AN EXTENSIVE STUDY ON A SIMPLE METHOD ESTIMATING RESPONSE SPECTRUM BASED ON A SIMULATED SPECTRUM

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SUMMARY

The response spectrum is significant in estimating the seismic coefficient in dynamic aseismic design. It was demonstrated in the previous work that the response spectrum for earthquake motions could be simulated by an artificial earthquake with two ground predominant periods. However, the simulation procedure took much time and it was practically impossible to assume more than two ground predominant periods for complexity of the computation. In order to overcome these difficulties a simple method estimating the response spectrum of building and building-appendage structure was developed.

The basic description of the procedure as follows will be briefly described in the paper. Corresponding to peaks of the response spectrum for the earthquake motion the component of the respective ground predominant period was taken. The acceleration amplification factor of a building structure for the respective predominant period above taken was obtained from the spectrum for the simulated earthquake with single predominant period. The rate of the respective component in summing these amplification factors was given by satisfying the ratio among the magnitude of the peaks of the spectrum. The summation was made by the principle of the square root of sum of squares. The procedure was easily applied to estimate the spectrum of the building appendage structure.

The method is attempted to extend for multi-storey building structure and appendage to this building. Analysis is made as for a two storey structure system the mode of which for the first natural frequency is that the amplitude ratio of the upper mass to the lower is 2 to 1, so that the mode shape is a reversed triangle. The behaviour of the system is dealt with by the normal coordinate. The amplification factors due to two ground predominant periods are estimated for the system with the first natural frequency. In this procedure the method developed for the single-degree-of-freedom system is directly applicable. The same method is used for the system with the second natural frequency. Thus estimated amplification factor for the mode of the respective natural frequency is summed again due to the principle of the square root of sum of squares after multiplying the excitation coefficient of each mode by the corresponding factor. It is made obvious that the estimate of the spectrum due to the method shows good agreement with that for the earthquake motions.

The estimate of the amplification factor of the appendage to this building structure is also made. The method used for the simple building-appendage system and that for multi-storey building system are combined. The results give very good agreement for this case, too. These investigations show that the response spectrum can be estimated from statistically evaluated simple spectrum even for multi-ground predominant periods, if the ground predominant periods, the natural periods of the structure and the rate of the contribution of the respective component are predicted. El Centro is mainly used as the earthquake motion through the paper.

1. Introduction

The response spectrum is significant in estimating the seismic coefficient in dynamic aseismic design of structure since it was proposed by Housner [1]. It was described that averaged for many earthquake motions and was characterized by parameters of earthquake such as the magnitude, the distance from the epicenter and so on. Data accumulation in this direction has been made by adopting the sort of ground characteristic in addition to the aforementioned parameters. The analysis made it obvious that the spectrum for the respective earthquake motions naturally fluctuate. It means that the fluctuation or the probabilistic characteristic should be taken into account when the spectrum for a specific earthquake motion is utilized for the procedure of practical aseismic design.

On the other hand earthquake motion is described by a process of random vibration. Investigation to give the response spectrum based on the simulation of the earthquake motion due to the random vibration theory have been made. It is expected to be able to estimate the spectrum which is originally provided with the probabilistic characteristic. Tajimi [2] assumed existence of the ground predominant period in the earthquake motions which can be described in terms of Kanai's [3] semi empirical formula. The maximum which should be estimated in giving the spectrum was evaluated by the standard deviation of the simulated process. It was pointed out thus estimated spectrum can well express the general characteristics of the spectrum such that the velocity spectrum is constant, the acceleration spectrum has a peak at the ground predominant period and so on.

As the result for the estimation of the maximum for which the theory by Rice [4] was applied, the characteristics of the estimated spectrum was ascertained. The method was extended aseismic design even not only for the principal building structure but also for the secondary machine structure, appended structure to the building. However the simulated spectrum can represent the general or averaged characteristic of the spectrum, the shape and the magnitude of the spectrum did not necessarily agree with that for the earthquake motion in detail. The evaluation by the simulated spectrum for the appended structure was much larger than that for the earthquake motion.

