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STUDIES ON THE DESIGN EARTHQUAKE MOTIONS IN ACCORDANCE TO THE REVISED JAPANESE BUILDING STANDARDS

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Abstract

The Japanese Building Standard has been revised to take into considerations of new concepts in defining the seismic design forces. This paper describes the concepts of defining the design ground motions in terms of the response spectrum, time history and hazard levels corresponding to structural performance.

Keywords: Outcrop engineering bedrock, time history, amplification, design response spectrum

1. Introduction

There are two types of design spectra. One is an envelope or integration of many expected ground motions which could possibly occur in certain future period of time. The second is one that is constructed based on the earthquake magnitude, distance and/or soil condition. From the viewpoint of time history generation, the latter assumption is suitable because the time history is primarily based on the image of the single earthquake event. The duration time, for example, depends on the earthquake magnitude. However, the former type is, in reality, frequently found as the standard spectrum in engineering practice. The time history includes many factors related to variation representing the accidental occurrence or irreproducibility of earthquake event, when it is generated for design purposes.

2. Design Ground Motion for General Buildings

The design earthquake load for seismic evaluation is specified both with earthquake ground motion and with seismic force in the revised Building Standard Law of Japan. The design earthquake motion is basically expressed in the form of the acceleration response spectrum as follows.

\[ S_a(T) = G_s(T) \{ ZS_0(T) \} \]  

Eq. 1

Where,

- \( S_a(T) \) : acceleration response spectrum for evaluation,
- \( Z \) : seismic zoning factor
- \( G_s(T) \) : soil amplification factor
- \( S_0(T) \) : basic acceleration response spectrum at exposed (outcrop) engineering bedrock.
- \( T \) : Period (sec)

The engineering bedrock is herein defined as a layer with more than approximately 400 m/s in shear wave velocity and with sufficient thickness.
The basic response spectrum for major earthquakes given in Eq.1 is illustrated in Figure 1. The left hand figure shows conventional methodology that gives the story shear force in the Japanese standard. The acceleration response spectrum in the right hand figure is assumed to give equivalent story shear forces.

3. Soil Amplification Factor

The enforced Japanese Building Standard Law includes concept of soil classification to differentiate its effect to seismic load. However, the classification is made so simply that the actual property of the surface soil may not be necessarily reflected with the geotechnical data of the site, even if it is available. It is important for engineers to design structures based on the field investigation result. Therefore, the design code should facilitate such option to utilize site specific data.

3.1 Evaluation Procedure for Soil Amplification Factor

The amplification factor can be calculated using a formula for one layer system supported by flexible bedrock. Using the vertical shear wave propagation and the hysteretic damping assumption, the amplification factor at the first two natural frequencies are,

\[
H(\omega_1) = \frac{1}{(\pi / 2)\xi_1 + \alpha} = \frac{1}{1.57\xi_1 + \alpha} \quad H(\omega_2) = \frac{1}{(3\pi / 2)\xi_2 + \alpha} = \frac{1}{4.71\xi_2 + \alpha}
\]

where,

\[
H(\omega) : \text{The amplification ratio between surface and outcrop flexible base layer}
\]
\[
\alpha = (pV_s) / (p_V \lambda)
\]
\[
\xi : \text{damping factor of the soil layer}
\]
\[
\rho : \text{mass density of the layer}
\]
\[
\rho_b : \text{mass density of the bedrock}
\]
\[
V_s : \text{shear wave velocity of the layer}
\]
\[
V_{ab} : \text{shear wave velocity of the bedrock}
\]

The amplification factor to be determined here is the ratio of response spectra. Therefore, the function \( H(\omega) \) is actually different from the \( G_s(\omega = 2\pi / T) \). It is easily imagined, however, that these two values are closely related and take similar values. \( G_s(T) \) will not be determined theoretically but estimate in an approximate manner employing the expression of \( H(\omega) \).

