actual habitation. In addition it was designed to allow an isolator to be inserted between the foundation and the superstructure, making the natural period of the building longer. A vibration damper was provided to reduce the seismic force acting on the building during an earthquake, thus improving the safety of the superstructure and aimed at preventing the secondary disasters that tend to occur during an earthquake. The building is a 2 story house of reinforced concrete (RC) construction, with its rigid structure of columns, girders, and the heavy walls. Construction type and methodology of the superstructure is sufficiently aseismatic in itself even if the base isolation system does not work. Fig. 1 below shows the outline of the building. The isolator used was 30 cm in diameter, 8.2 cm in height and was made of stainless steel and rubber vulcanized under high temperature and pressure. Four types of vibration dampers were tested for the purpose of examining the specific compatibility of their performance as follows:

(1) Elasto-plastic type: makes use of a cantilevered steel rod fixed to the superstructure

(2) Sand type: makes use of the friction resistance between a steel rod fixed to the superstructure and sand

(3) Friction type: makes use of the friction force that acts between a steel rod and the pressure bearing steel plate

(4) Pre-cast concrete (PC) plate type: makes use of the friction force that acts between the dry area shielding the PC plate and the top of the side wall

3. Vibration experiments

3.1 Observation of microtremors

A high-sensitivity microvibration meter was used for measuring the microtremors and the measured wave form was recorded on a data recorder through the integrator. From the measured wave form, the apparent primary natural period was 1.37 sec and the natural period of the building obtained from the spectro-ratio (roof top/ground surface) was 1.33 sec. From the resulting measurements of rocking vibrations, the apparent natural period was 0.13 sec and the period obtained from the spectro-ratio was 0.12 sec, suggesting that the natural ground properties have relatively little effect on the period of the building.

3.2 Forced vibration experiment

Two sets of vibration generators (BCS-B-75 type, maximum vibration generation power 10 tonf) were installed on the rooftop and vibrations were generated by simultaneously synchronizing them. The vibration frequency was in the range of 0.3 - 2.0 Hz. Four cases of forced vibration were applied in total, the results of which are shown in Table-1. When the dampers were installed, the forced vibration was applied to the PC plate damper and the sway ratio and rocking ratio were obtained from the maximum acceleration ratio of the rooftop (RF) and first floor (1F). The damping

Fig.1-a Elevation

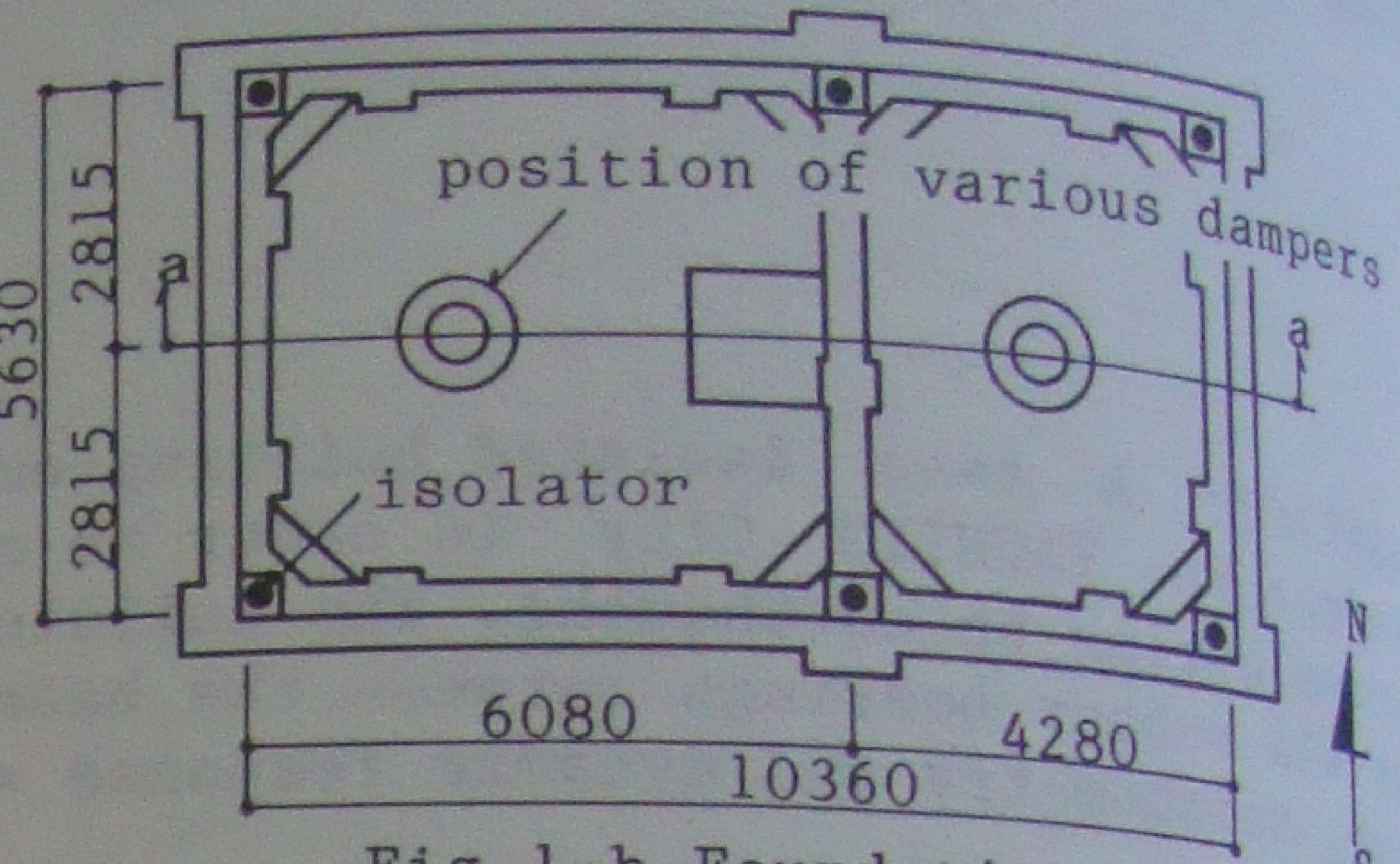


Fig.1-b Foundation plan

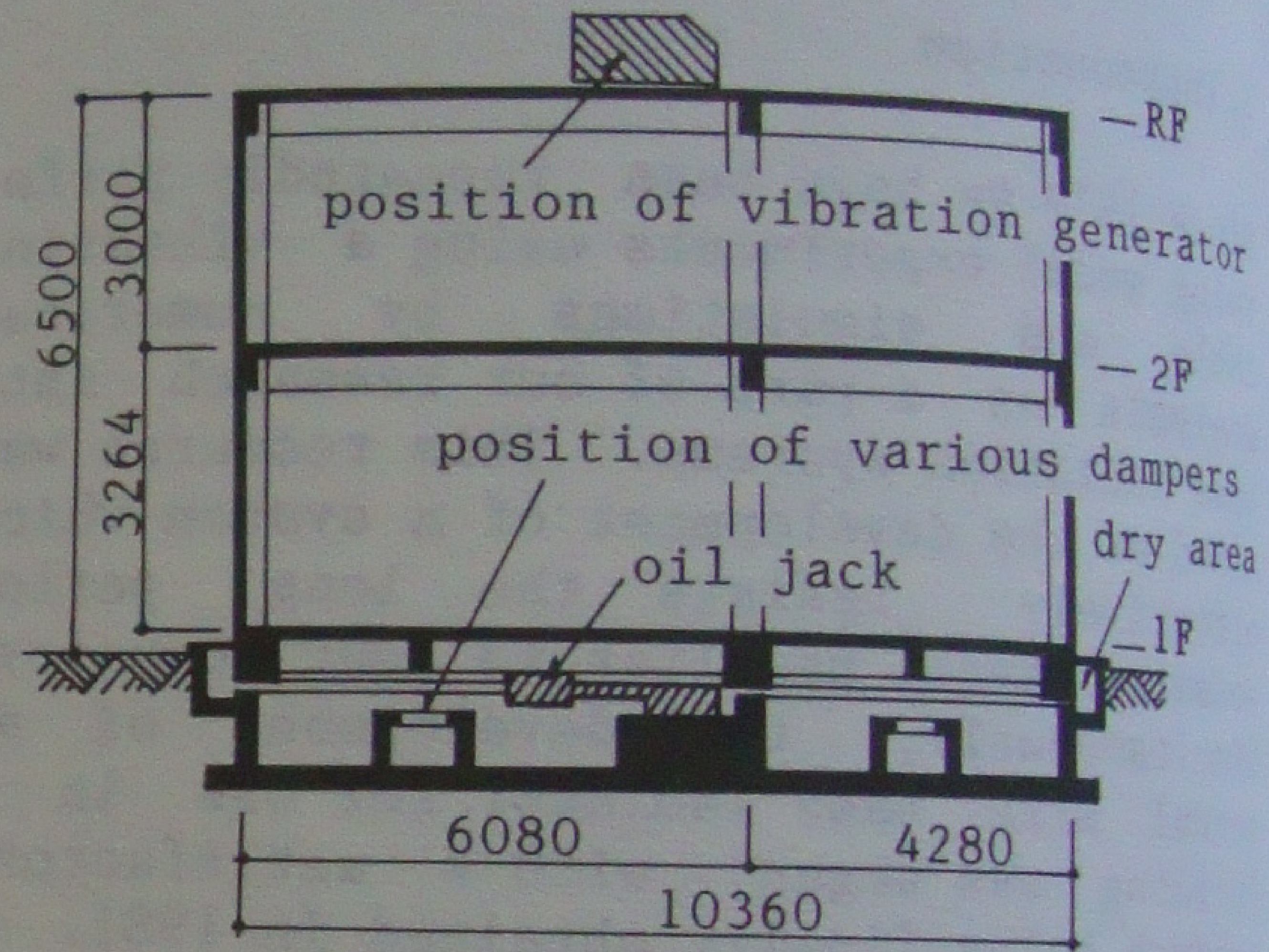


Fig.1-c Cross section (a-a)

Table-1. Results of the forced vibration

case	frequency		damping factor	sway ratio	rocking ratio
	1st	2nd			
N-S	0.675Hz	0.905Hz	0.026	96%	≒0%
E-W	0.7Hz	—	0.033	98%	6%
torsion	0.686Hz	0.885Hz	—	—	—
E-W*	1.55Hz	—	—	—	—

* with damper

factor was calculated from the resonance curve using the $1/\sqrt{2}$ method. The resonance points that can be obtained from the torsional oscillation and the parallel oscillation are significantly close to each other. The vibration mode shape at the resonance point of the parallel moving contained considerable torsion, making it impossible to completely separate the parallel moving mode from the torsional mode. Therefore, from the viewpoint of considering the vibration properties of this building, it was important to consider the torsion. The sway ratio was 96% in the short axis direction and 98% in the long axis direction, with the rocking being almost negligible for both directions. The resonance point, when the dampers were installed, was 1.55 Hz. This indicates that the dampers created not only a damping effect but also a complementary increase in rigidity, resulting in the amplitude of the vibration characteristics being changed by several millimeters.

