EVALUATION OF POTENTIAL DESTRUCTIVENESS FROM RECORDED STRONG MOTION ACCELEROGRAMS

T. Minami,[1)]Y. Sonoda[2)]and Y. Osawa[3)]

ABSTRACT

More than 130 strong motion accelerograms recorded in northeastern Japan have been analyzed to evaluate the potential destructiveness of earthquake motions. Particular characteristics of ground acceleration have been studied in detail by means of Running Window Fourier analysis and non-stationary digital filtering techniques. It has been found that some buildings may undergo extremely large plastic deformations if degradation of building stiffness occurs during the initial stage of earthquake excitation.

INTRODUCTION

The elastic-plastic earthquake response of buildings is uniquely determined when the input ground motion and the properties of the structural model are fully described. Conversely, the potential destructiveness of strong motion accelerograms can be evaluated by comparing the results of earthquake response analyses of certain structural models.

The potential destructiveness of accelerograms is assessed in terms of the critical yielding strength, $k_{y\ cr}$, the values of which depend not only on the random nature of the earthquake excitation, but also on the physical parameters of the building. The input acceleration records are decomposed into Running Window Fourier Spectra (RWFS), in unfavorable cases, to determine which part of the accelerogram has the dominant influence on increasing the seismic response. Close investigation of the time history of the response indicates complex relationships to exist between the time-dependent spectra of input ground motion and the changing structural stiffness of the building.

Analytical results thus obtained may be utilized not only to evaluate the potential destructiveness of each accelerogram but also to establish a more practical criteria for generating standard design earthquakes.

STRONG MOTION ACCELEROGRAMS

The records of 134 strong motion accelerograms obtained at nine observation stations in northeastern Japan have been analyzed (figure 1). The maximum amplitude of the records, the magnitudes of the earthquakes, and the epicentral distances vary in the range 19 - 403 gal, 5.6 - 7.9, and 15 - 415 km, respectively. Fourier amplitude spectra of the accelerograms obtained at Kushiro and Hiroo are illustrated in figure 2. Although the individual spectra vary, the overall features appear to reflect the amplification characteristics of the local soil formation at each observation station.

ANALYTICAL MODEL OF BUILDINGS

In order to simplify the analytical interpretation, single degree of

---

1) Associate professor, Inst. Stru. Eng., Univ. of Tsukuba, 2) Graduate student, Univ. of Tokyo, 3) Professor, Earthq. Res. Inst., Univ. of Tokyo

freedom, stiffness deteriorating, bi-linear restoring force models of the buildings were used in this investigation (figure 3). The idealized structures follow the standard bi-linear hysteretic rules up to a certain displacement, d'_y, beyond which the stiffness deteriorates in proportion to the difference between the maximum and minimum displacements.

Earthquake response analyses of the buildings with various levels of strength expressed by the ratio, "α", of the yielding acceleration to the maximum ground acceleration, and with different initial natural periods, T_0, is carried out. The four models in particular are used for illustrative purposes in the following discussions.

Model A-10 ... (α=1.0, T_0=0.2 sec), Model A-15 ... (α=1.5, T_0=0.2 sec)
Model B-10 ... (α=1.0, T_0=0.3 sec), Model B-15 ... (α=1.5, T_0=0.3 sec)

CRITICAL YIELDING STRENGTH

The elastic-plastic response analysis shows that buildings with relatively high yielding strength undergo displacement response similar to those of elastic buildings. As the yielding strength of the buildings decreases, the displacement response increases suddenly at a certain critical value of the yielding strength, α. Curves of yielding strength plotted against ductility factor for two typical accelerograms are shown in figure 4. Although each curve differs somewhat from each other for different ground motions and different initial periods, the common feature of a sudden increase in the plastic displacement at a critical yielding strength is quite apparent. As a measure of potential destructiveness of strong ground motions, the critical yielding strength, $k_{y\ cr}$, is defined as the yielding strength below which the ductility factor exceeds 4. In these analyses, the critical yielding strengths were found to vary more than expected, and the maximum and minimum values for the structure with 0.2 sec initial natural period are approximately 2.0 and 0.4, respectively.