This tendency was explained by assuming plural ground predominant periods. The magnitude of the simulated spectrum was diminished and good agreement was obtained by this analysis. However this approach was rather complicated and appropriate parameter giving the merging rate of the respective ground model with predominant period has to be chosen to adjust the amplification factor of the estimated spectrum by the theory to that by the earthquake motion.

2. The Response Spectrum for the Simulated Earthquake

2.1 Basic Equations and the Case of Single Ground Predominant Period

It has been expected to develop simple method to give a spectrum compatible with that for a specific site which might have plural ground predominant periods. A method composing the spectrum based on the principle of the square root of sum of squares [5], which would be abbreviated as SRSS in the following, was proposed. The simulated spectrum by the single ground predominant period was used as the basic spectrum in the method. In this paper the method developed for the basic building and building-appendage structure system in which the respective systems are single-degree-of-freedom system is attempted to extend for the analysis of the building structure system of the multi-degrees-of-freedom.

At first the investigation made so far would be summarized. Fig.1 shows the schematic model of the ground and the structure system to estimate the response spectrum for the simulated earthquake described by the random vibration theory. The earthquake motion at the base is represented by the process with stationarity and gaussian distribution. It is supposed that the ground characteristic is equivalently described by single-degree-of-freedom system. The building and the appended structure to this is respectively illustrated by single-degree-of-freedom system. The mass ratio of the latter to the former is very small in general.

The maximum of the random vibration simulating the earthquake motion and that of the response of the structure is evaluated by the assumption that it is realized by the estimate where the probability density function $p(y)$ of the extreme is small enough, where y means normalized amplitude. $p(y)$ was given by Rice [4] as follows,

$$p(y) = (1/\sqrt{2\pi}) \exp(-y^2/(2\epsilon^2)) + (\sqrt{1-\epsilon^2}/2) y \exp(-y^2/2) \{1 + \operatorname{erf}(\sqrt{1-\epsilon^2}/(\sqrt{2}\epsilon))y\} \quad (1)$$

where

$$\epsilon^2 = 1 - (I_2^2 / (I_0 I_4)) \quad (2)$$

$$y = I(t) / \sqrt{I_0} \quad (3)$$

$$I_0 = (1/2\pi) \int_0^\infty |H(s)|^2 K d\omega \quad (4)$$

$$I_2 = (1/2\pi) (1/4\pi^2) \int_0^\infty |H(s)|^2 K d\omega \quad (5)$$

$$I_4 = (1/2\pi) (1/16\pi^4) \int_0^\infty |H(s)|^2 K d\omega \quad (6)$$

$I(t)$ is the random vibration. $H(s)$ is given by the following equations for the earthquake motion, and the response of the building structure and the appended structure respectively. K is a constant related with constant power spectrum at the bottom of the base. ω is circular frequency, and $s = j\omega$ as j is unit of imaginary.

$$H(s) = H_g(s) \quad (7)$$

$$H(s) = H_b(s) H_g(s) \quad (8)$$

$$H(s) = H_m(s) H_g(s) \quad (9)$$

where

$$H_g(s) = (2\omega_g h_g s + \omega_g^2) / (s^2 + 2\omega_g h_g s + \omega_g^2) \quad (10)$$

$$H_b(s) = (2\omega_b h_b s^3 + (\omega_b^2 \cdot 2\omega_m h_m + \omega_m^2 \cdot 2\omega_b h_b) s^2 + (\omega_b^2 \cdot 2\omega_m h_m + \omega_m^2 \cdot 2\omega_b h_b) s + \omega_b^2 \cdot \omega_m^2) / \Delta_1 \quad (11)$$

$$H_m(s) = (2\omega_m h_m s + \omega_m^2) / \Delta_1 \quad (12)$$

$$\Delta_1 = s^4 + \{2\omega_b h_b + (1+\gamma)2\omega_m h_m\} s^3 + \{\omega_b^2 + (1+\gamma)\omega_m^2 + 2\omega_m h_m \cdot 2\omega_b h_b\} s^2 + (\omega_b^2 \cdot 2\omega_m h_m + \omega_m^2 \cdot 2\omega_b h_b) s + \omega_b^2 \omega_m^2 \quad (13)$$

h is damping ratio, γ is mass ratio of the appendage structure to the main building, and the suffix b and m denote the building and the appendage.