3.3 Free vibration experiment

An oil jack was used to generate a forced displacement and free vibration was induced by securing a notched steel rod designed to break at a predetermined displacement. Experiments were performed on a total of five cases without dampers and on four with different types of dampers. Fig. 2 shows the relationship between the logarithmic damping factor, the period (obtained from the wave form of the observed relative horizontal displacement of the foundation and the 1F floor), and the displacement amplitude. The tendency of change of the damping factor can be classified into the friction type and the PC plate type (where it increases as the displacement amplitude becomes smaller), the elasto-plastic type (where it inversely decreases), and the sand and no damper type (where the damping factor stays almost constant irrespective of the displacement). The period became shorter as the displacement decreased, irrespective of the type of damper used. Although it is not shown in this report, when the hysteresis curves of various dampers were compared, the size of the area surrounded by the curve was largest in the cases of the friction type and the PC plate type.

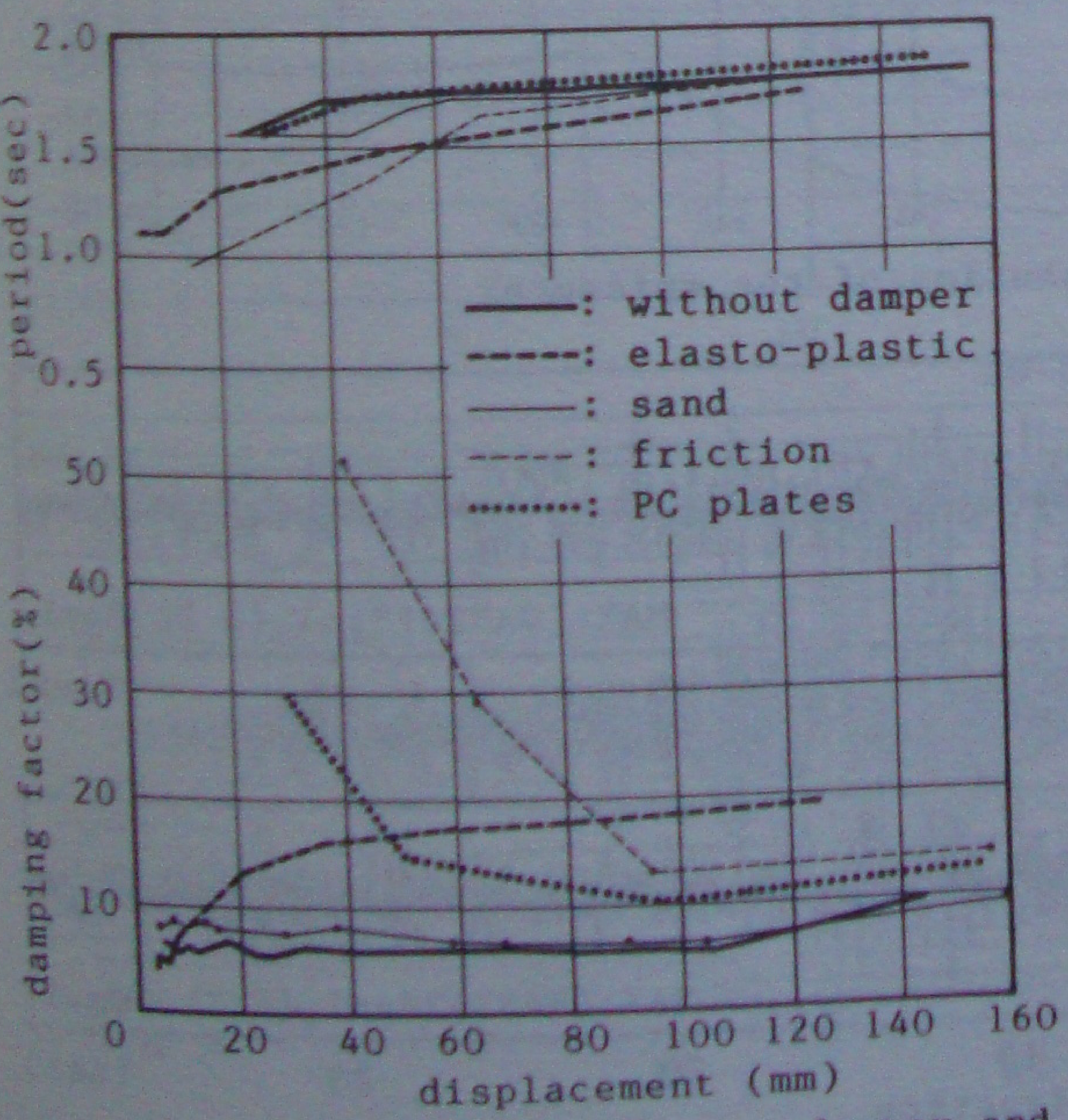


Fig.2 Dependence of damping factor and period on displacement

By combining the results of the various vibration experiments performed upon completion of the structural work of the building (January 1983), the following information was obtained:

(1) Regardless of whether or not a damper was used, as the displacement amplitude decreased the natural period became shorter. Where an isolator only was used, the period changed from the large deformation amplitude to the microtremor amplitude (i.e. 1.8 sec to 1.37 sec).

(2) Regardless of whether or not a damper was used, no abnormalities were seen in the loading capacity or the restitutive force of the isolator against the maximum displacement of approximately 16 cm.

(3) In the experiment using a damper, the damping factor was 20 - 5% for elasto-plastic damper, 7 - 8% for the sand damper, 10 - 50% for the friction damper and 10 - 30% for the PC plate damper, as compared with 5.5% in the case of the isolator only. These results the respective effectiveness of each type of damper. In all cases, the effectiveness was clearly shown in view of a decrease in the displacement amplitude and shortening of the vibration convergence time.

4. Observation of seismic motion

4.1 Outline of observation

Earthquake observation using strong motion seismographs was performed in April 1983 by installing 3 sets of acceleration-type strong motion seismographs (Lion, SM-10A type: 1 sets; SM-10 type: 2 sets) on the foundation, 1F floor, and rooftop (RF), respectively. These were simultaneously worked on March 1984 by installing an additional 4 sets of velocity-type strong motion seismographs (Muramatsu Type, Tokyo Sokushin VS-335 type: 3 sets, VS-235 type: 1 sets). These observations were aimed at verifying the interchangeability of the measured values of acceleration and velocity as a means of contributing to the understanding of the displacement behaviors. The velocity-type seismographs was equipped with a delay device (5 sec). After the vibration experiments had been completed, a PC plate damper was used but subsequently replaced with a plywood plate. This measure was taken to eliminate the friction force acting between the PC plate and the top of the side wall in the dry area, so as to clarify the behavior of the base isolation system during a small scale earthquake between June 1983 and November 1984.

4.2 Observed earthquake wave

To date, data for 17 medium and small scale earthquakes have been collected. Distribution of the epicenters shown in Fig. 3 was prepared based on "Outlook of Earthquakes and Volcanoes" published by the Earthquake and Tsunami Monitoring Section of the Japan Meteorological Agency. From Fig. 3 it can be seen that in Chiba city, near the site, the seismic scale of the earthquakes that occurred was 4 on three occasions, 3 on five occasions