FOURIER AMPLITUDE SPECTRUM

In linear analyses, the response of a building depends greatly on the magnitude of the Fourier amplitude of the input accelerogram at the natural frequency of the building, since a slightly damped structure acts as a narrow band filter in the frequency domain. For illustrative purposes, the displacement response spectra of the filtered accelerograms are calculated which display a close coincidence with those of the original records (figures 5 and 6).

In the elastic-plastic behavior of buildings, the situation becomes complicated due to the increasing apparent period of the structure caused by increased displacement response in the plastic region. The apparent natural frequencies at the beginning and at the end of the excitation are denoted by arrows in figure 7 for several ground motions. Apparent natural frequency is determined from the linear stiffness shown by lines B-B' and C-C' in figure 3. A significant shift in the apparent frequency occurs when large Fourier amplitudes prevail in the low frequency range. For buildings with relatively high strength, however, shifts to the lower natural frequency depend not only on the low frequency components, but also on the magnitudes of the Fourier amplitudes between the initial and final apparent frequencies.

Although no definite rules for predicting the final frequencies have been established analytically, results of the numerical analyses have indicated the necessary requisites for the occurance of significant shifts in the natural frequencies. They are: 1) the presence of high energy concentration in the low frequency range, and 2) increasing Fourier amplitudes at frequencies less than the natural frequency of the buildings.

RUNNING WINDOW FOURIER SPECTRUM

The changing sequences of apparent natural frequencies are shown on the Running Window Fourier Spectrum (RWFS) of input accelerograms in figures 8a through 8d. The figures show contours of Fourier acceleration amplitude in the time-frequency domain. Running spectrum analyses are performed to determine the time-dependent spectrum behavior of the earthquake motion. Because of the different amplification effects of the soil layer formation at each observation site, the four typical ground motions shown in figures 8a-8d yield different patterns of Fourier amplitude distribution. In the figures, areas of high contour density denote regions of high energy concentrations. The four building models mentioned previously were analyzed; those with the initial natural periods of 0.2 sec (5 hertz) and 0.3 sec (3.3 hertz) being denoted in the figures by the bold lines and broken lines, respectively. The 199-HK006(EW) accelerogram observed at Hiroo during the Tokachi-oki earthquake (1968) possesses high energy concentrations within a relatively wide band around 2.0 hertz. For buildings with 0.2 sec initial natural period, strikingly large discrepancies are observed in changing frequency between buildings with 1.0 and 1.1 strength levels. In these cases, the major change of apparent natural frequencies occur later in time, and in a relatively short interval, when the main shocks are passing.

Similar observations were made for the 157-TH019 (NS) record, except that two minor clusters of energy concentrations which appear during the initial stage of excitation around 3 and 4 hertz may have had some influence on the changing apparent frequency. No significant shift in the apparent natural frequencies occur even for buildings with low yielding strength (Models A-10 and B-10). Only those buildings with strength levels less than 0.5 undergo frequency shifts across the main energy band. The elastic-plastic response of these buildings are, in general, very sensitive to this type of excitation. Large discrepancies in the final apparent frequencies are again observed due to slight difference in the yielding strength (α=0.5 and α=0.6). Because of the extremely simple amplitude distribution, deviation from the main energy belt hardly occurs once the apparent natural frequency is trapped in this region.

A different type of response is found in the 200-TH020(NS) accelerogram which possesses widely scattered Fourier amplitudes in the frequency range. It should be observed that the buildings having the same yielding strength undergo at an early stage of time almost identical patterns of stiffness deterioration for different initial natural periods. This is a common feature of ground motions with widely scattered amplitudes, since no essential difference in structural properties is recognized when the apparent natural frequencies coincide during the excitation. Because of the complex distribution of Fourier amplitudes in the time-frequency domain, the apparent natural frequency changes gradually in several small decrements.

These tendencies are more apparent in figure 8d in which the 202-TH029(EW) earthquake as seen by the structural Model A-10 is shown. In this case, the stiffness deterioration occurs almost along the entire length of excitation. Final natural frequencies are again likely to depend heavily on the stiffness decrease which occurs during the early stages of excitation.