2.2 The Case of Two Ground Predominant Periods

Fig.2 and Fig.3 depict a standard acceleration spectrum by the simulation process for the respective structural system [6]. The spectrum can be also given in form of table. The spectrum in the former shows simple shape with single peak, when the natural period of the building structure agrees with the ground predominant period. It covered the spectra for many earthquake motions as an envelope. The spectrum for earthquake motion usually have several peaks and the magnitudes of the peaks are likely to be lower than that of the simulated spectrum. The effect of the parameters to the spectrum, which cannot be easily found in the spectra for the earthquake motion because of obscure frequency characteristic of the earthquake motion, can be identified by this theoretical approach especially for the appendage system in which number of the parameters increases. The extent that magnitude of the spectrum for the simulated earthquake is larger than that for the earthquake motion where

the natural periods of the respective structure systems are made equal is intensified.

These discrepancies were given explanation by assuming two ground predominant periods in the simulation process aforementioned, that is, instead of eq. (10) the following relation was utilized as the simplest example [7] [8].

$$H_g(s) = \{(2\omega_{g1}h_{g1}s + \omega_{g1}^2)/(s^2 + 2\omega_{g1}h_{g1}s + \omega_{g1}^2)\} + \lambda \{(2\omega_{g2}h_{g2}s + \omega_{g2}^2)/(s^2 + 2\omega_{g2}h_{g2}s + \omega_{g2}^2)\} \quad (14)$$

The suffix 1 and 2 represent the first and the second system of the ground predominant period and λ gives a parameter specifying the contribution of the second system.

Taking the natural periods of the simulated process equal to these for earthquake motion and choosing adequate λ , the shape and the magnitude of the spectrum could be made agree with that for the earthquake motion. The magnitude of the spectrum for the appendage system where the natural period of the system was equal to that of the building and one of the ground predominant period remarkably diminishes and agreed well with that for earthquake motion again. The analysis made it obvious that the coexistence of the plural components of the ground predominant period diminished the magnitude of the acceleration amplification factor.

The result also suggests that there would be a simpler method summing the spectrum for the respective period component. A simple method to simulate a specific response spectrum based on the principle of SRSS was investigated. As the amplification factor for the original estimate, the evaluation by the single ground predominant system which was shown in Fig.2 for the building structure and in Fig.3 for the appendage structure respectively was used.

3. A Simple Method Estimating the Response Spectrum Based on a Standard Spectrum [9]

Fig.4 shows a flow chart of the procedure of this method for the building structure. The method applied for composing the spectrum equivalent to that of El Centro would be summarized. The ground predominant periods T_{g1} and T_{g2} can be given as 0.25s and 0.5s for the spectrum of El Centro. For $T_b=0.2s$ where T_b is natural period of the building structure the acceleration amplification factor can be given as follows from the spectrum as Fig.2 or table,

$$T_b/T_{g1}=1.0 : A_{b11}=2.96 \quad (15)$$

$$T_b/T_{g2}=0.4 : A_{b21}=1.64 \quad (16)$$

The damping ratio of the structure is now given as $h_b=0.07$. If the contribution of a factor to the total sum of the respective factors is represented by η , the amplification factor at $T_b=0.2s$, $A_{T_b=0.2}$ can be estimated by the method of SRSS,

$$A_{T_b=0.2} = \sqrt{(A_{b11})^2 + \eta^2 (A_{b21})^2} / \sqrt{1 + \eta^2} \quad (17)$$