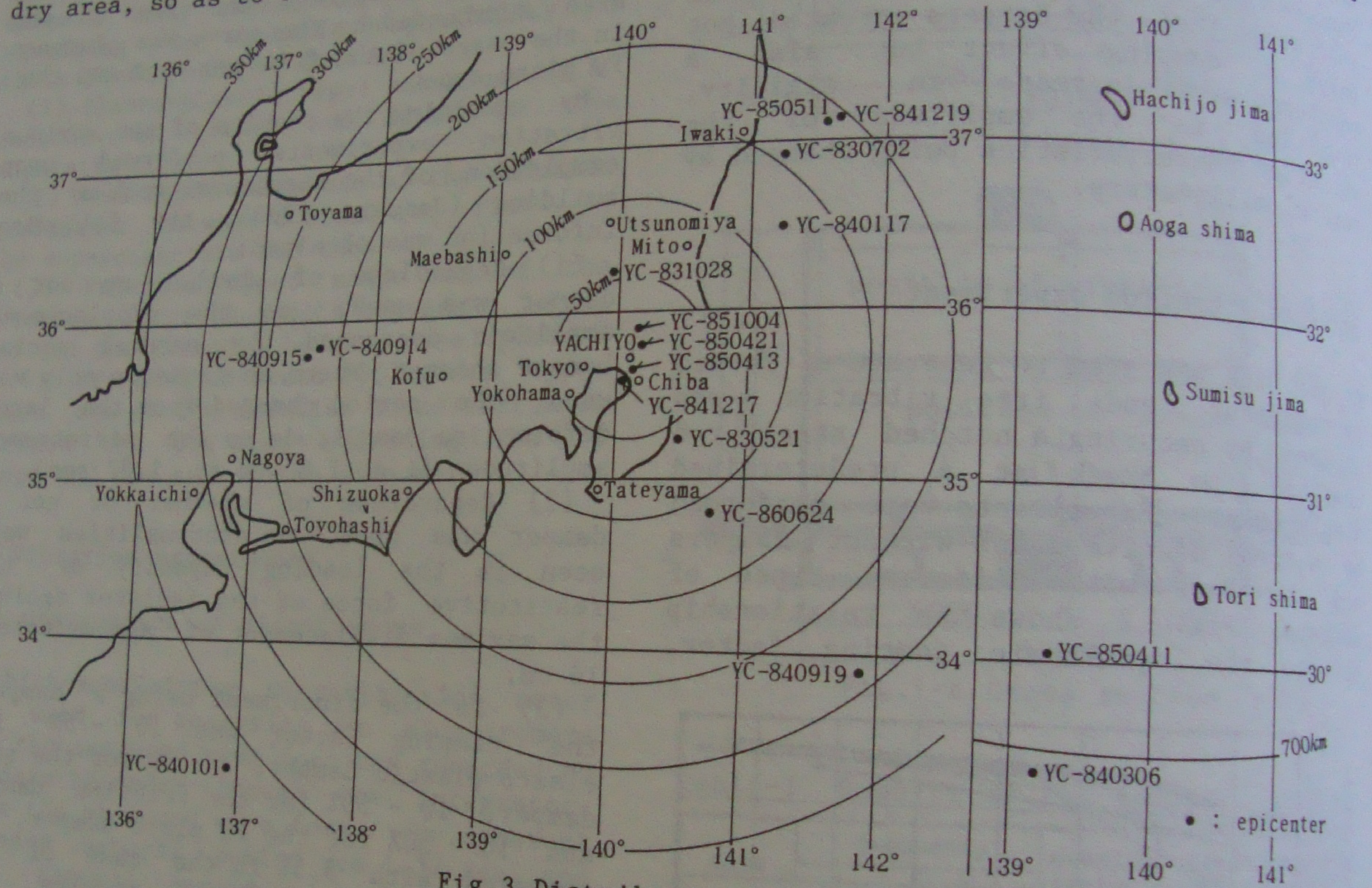
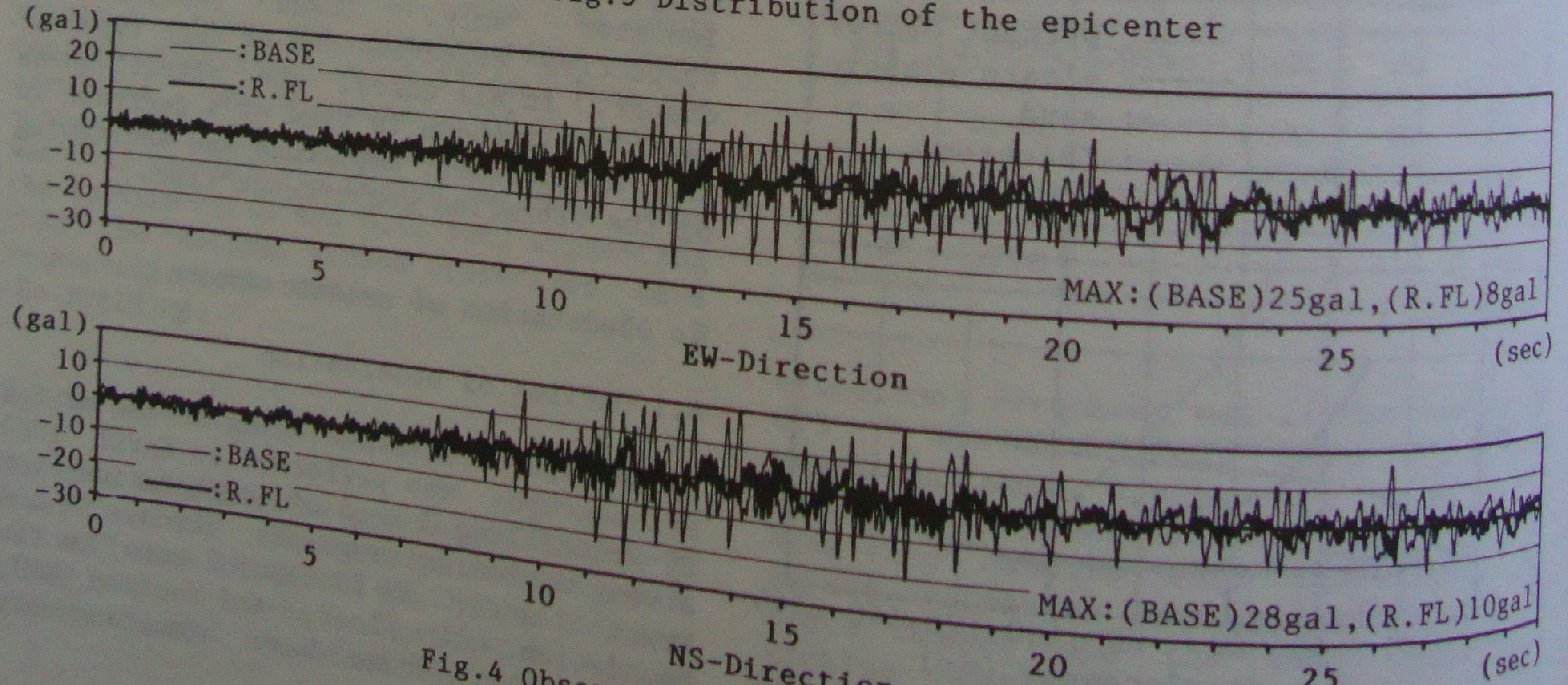


Fig.3 Distribution of the epicenter



EW-Direction

NS-Direction

Fig.4 Observed earthquake records (YC-840101)

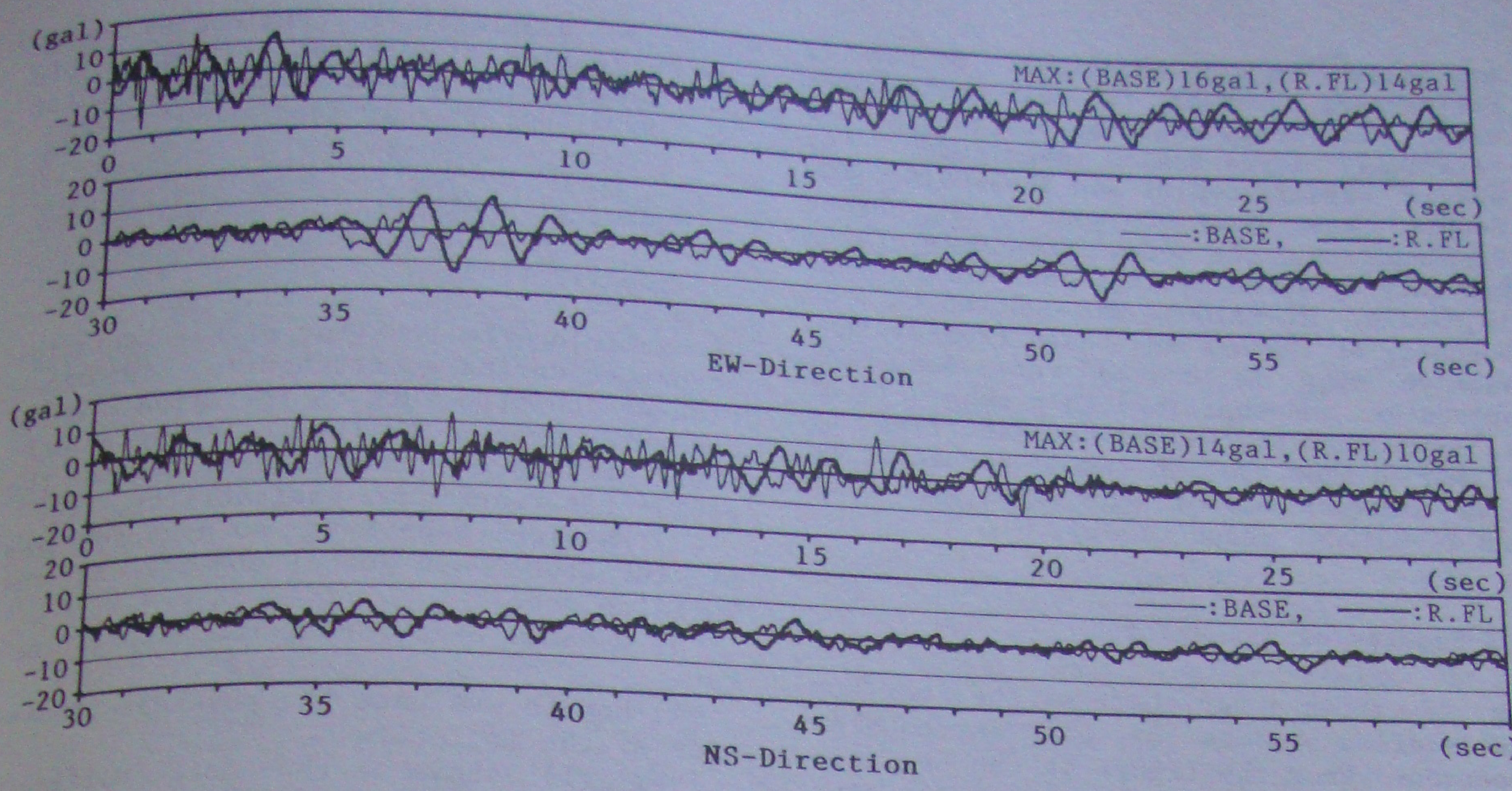


Fig.5 Observed earthquake records (YC-840306)