The amplification of the uniform surface soil layer to the outcrop engineering bedrock is obtained by using the one-dimensional wave propagation in frequency domain. The transfer function of the surface soil layer and the engineering bedrock to the outcrop one are expressed as follows: a) surface/outcrop engineering bedrock; \( G_s(T, \xi_s, \alpha) \), and b) engineering bedrock/ outcrop engineering bedrock; \( G_b(T, \xi_b, \alpha) \). An equivalent shear modulus, \( G_s \), and an equivalent damping ratio, \( \xi_s \), of each soil layer are calculated through \( (G - \gamma) \), \( (\xi - \gamma) \) relationships of soil properties considering the nonlinear characteristics of the surface soil layers.
The computations of amplification factors are summarized as follows.

\[
G_s(T) = G_{s1}\frac{T}{0.8T_1} \quad T \leq 0.8T_1
\]

\[
= cT + d \quad 0.8T_1 < T \leq 0.8T_1
\]

\[
= G_{s1} \quad 0.8T_1 < T \leq 1.2T_1
\]

\[
= \frac{e}{T} + f \quad 1.2T_1 < T \leq 10
\]

\[H_i, : \text{ thickness of the i-th layer}\]

\[\rho_i, : \text{ mass density of the i-th layer}\]

\[V_s, : \text{ Shear wave velocity of the i-th layer}\]

\[G_{ai}, : \text{ Shear modulus of the i-th layer} \quad \left( G_{ai} = \rho_i V_s^2 \right)\]

\[T_1, T_2 \text{ can be computed with the following equations.}\]

\[T_1 = 4\left(\sum H_i^3\right) / \sum G_i / \rho_i H_i, \quad T_2 = T_1 / 3\]

Eq.3

The acceleration response spectrum on the ground surface is evaluated considering the strain-dependency of shear modulus and damping factor of soils. [Miura et al., 2000]

4. Evaluation of Design Ground Motion Time Histories

The notification for time history specification in the revised Building Standard Law of Japan is summarized with flow chart in Fig. 3. The notification gives priorities in sufficient duration time, and the numbers of time histories to be used in the dynamic analysis.

4.1 Types of Time Histories

There are three types of motions considered in the current design of specific buildings.

4.1.1 Standard type includes the well-known El Centro/1940 NS, Taft/1952 EW and Hachinohe harbor for Tokachi-oki earthquake/1968 EW. These motions have become a standard in Japan. The motion of this type has no variation and is mainly used to examine the overall validity of the design judging form the past experience. Because those standard motions are used in most of the design practice. Therefore, the designer can check the level of seismic performance in reference to other design examples. As a design practice of Japan, the recorded motions have been scaled with maximum velocity amplitudes, i.e., the major level of 50 cm/s and the minor level of 25 cm/s.

4.1.2 Site-specific type includes the modified motions recorded at the site or nearby sites, and the simulated motions based on the event that has the largest influence to the building concerned.

The ground motion of this type can be evaluated as the motion due to the selected specific earthquake. The motion has variation based on e.g. the rupture process uncertainty of the causative fault that is specified as of the largest influence in the area. The use of this technique is limited because the design engineers who could handle it are still few in number.
4.1.3 Design spectrum-compatible type includes two options. One is the motion that has clear definition of corresponding to an earthquake event. The other is not necessarily related with some specific event, since the spectrum is determined from the statistical analysis of variety of motions. Here, a strategy to fix the ground motion parameters to generate time histories is needed. The motion of this type had been frequently used in the past design practice. The technique for generating ground motion of this type is widely available. [Ohsaki, et al., 1978] We will mainly focus on type in 4.1.3 in this paper.

![Flowchart](image)

**Fig. 3 The flow chart for evaluating the design ground motion time history**

The primary factors causing ground motion variation might be as follows; From the seismological viewpoint, it is associated with earthquake occurrence or fault rupture. In engineering – these factors are involved in randomly distributed Fourier phase angles all together. The variation of time history properties includes response spectra, peak amplitudes, energy spectra, etc.
The variation of the structural response involves non-linear response, responses of multi-story buildings etc. The commonly used waveform for the time history of ground motion is as follows:

\[ \alpha(t) = E(t) A_i \cos(\omega_i t + f_i) \quad \text{Eq. 4} \]

where, \( \alpha(t) \) is acceleration time history with uniform time interval, \( E(t) \) is the envelope function to make wave non-stationary. \( A_i, \omega_i, f_i \) are amplitude, circular frequency and phase angle of the \( i \)-th component, respectively. The target response spectrum is generally given for 5% of critical damping. It is necessary for the generated motion to be compatible to only the 5% damping response spectrum. It is not a general requirement, however, that the generated motion must be compatible to the spectral values for damping other than 5% of critical. The property of the design ground motion specified in the notification No.1461 in the revised Japanese Building Standard Law should be as follows;