RESPONSE ANALYSIS OF FILTERED ACCELEROGRAMS

In order to see which portion of the Fourier amplitudes have the greatest influence on the seismic response of buildings, the changing natural frequencies of the model are calculated for different types of filtered accelerograms. Each filter consists of several band pass filters of different band widths, and a changing central frequency that is varied in such a way that the moving apparent frequencies of the building Model A-10 are always contained in the band range.

Five filtered waves are generated, for example, from the 200-TH020(NS) accelerogram as shown in figure 9a. Wave forms of the typical filtered ground motions are shown in figure 10 together with the original accelerogram. Portions of the Fourier amplitudes eliminated from the original accelerogram increase in alphabetical order in the figures. Maximum response of the building Models A-10 and A-15 to all the filtered accelerograms are illustrated in figure 11. The calculated apparent natural frequencies of building Model A-10 to filtered waves C and E are shown on the corresponding RWFS in figures 7b and 7c. Variation of the natural frequencies in response to wave C is somewhat similar to that of the original accelerogram, although a considerable portion of Fourier amplitudes have been removed from the original RWFS. The filtered wave E, on the contrary, loses potential destructiveness inherent in the original accelerogram for both building Models A-10 and B-10. This difference results mainly from the different Fourier amplitude patterns during the early several seconds of excitation, especially due to the absence of high frequency components in the wave E. The time history of displacement response to both waves (figure 12) also suggests that small differences in apparent natural periods at an early point in time may have significant influence on the later response of the buildings.

In order to study the random nature of the seismic responses, two types of initial conditions were introduced at an arbitrary instant of time during the response analysis. Arbitrary initial values of response displacement and response velocity were first set in such a way that the total of the kinetic and strain energy in the structure remained unchanged. It was concluded from this analysis that, with the specified initial conditions, the energy level of the structure at early instants of time were not high enough to influence the later response of the structure. Therefore, to determine the effect of higher system energy, another type of initial conditions was established such that the response velocity was arbitrarily doubled at some early time in the analysis. In this solution, the displacement value remained unaltered, and only the velocity was modified. The dotted line A in figure 9c shows the changing natural frequency due to the second type of initial condition initiated at 2.6 sec into the filtered wave E

Finally, the filtered wave E was suddenly applied, after 2.6 sec elapsed time, to buildings with different natural frequencies. No significant decrease in the apparent frequency were observed for any natural period, as shown in figure 9d. This indicates that the elongation of the natural periods is not the only factor for producing large plastic displacements, but a certain level of energy must be maintaned in the structure.

It is concluded from the above discussion that the potential destructiveness of the less harmful filtered waves may be increased by: 1) decreasing the natural frequencies of the building, and/or 2) increasing the kinetic and strain energy in the structure at early points of time during the earthquake.

CONCLUDING REMARKS

Elastic-plastic response of buildings depends mainly on the magnitue of Fourier amplitudes of input excitation not only at the natural frequency but also in a wide range of frequencies. The accelerograms, whose Fourier amplitude is increasingly large at the frequencies less than the natural frequencies of the building, are likely to increase the seismic response of structures considerablly.

Detailed study on the modified accelerograms by means of non-stationary digital filtering indicates a complex relationship between Fourier amplitude distributions of the ground motion (RWFS) and decreasing natural frequencies of certain buildings. Extremely large structural response results from elongated apparent natural period for stiffness deteriorating type of restoring force models. High frequency components in the initial part of the accelerograms have particular influence on the elastic-plastic response of structures as they increase the kinetic and strain energies of the building.

Research on this subject is in progress to clarify the relation between the characteristics of strong ground motion accelerograms and building properties. It is believed, however, that the investigation on the potential destructiveness of observed accelerograms may lead to establishing a practical procedure for generating standard design earthquakes for buildings of different characteristics.