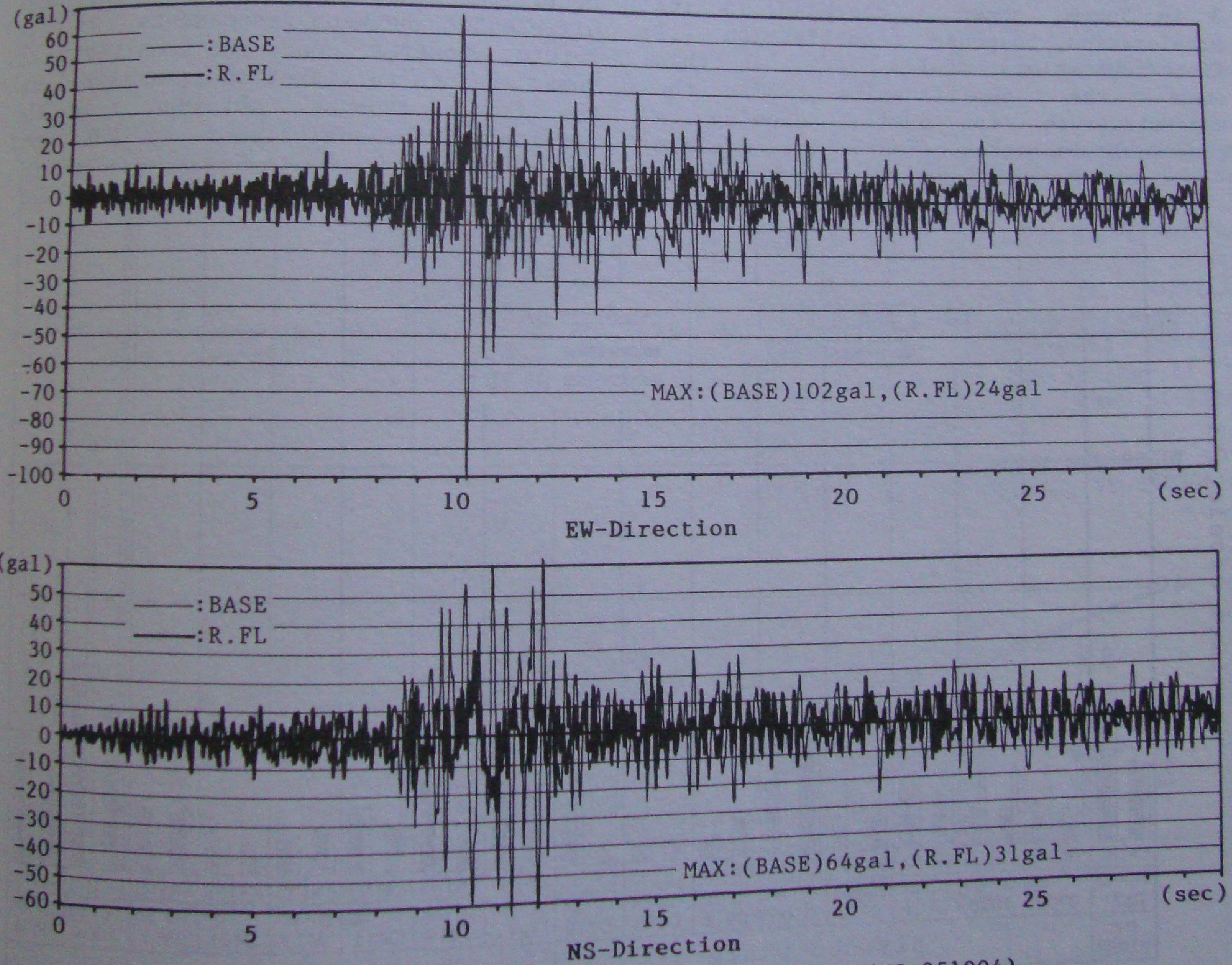


Fig.6 Observed earthquake records (YC-851004)

and below 2 on nine occasions. Of the 17 earthquakes observed, the only earthquakes with deep-focus marine epicenters and relatively large scales (magnitude 7 or above) were YC-840101 and YC-840914. YC-840914 was centred west of Nagano Prefecture but the seismic scale in Chiba was only 2, which was not considered large in scale. YC-851004 was centred on the boundary of Ibaragi and Chiba Prefectures. Yachiyo City is located very near the epicenter and therefore this record is of a "Just-under-seated" earthquake. Figs. 4, 5 and 6 show the observed acceleration wave form records of YC-840101, YC-840306 and YC-851004, respectively.

4.3 Results of observation

Fig. 7 shows a bar chart of the maximum acceleration values of all earthquakes observed. From the figure it can be seen that for the seismic motion records with maximum accelerations of 20 gal or larger at the foundation, the response value of the superstructure decreased. From the records, YC-851004 with a seismic scale of 5 in Tokyo, shows a decrease in its acceleration response magnification (1F floor/foundation) of 1/3 - 1/5. In this case the amplification of the superstructure is small, showing a remarkable isolation effect. The maximum relative displacement obtained by using the Fourier integral from this acceleration wave form (band-pass filter Ts = 0.02 sec, Tl = 10 sec) was 12.5 mm.

5. Numerical analysis

5.1 Idealization

In examining the behavior of the isolation structure during an earthquake, idealization of the structure is performed, while observing closely to the following points:

(1) Effects on human beings, such as the resident's reactions, habitability, etc.

(2) Physical behavior, such as toppling of furniture and other objects in the building, etc.

(3) Dynamic behavior of the superstructure

(4) How to evaluate the physical properties of the isolator.

Item (1) above is the most difficult subject to evaluate quantitatively since there are various factors involved. These factors are the manner in which the vibration is propagated, the frequency component, the magnitude, and the individual differences between respondents. In the future, however, once the sensitivity of human beings to vibration is analyzed and the floor response (obtained from the results of the analysis of an idealized