The same procedure can be followed for $T_b=0.5s$. The amplification factors for the basic spectrum are given as

$$T_b/T_{g2}=2.5 : A_{b21}=1.41 \quad (18)$$

$$T_b/T_{g1}=1.0 : A_{b22}=2.96 \quad (19)$$

as the factor at $T_b=0.5s$, $A_{T_b=0.5}$, is obtained as

$$A_{T_b=0.5} = \sqrt{(A_{b21})^2 + \eta^2 (A_{b22})^2} / \sqrt{1 + \eta^2} \quad (20)$$

Referring to the spectrum for El Centro, the amplification at these periods are equal, then

$$A_{T_b=0.2} = A_{T_b=0.5} \quad (21)$$

η can be obtained by solving this equation. Then the estimate of the spectrum is made by using this η .

Fig.5 compares thus estimated spectrum with that for the earthquake motion. This illus-

trates that the former derived by the proposed simple method fits well with the latter. It also means that the estimated spectrum agrees well with that by the spectrum due to the simulated earthquake assuming two ground predominant periods, which required much more complicated computation procedure. It is feasible to take the effect of more than the third ground predominant period into consideration by this method, which was impossible by the theoretical approach aforementioned.

The method is applicable to estimate the spectrum as for the appendage system attached to the building structure, which is represented by two-degrees-of-freedom system and the mass ratio of the appendage system to that of the main system is very small. Statistically estimated response spectrum assuming the single ground predominant period is also dealt with as the standard spectrum, and η obtained by eq. (27) is also used.

Again the spectrum by El Centro is taken as an example. The spectrum is obtained by that the natural period of the appended structure T_m is varied around that of the building structure T_b . The spectrum of $T_b=0.2s$ in which $T_m=0.2s$ makes the maximum acceleration amplification factor is discussed. If the system parameters are given as $\gamma=0$, $h_{b2}=0.07$ and $h_m=0.02$, for two ground predominant period $T_{g1}=0.2s$ and $T_{g2}=0.5s$, so that

$$A_{m1}=37.2 \quad \text{for } T_b/T_{g1}=1.0 \quad (22)$$

$$A_{m2}=14.5 \quad \text{for } T_b/T_{g2}=0.4 \quad (23)$$

are extracted by the table of the standard spectrum due to the theoretical computation.

If the amplification factor of the building structure is represented by A_{T_b} , for T_{b1}/T_{g1} and $A_{T_{b2}}$ for T_{b2}/T_{g2} , the allocated amplification factors to the appendage system A_{app1} and A_{app2} for the respective combination of the natural period of the system, which can be considered as the independent mode of vibration, are described as follows,

$$A_{app1}=A_{m1}/A_{T_{b1}} \quad (24)$$

$$A_{app2}=A_{m2}/A_{T_{b2}} \quad (25)$$

The effect of two ground predominant periods is evaluated again by the method of SRSS of the factors for the respective modes of vibration, so that the synthesized amplification factor A_{app} is provided by

$$A_{app}=\sqrt{(A_{app1})^2+\eta^2(A_{app2})^2}/\sqrt{1+\eta^2} \quad (26)$$

It is shown that the evaluation of the spectrum which is obtained by varying the period agrees well with that by El Centro in its magnitude and shape.

4. Extensive Application of the Simple Method for Multi-Degrees-of-Freedom System

4.1 Description of the Basic Parameters and Application for Building Structure System

In this paper the method is extensively applied for the analysis of the building structure of multi-degrees-of-freedom system and the appendage structure to the any floor of this building structure. The example of the analysis is performed by a building structure of two-degrees-of-freedom system.