REFERENCES

[1] T. Minami, T. Tanaka, Y. Sonoda and Y. Oswa, "Non-Stationarities Observed in Strong Motion Accelerograms and Their Effects on Earthquake Response of Structures", Proceedings, 6th World Conf. Earthq. Eng., 1977

[2] T. Tanaka and S. Yoshizawa, "Vibrational Characteristics of th Ground as Derived from Strong Motion Earthquake Records", Proceedings, 4th Japan Earthq. Eng. Symp., 1975

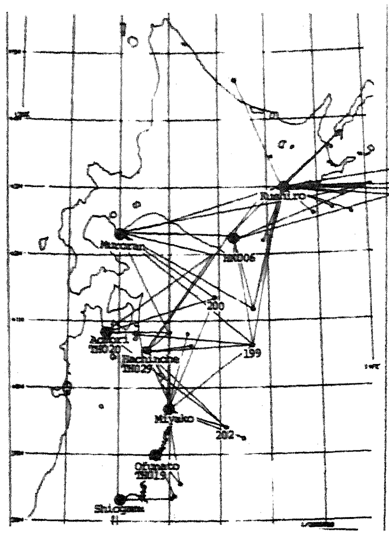

Fig 1 Location of Earthquake Epicenters and Observation Stations

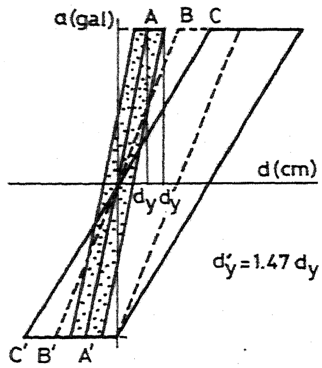