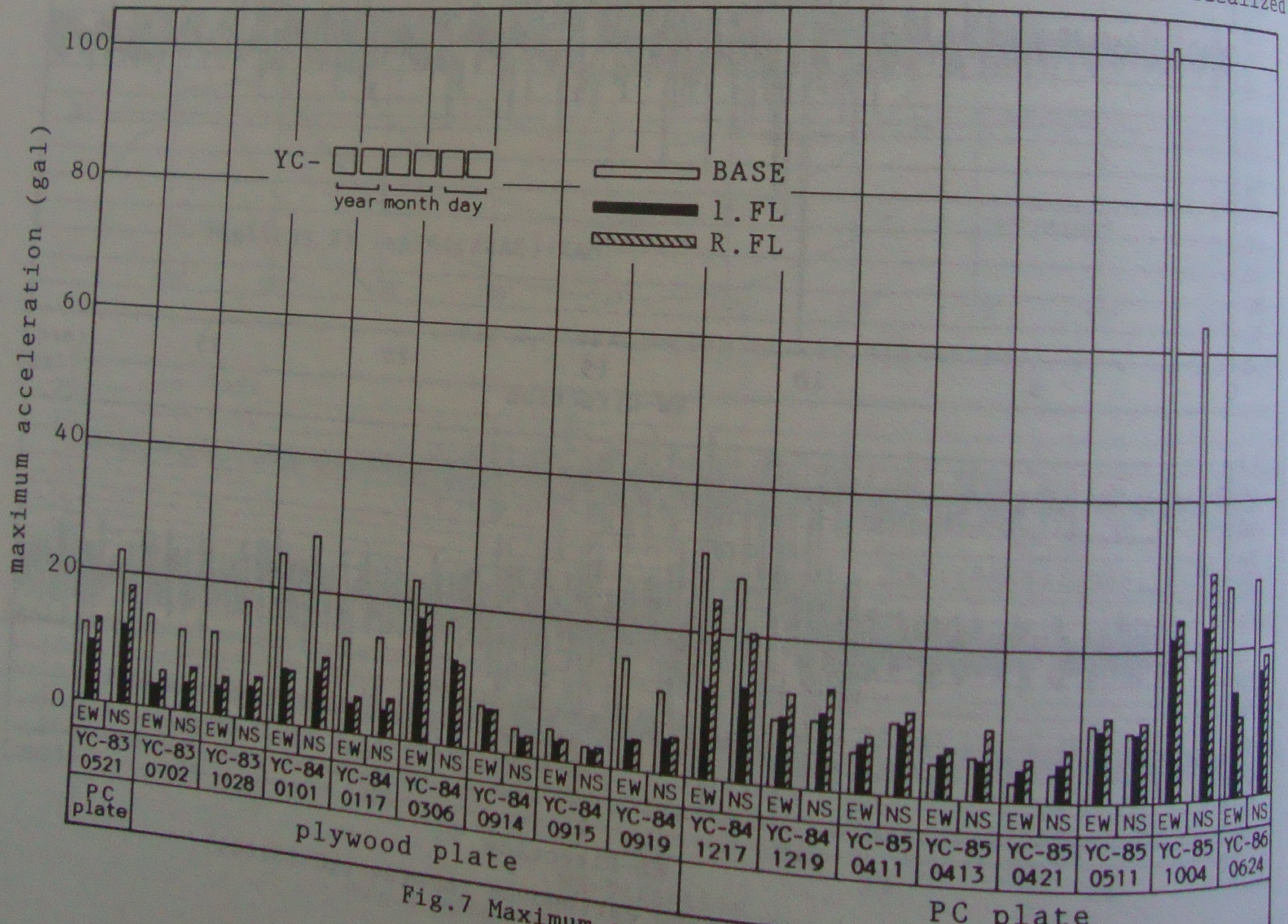


Fig.7 Maximum acceleration

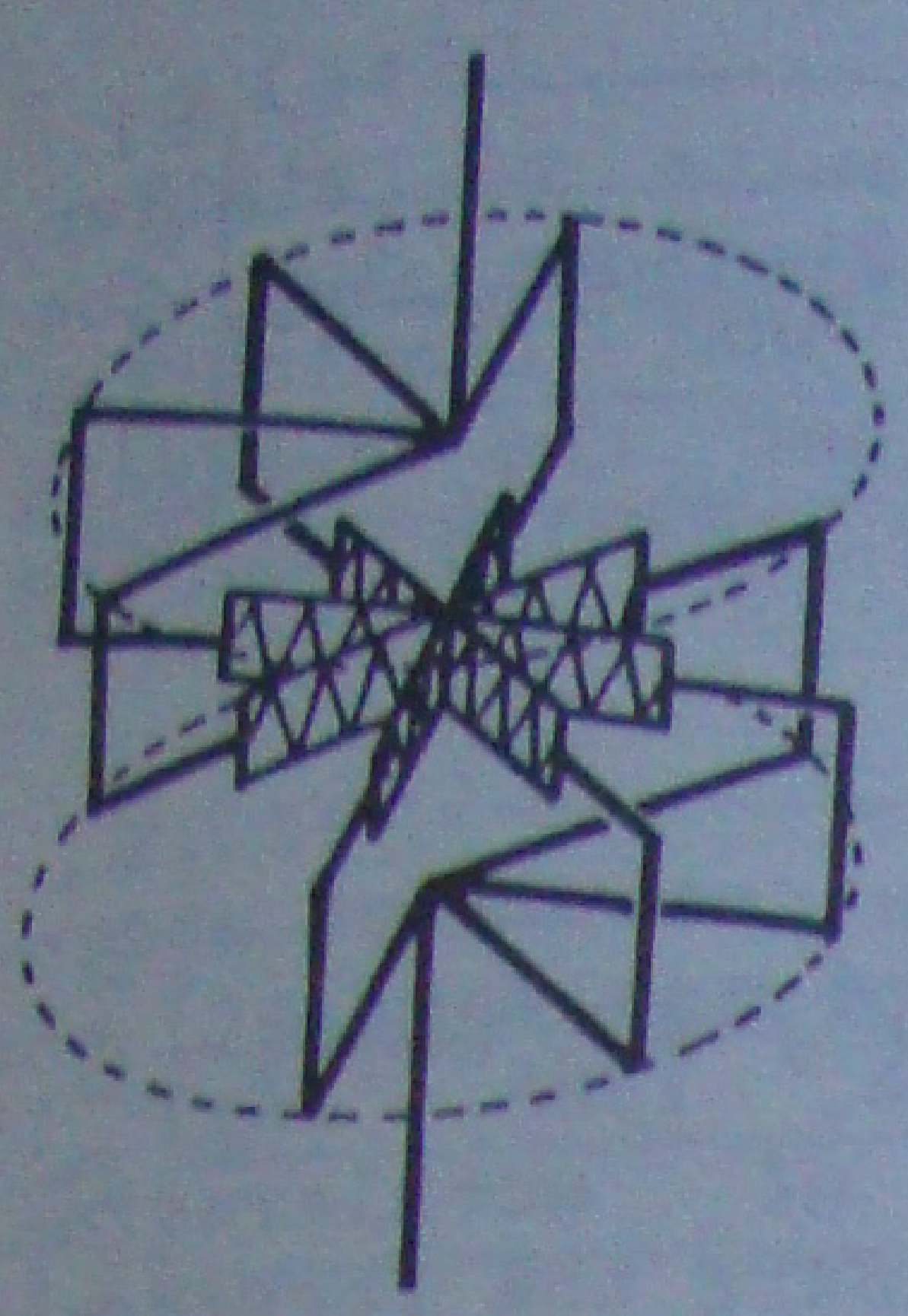
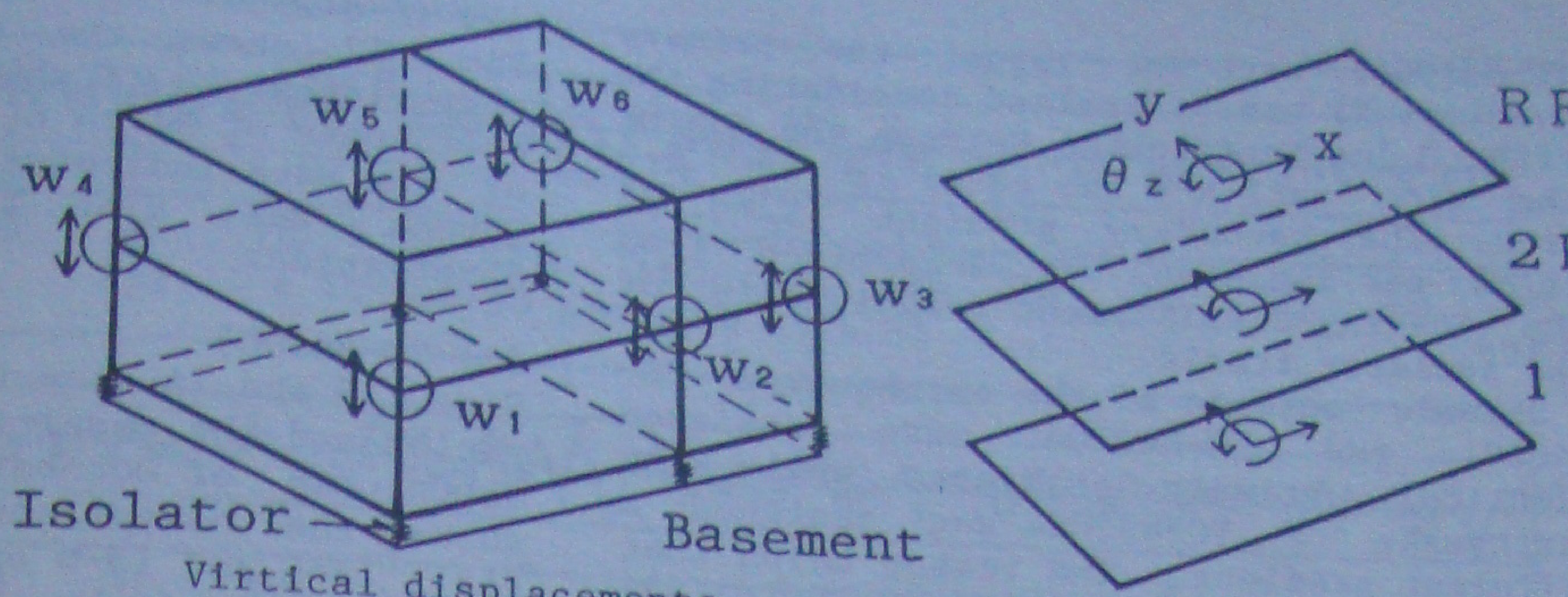


Fig.8 MSS spring



Virtical displacements

Horizontal displacements

Fig.9 Structural idealization and displacement components

model as close to actual size as possible) is input into the vibration table, qualitative evaluation will be made clearer.

Item (2) is being researched at present but it is necessary for the floor response to be obtained as accurately as possible through dynamic analysis. In particular, places where priceless articles are handled or vibration sensitive objects are stored, (such as fine art galleries, IC plants, etc.), models that take into account the higher order modes as described in this paper seem to be effective.

In view of the dynamic behavior of the superstructure in item (3), idealization of the model as close to the actual structure as possible is considered necessary. However, from the viewpoint of the dynamic analysis which is used as a reference during the design phase, a simplified model is more effective. If the correlation between the model described here and results of the simplified model can be understood, a simple model could be used in the design, allowing on easier understanding of the overall properties. For the basic data, it is important to idealize the model as close to the actual structure as possible.

The idealization of the isolator model in item (4) above uses 8 elasto-plastic springs arranged in the horizontal direction at equal angles, as shown in Fig. 8.

This model attempts to represent the loading-displacement relationship of the isolator as accurately as possible, taking into account the effects of the two directional shearing force.

Summarizing the above, the following idealization (Fig. 9) is provided in this report to create phenomena as close to the actual condition as possible.

(1) The superstructure is represented by an elastic three-dimensional rigid frame structure.

(2) The floor slab is represented by a rigid floor in the horizontal plane. Three components of displacement x, y and θz are considered for each floor.

(3) The idealization takes into account the higher order modes caused by the vertical vibration, mass points at each column position that demonstrate the force of inertia against vertical vibration.

(4) The isolator, as mentioned above, used MSS springs. The mutual effect of the two-directional external force is considered in the horizontal plane and the elastic force in the vertical direction.

5.2 Establishment of each parameter and the characteristics of the building

The superstructure is represented by an elastic body which consider the bending deformation of the frame work, deformation in the axial direction, shearing deformation and rigid zone in beam column joints, and the damping factor of 0.5%. Properties of the isolator were established with reference to the experiments performed previously and each MSS spring of the isolator was designed to have bi-linear properties (Fig. 10).

Since the seismic input motion of three earthquake waves (YC-840101, YC-840306 and