"The simulated motion should be compatible in acceleration response spectrum with 5% critical damping specified in the notification No.1461. The compatibility to the target spectrum (design spectrum) should be checked in the period range between 0.02 and 5 second. However, under some specific conditions such as the deep sediment in the ground surface (here within the scope as deep as up to layer with shear wave velocity of 3,000m/s), much longer component than 5-second should be considered, since the deep subsurface conditions sometimes generate surface waves that dominates in longer period component. The typical areas in Japan include the plain areas (Kanto plain, Osaka plain, Nojiri plain etc., refer BRI,BCJ,1992)"

5. Variations of the Generated Ground Motions

Time histories compatible to the design spectra are generated and their variations are examined. Four types of duration time, i.e., 10, 20, 60, 120 seconds were used to generate the ground motions as shown in Fig.4. The design spectra used here is an acceleration response spectrum. For each duration time, thirty time histories were generated. The non-stationary property, given with three parts, i.e., build-up, constant, and decay, are identical of a proportion to total duration time. The wave forms and the frequency distribution of peak acceleration and velocity are shown in Fig.5. It is seen that shorter duration time gives larger variations. The variation for the 120-second motion is much less than the shorter duration cases. The right hand figure shows the same distribution for peak velocities. It is also seen that the longer duration time shows less variations with peak amplitudes.
5.1 Variation of Response Spectra

The averages of the ratio to the target spectra (5%) are computed for durations of 10 and 120 seconds for 1, 2, 10, 20 % damping. The variation of the acceleration spectral values with damping at the longer period range becomes less for shorter duration time histories. This is because that the wave number is not enough for the response to grow for shorter duration and longer period. As a result, the response value is less varied with damping.

5.2 Nonlinear Response Characteristics

Time history analysis is mainly used in nonlinear response analysis. The SDOF (Single Degree of Freedom) bi-linear model was used to compare the non-linear response properties. The parameters used are the skeleton curves, stiffness ratio, building period, stiffness ratio. It could be said that the displacement response depends on duration time. The longer building period gives larger variation. The smaller yield strength gives larger variation in peak displacement. For the cases of elastic building period less than 1 second, the response displacement does not depend too much on the duration time. Although the displacement response and variation become larger when the stiffness ratio is very small, the response becomes smaller and almost same regardless of the stiffness ratio when the ratio is greater than 0.1 and as the duration becomes longer. It is also seen that the displacement response does not depend on the strength except for the duration of 10 second.

Fig.6 shows the superimposed plot of the acceleration response spectra for damping of 2, 5, 20 % with 16 generated spectrum-compatible motions. In this simulation, the duration of 120 second was used. In addition, the phase angles of the recorded motion are used to give the non-stationarity. It is seen from the Fig.6, the expected average spectra for ten generated motions slip out of the spectra computed with $F_x$. It can be pointed out that the assumed wave form with duration does not promise the relation $F_x$.

![Fig. 6 The variations of response spectra of fitted motions to 5% damping spectra](image)
(The dotted line shows the expected curve using the damping correction factor $F_x=1.5/(1+10\xi)$)

Conclusions

Dynamic analysis based on time histories are becoming common because of advanced computer technologies and availability of computer programs which are easy to use. However, the factors which causes variations in time histories and response properties are still not widely understood and remain unsolved. It is important to recognize the extent of the effect of uncertain parameters in the analysis. The variation should be related with the randomness involved in earthquake occurrence, such as rupture process, complexity of wave propagation and the surface soils. It is necessary for engineers to incorporate the uncertainties all together in evaluating the future strong ground motions. The number of time histories applied to the design analysis is quite limited. The importance is to know the possibility of loads or responses under such total uncertainties. In addition, the right position of time history analysis in design practice should be re-established.

Reference

(1) Building Research Institute, Building Center of Japan, "A Technique for Evaluation of Design Earthquake Ground Motion", Building Center of Japan, 1992