Fig 3 Stiffness Deteriorating Bi-Linear Model

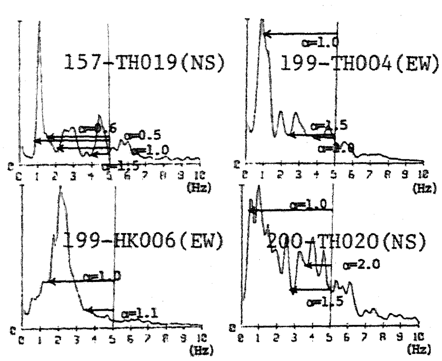

Fig 7 Initial and Final Natural Frequencies of Certain Buildings

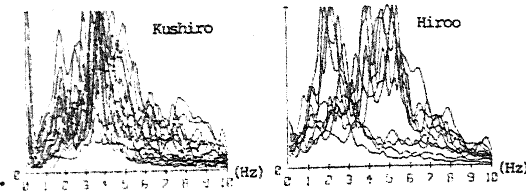

Fig 2 Fourier Spectra of Accelerograms Observed at Kushiro and Hiroo

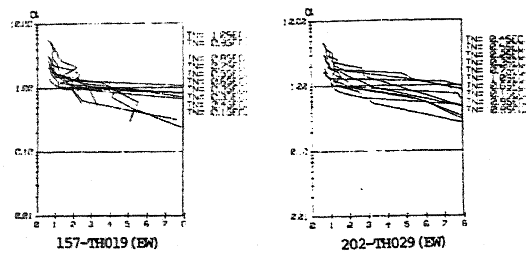

Fig 4 Yielding Strength versus Ductility Factor Curves

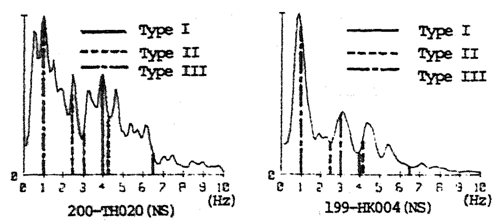

Fig 5 Band Pass Filters Used in Linear Response Analysis

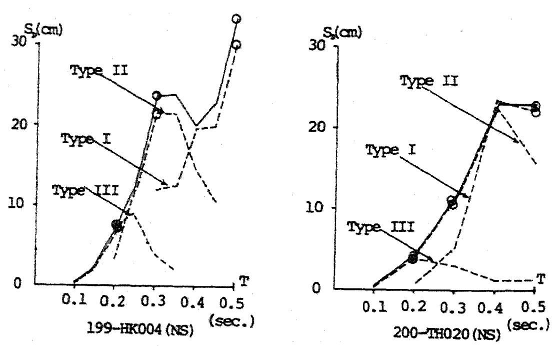

Fig 6 Displacement Response Spectra for Filtered Accelerograms