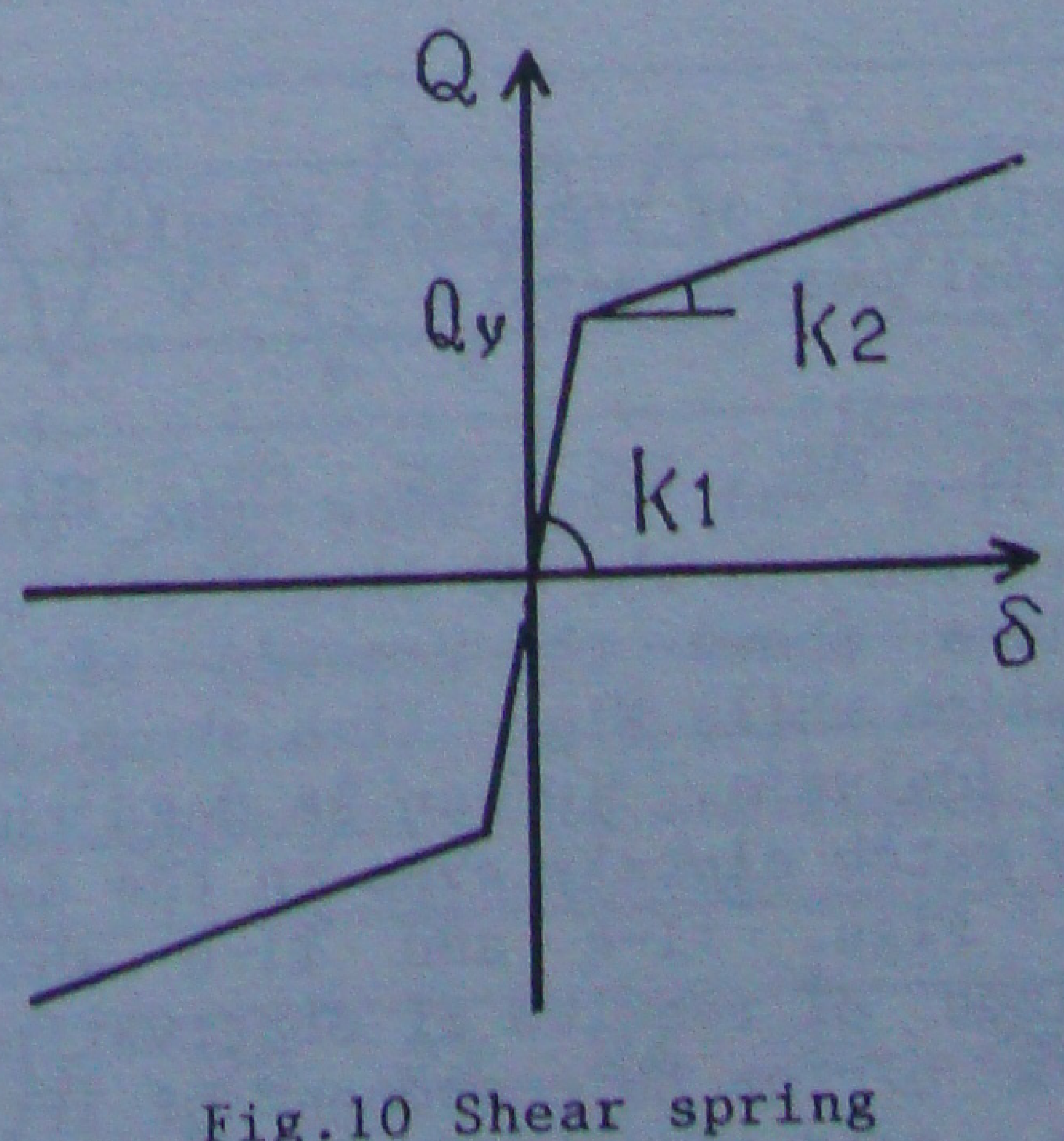


Fig.10 Shear spring

YC-851004) were not large, the primary gradient K1 was determined considering the effect due to friction between the top of the side wall and the cover in the dry area. The secondary gradient (K2=0.634 tf/cm per isolator) was determined from the loading-displacement relationship of the isolator itself.

Seismic motions of the earthquakes YC-840101 and YC-840306 were assigned identical primary gradients while the earthquake of YC-851004 was assigned a different gradient. The reason being that for the two earlier earthquakes (K1=2.536 tf/cm, Qy=0.03333 tf per each isolator) plywood plates were used for the dry area cover while the latter (K1=5.072 tf/cm, Qy =0.03333 tf per each isolator) used PC plates. The spring constant in the vertical direction was determined to be Kv=380.0 tf/cm and a damping factor of 3.5% in both the horizontal and vertical directions.

Based on the parameters established above, the natural period was obtained, as shown in Table-2.

Table-2 Natural period (sec)

Stiffness		YC840101 YC840306	YC851004	k2 only
	K1 K2	2.536 0.634	5.072 0.634	0.634
Mode	1	0.77	0.55	1.52
	2	0.76	0.54	1.51
	3	0.64	0.46	1.27
	4	0.10	0.10	0.10
	5	0.092	0.091	0.093
	6	0.078	0.078	0.078
	7	0.065	0.066	0.066
	8	0.060	0.060	0.060
	9	0.051	0.051	0.051
	10	0.041	0.041	0.041
	11	0.036	0.036	0.036
	12	0.033	0.033	0.033
	13	0.031	0.031	0.031
	14	0.029	0.029	0.029
	15	0.023	0.023	0.023

5.3 Comparison of analysis results and actual measurement

(1) YC-840101

Figs. 11-a and 11-b show the response acceleration in the NS direction of 1F. Fig. 11-a shows the records of actual observation while Fig. 11-b shows results of this analysis. It can be seen that the results match closely even in the detailed points. Figs. 11-c and 11-d show the comparison of results of observation and analysis of the EW component of 1F, also showing a good correlation.

(2) YC-840306

Fig. 12 shows the results of similar comparisons to YC-840101 above for the earthquake of March 6, 1984. Examination of the data indicates that the analysis agrees well with the results of the observation.

(3) YC-851004

Figs. 13 and 14 show the records of observation and the results of analysis of the earthquake of October 4, 1985. Fig. 13 shows the comparison of acceleration. Fig. 13-a and 13-b compare the records of observation and the results of analysis in the NS direction of 1F, respectively, while Fig. 13-c and 13-d show those in the EW direction in a similar manner. It can be seen that the results, such as the maximum value, configuration of the wave form, and condition of higher order vibrations, show a close correlation. The same applies to the case of the two former earthquake (i.e., the acceleration response of 1F compared with the seismic acceleration in both the NS and EW directions decreased considerably), representing the effect of the isolation system.

Fig. 14 shows the results of an numerical study using a model in which the superstructure is assumed to be a rigid body where the isolator alone is deformed. Although the maximum value matches the observed value, we cannot conclude that this simple model reproduces the overall wave form since the higher order vibrations cannot be represented. Generally, however, the superstructure of the base isolation structure is designed to be elastic and only requires the maximum response value. Hence, this simple model is considered sufficient from the viewpoint of structural design.

6. Conclusion

As the earthquake observation to date has not yet included a large scale earthquake, the evaluation of the observed data cannot be too highly regarded. However, it may be concluded that the results obtained were effective in considering the behavior of the base isolation system in response to medium to small scale earthquakes.

Also, we were able to establish that the dynamic analysis is effective in the evaluation of the base isolation structure and that the roles played by the simplified model and the elaborate model were well defined.

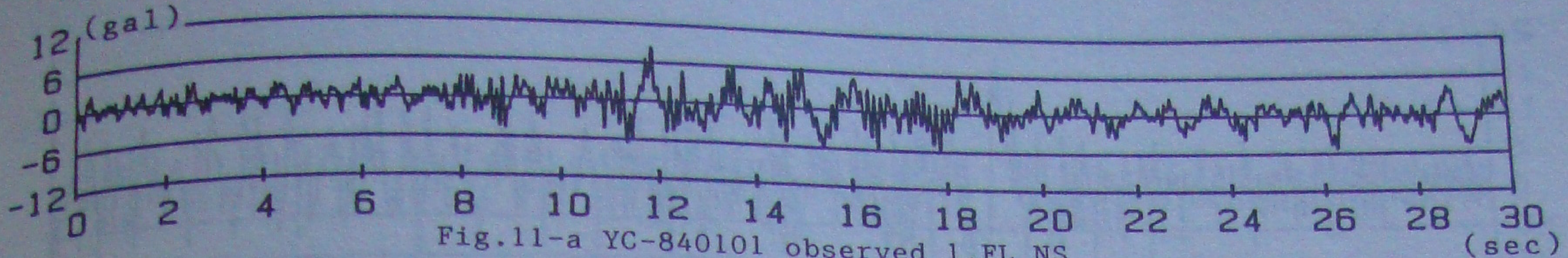


Fig.11-a YC-840101 observed 1.FL NS

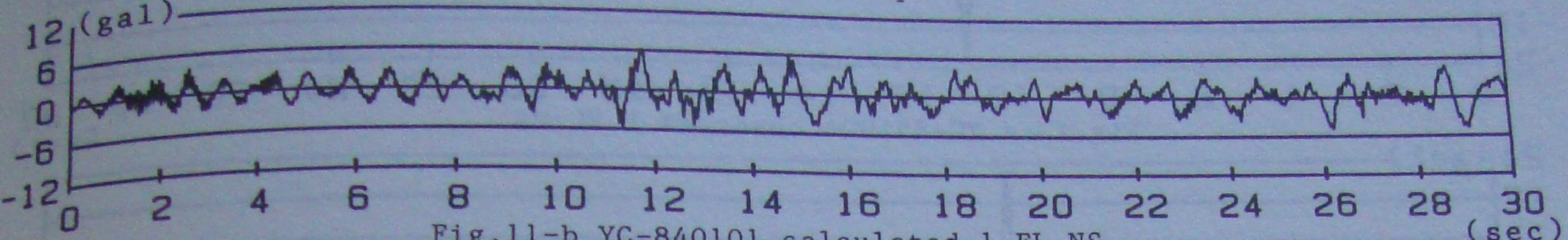


Fig.11-b YC-840101 calculated 1.FL NS

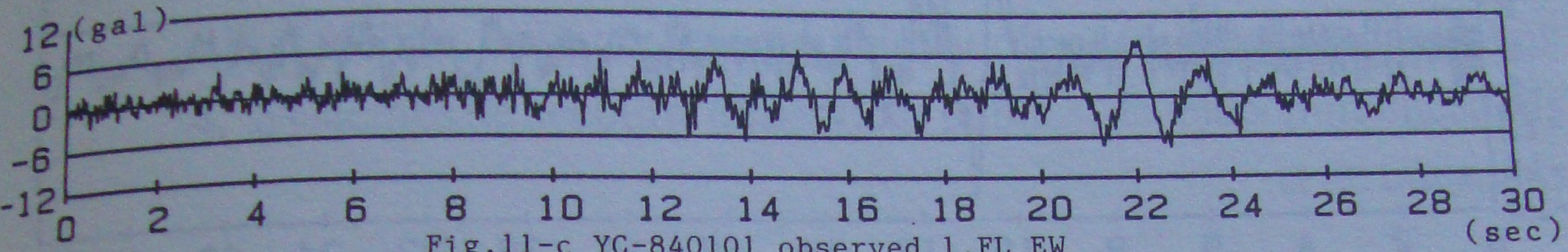


Fig.11-c YC-840101 observed 1.FL EW

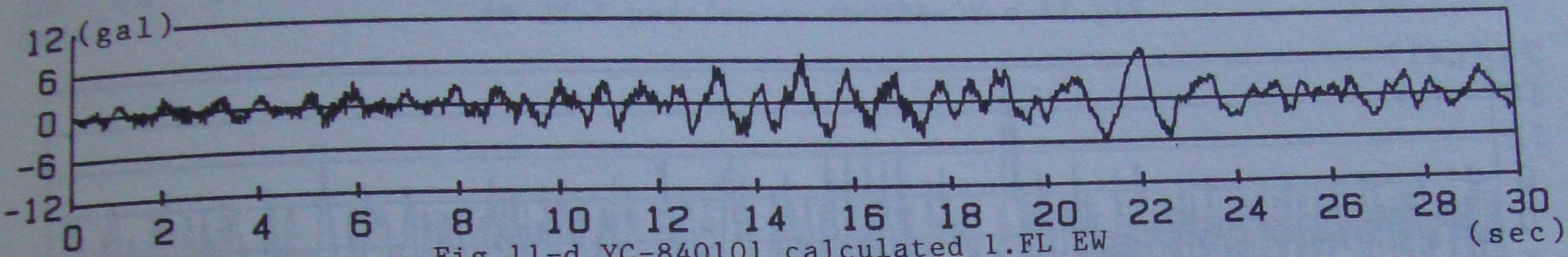


Fig.11-d YC-840101 calculated 1.FL EW

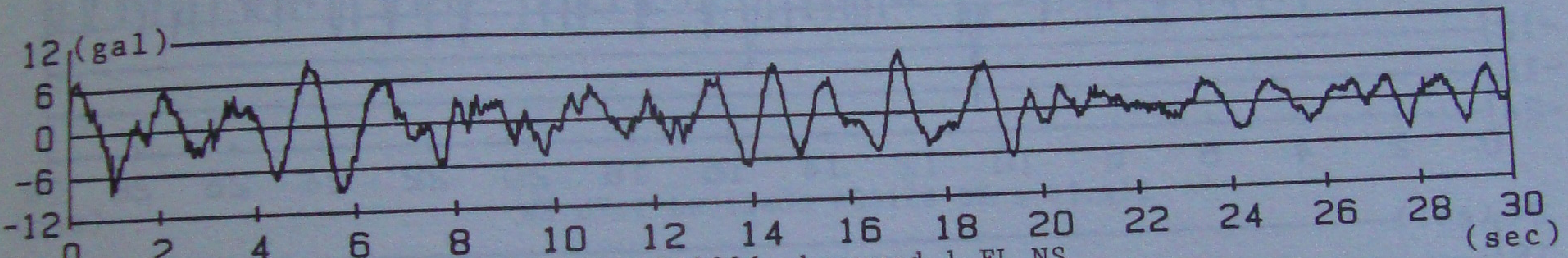


Fig.12-a YC-840306 observed 1.FL NS

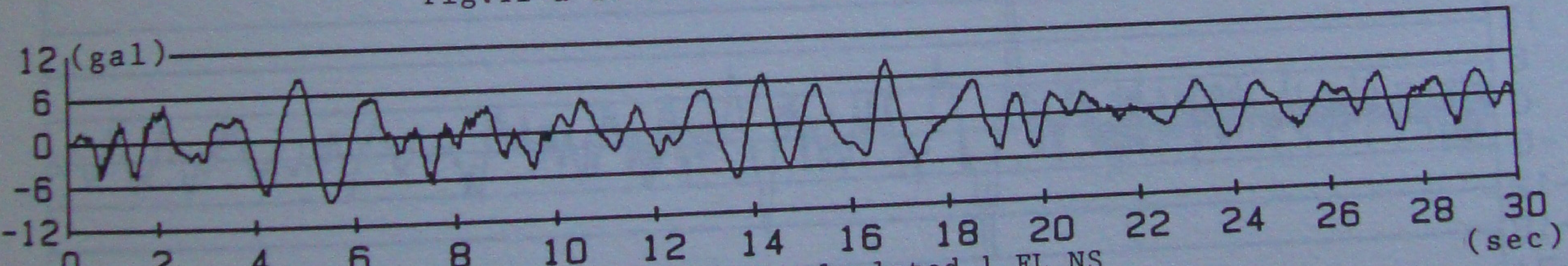


Fig.12-b YC-840306 calculated 1.FL NS

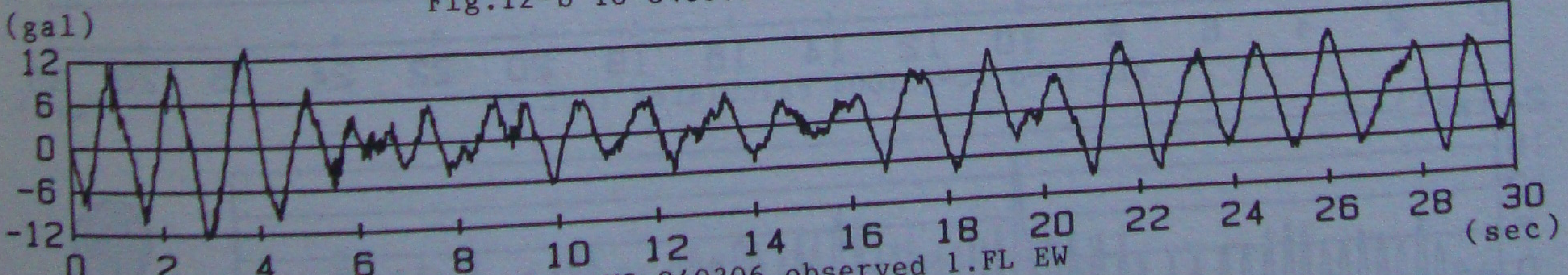


Fig.12-c YC-840306 observed 1.FL EW