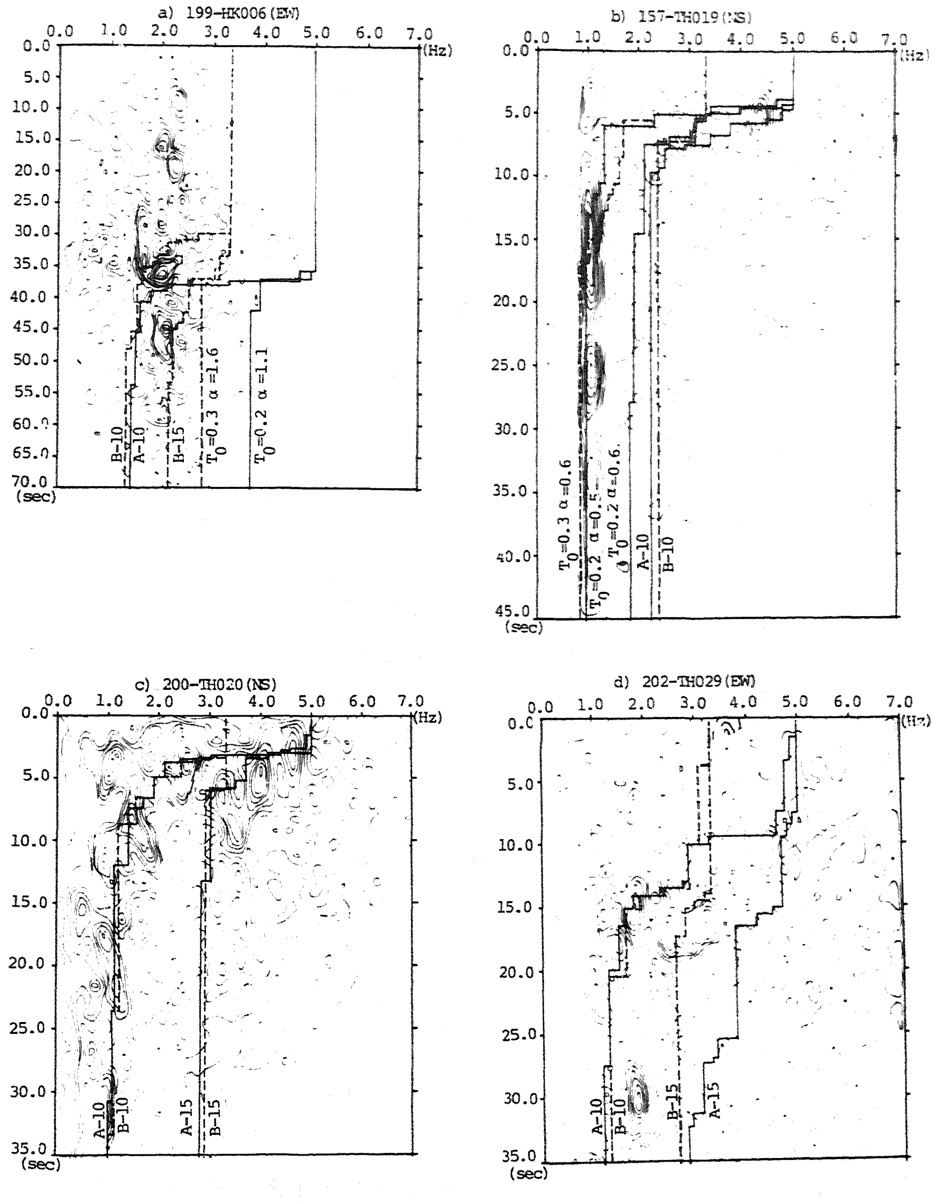

Fig 8 Time History of Apparent Natural Frequencies for Typical Accelerograms

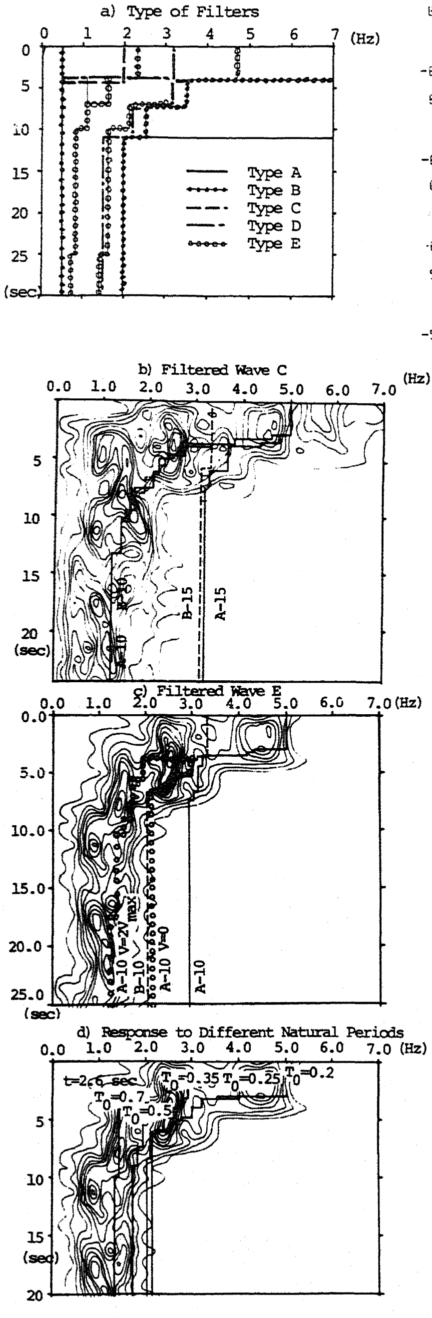

Fig 9 Time History of Apparent Natural Frequencies for Filtered Waves

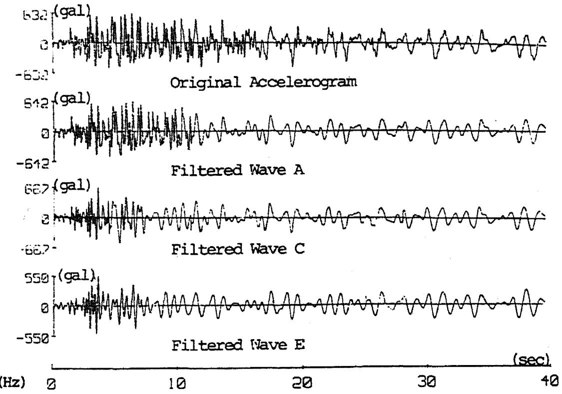

Fig 10 Typical Filtered Waves for 200-TH020 accelerograms

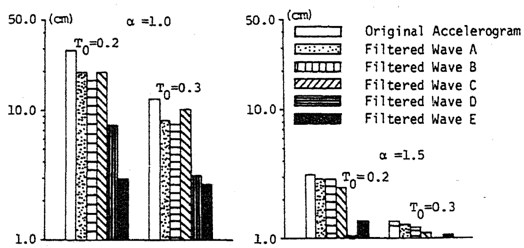

Fig 11 Comparative Displacement Response of Filtered Waves

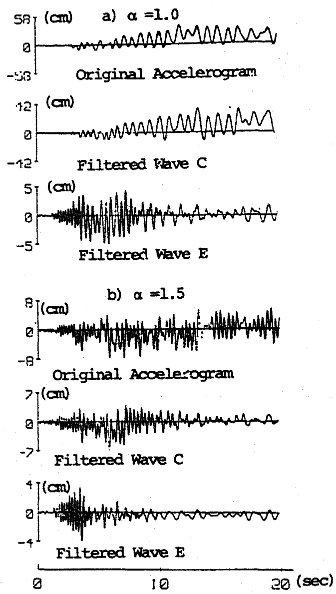

Fig 12 Time History of Displacement Response of A-10 and A-15 Models