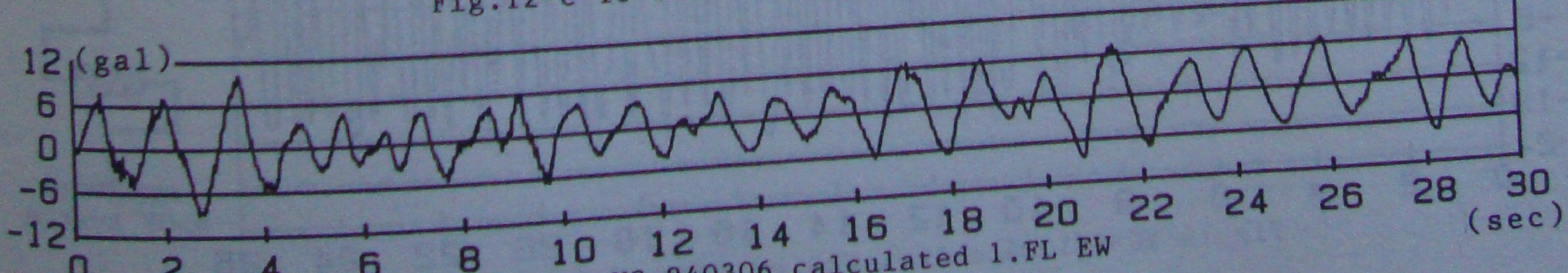


Fig.12-d YC-840306 calculated 1.FL EW

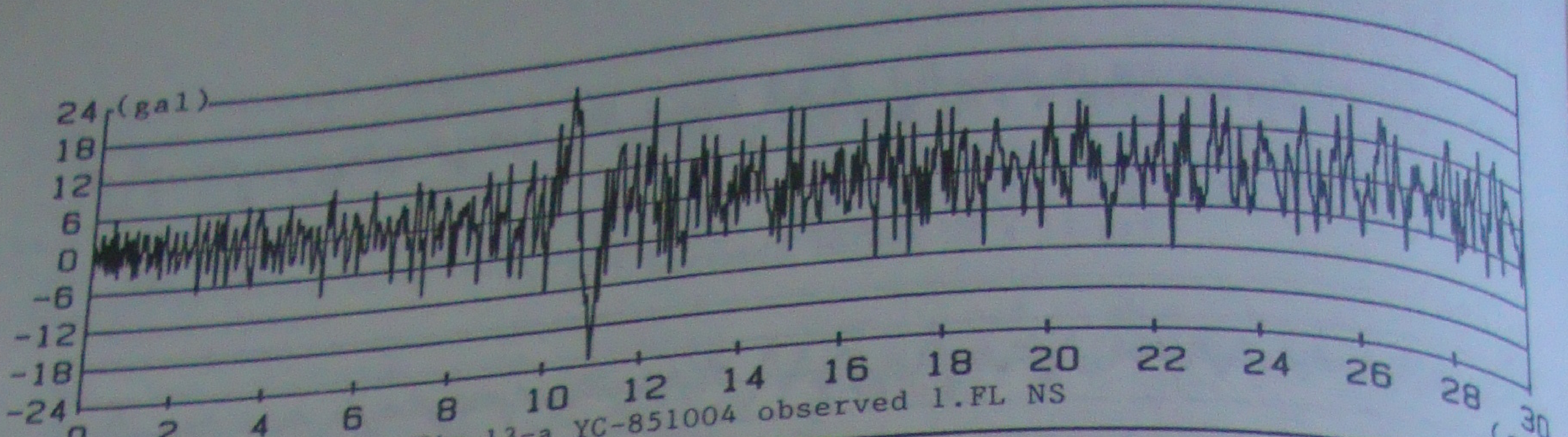


Fig.13-a YC-851004 observed 1.FL NS

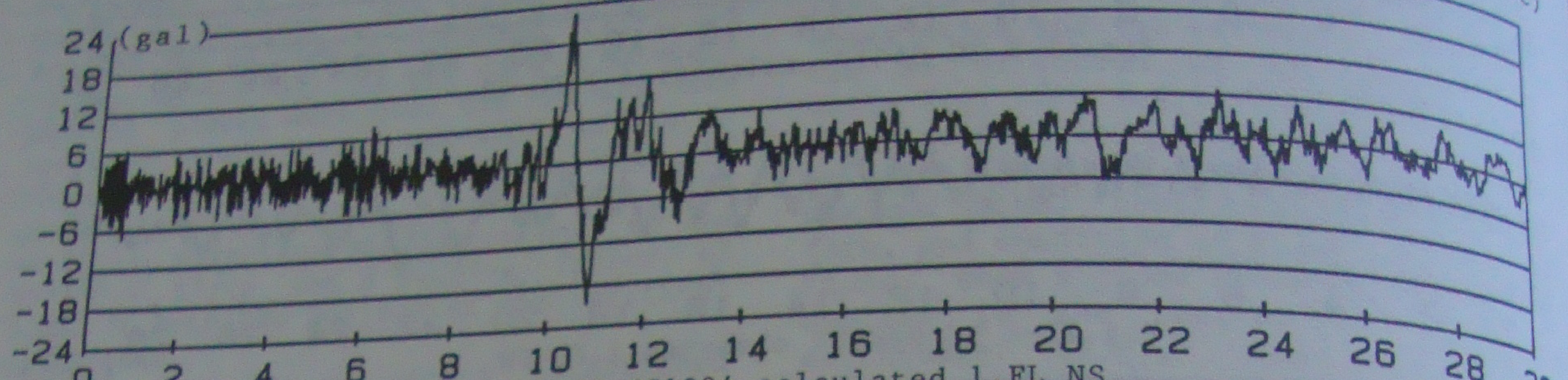


Fig.13-b YC-851004 calculated 1.FL NS

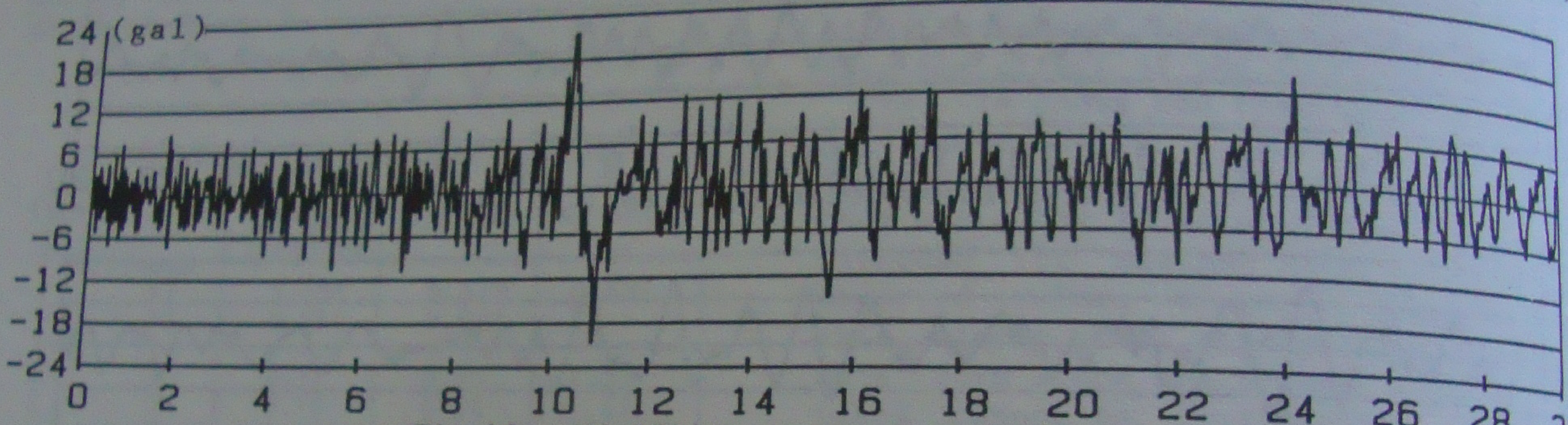


Fig.13-c YC-851004 observed 1.FL EW

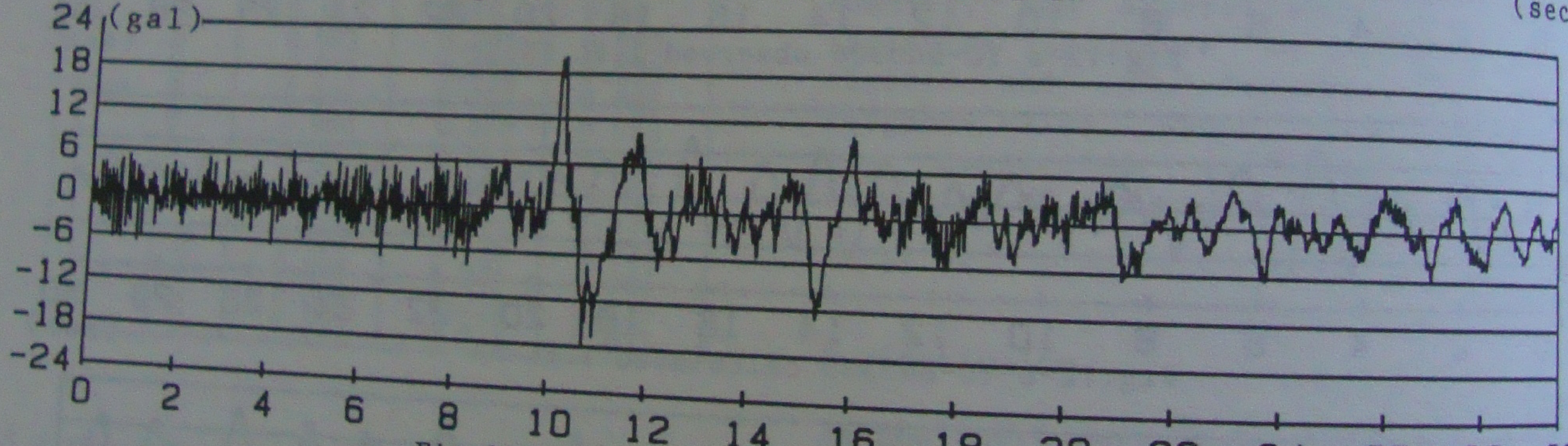
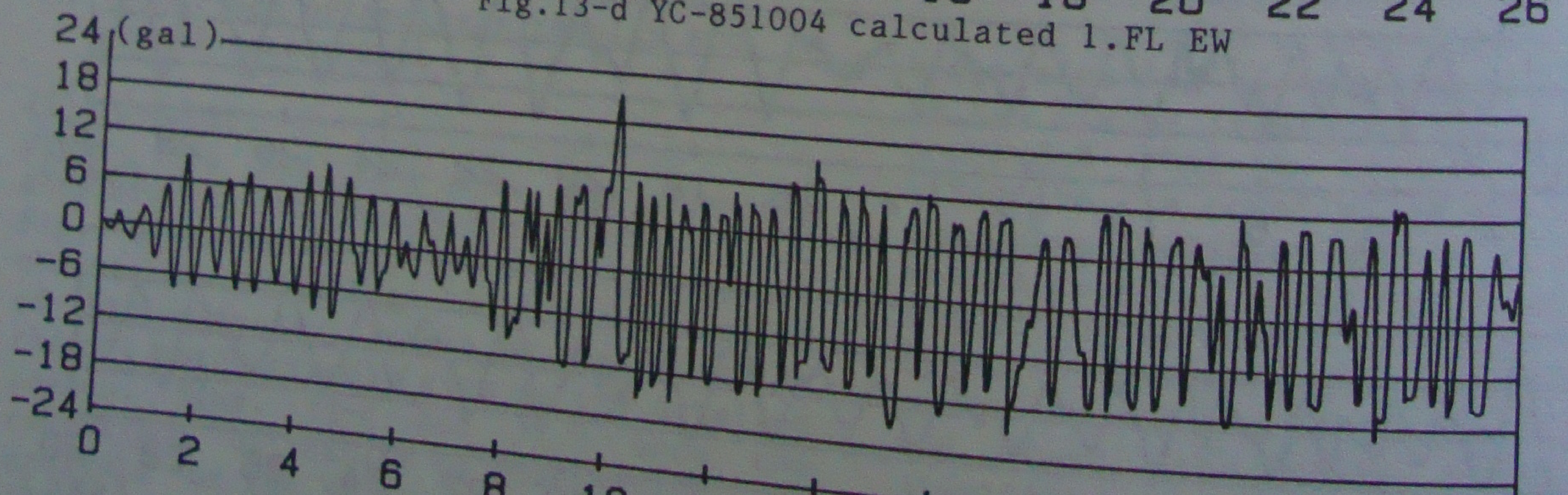
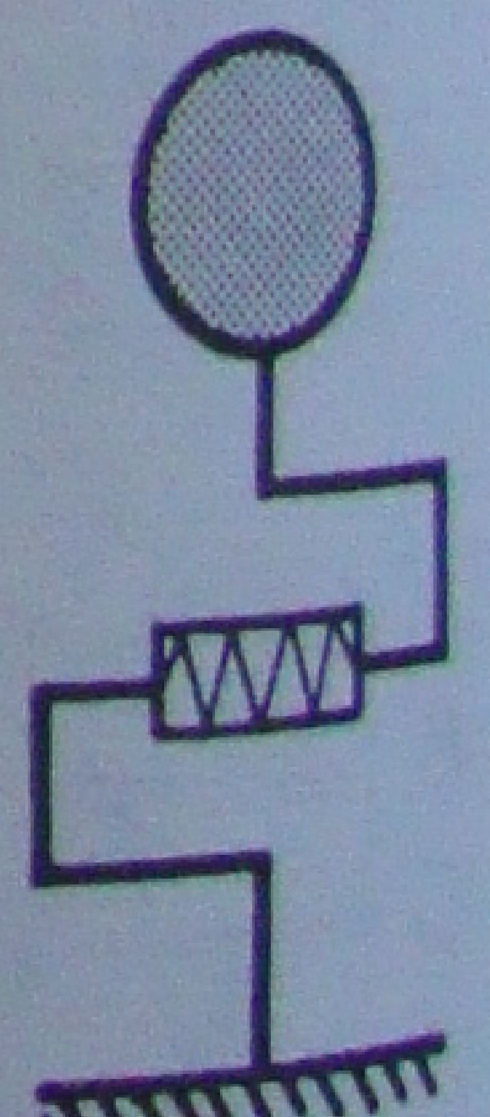


Fig.13-d YC-851004 calculated 1.FL EW





SDOF system

Fig.14 YC-851004 calculated by SDOF (1.FL EW)