The distribution of stiffness of the building structure is assumed so that the mode of the first natural frequency may be a triangular as shown in Fig.6 (a). The equations of motion for multi-degrees-of-freedom system without dynamically coupled term are given [10] as

$$m_j \ddot{x}_j + \sum_{k=1}^n (c_{jk} \dot{x}_k + k_{jk} x_k) = -m_j \alpha(t) \quad j=1, 2, \dots, n \quad (27)$$

where m is mass, k is stiffness, c is damping coefficient and $\alpha(t)$ is ground acceleration. The suffix j denotes the number of the mass. For the simplicity m_1 is taken to be equal to m_2 for the two-degrees-of-freedom system to be analyzed. The relation between k_1 and k_2 can be

given as

$$k_2 = (2/3)k_1 \quad (28)$$

in order to satisfy the mode shape of vibration. The first and the second natural circular frequencies ω and ω are obtained as

$$\omega_1 = (1/\sqrt{3})\sqrt{k_1/m_1} \quad (29)$$

$$\omega_2 = \sqrt{2} \cdot \sqrt{k_1/m_1} \quad (30)$$

As the relation between the first and the second natural period T_I and T_{II} ,

$$T_{II} = T_I / \sqrt{6} \quad (31)$$

can be derived.

The normal function ψ_{jP} , where p denotes the mode of vibration, which is given by substituting the natural frequency into the characteristic equation is given as follows,

$$\psi_{1I} / \psi_{2I} = 1/2 \quad (32)$$

$$\psi_{2I} / \psi_{2II} = -2.0 \quad (33)$$

This gives the respective mode shape for the natural frequency. The participation function ϕ_{jP} is evaluated by these relations as

$$\phi_{jP} = \left[\left\{ \sum_{j=1}^n m_j \psi_{jP} \right\} \left\{ \sum_{j=1}^n m_j \psi_{jP}^2 \right\} \right] \psi_{jP} \quad (34)$$

The normalized damping ratio h_P is assumed as

$$h_P = c_P / (2m_P \omega_P) \quad (35)$$

where

$$c_P = \sum_{j=1}^n \sum_{l=1}^n c_{j,l} \psi_{jP} \psi_{lP} \quad (36)$$

$$m_P = \sum_{j=1}^n m_j \psi_{jP}^2 \quad (37)$$

$$k_P = \sum_{j=1}^n \sum_{l=1}^n k_{j,l} \psi_{jP} \psi_{lP} \quad (38)$$

$$\omega_P = \sqrt{k_P / m_P} \quad (39)$$

Fig.7 shows a flow diagram describing the procedure of the method to estimate the amplification factor or the response spectrum without making the time historical response computation as for the system shown in Fig.6. In the box (1) the response spectra with the normalized damping ratios of the respective modes of vibration are obtained according to the method developed for the building structure of single-degree-of-freedom system which is mentioned in the chapter 3. The coefficient of the contribution of the higher mode to the total amplification factor η_P is estimated for the respective mode of vibration. Only when the spectrum to be estimated is compared with that for earthquake motion, it is required that the response spectrum for the earthquake motion is given by time historical computation for the normalized damping ratio.

In the box (2) the amplification factor for the respective modes of vibration is estimated by making use of η_P and the principle of SRSS. The amplification factors of the respective modes are obtained from the table aforementioned taking the ratio of the natural period to the ground predominant period as the parameter. The amplification factors for the respective masses of the building structure are obtained by the equation in the box (3). It is again based on the same principle of computation SRSS although the participation function is taken into account.

Fig.8 compares the spectrum of the system for El Centro with the estimated one. The damping ratio of the first and the second mode are given as $h_1=0.04$ and $h_2=0.09$. Good agreement is obtained as for the magnitude of the amplification factor at $T_1=0.2s$ and $0.5s$, and

the shape of the spectrum. The estimate due to the method is larger around the period where the spectrum for the earthquake motion shows trough $T_I=0.3s$. This provides an estimate in safety range as the evaluation of the practical aseismic design.

4.2 Application for the Estimate of the Floor Response Spectrum

The method is developed to apply for the appendage structure system which is attached to the floor of the building system above analyzed, which corresponds to the respective masses. The response analysis of such system has been made by so called floor response analysis. The acceleration response of the floor by time historical computation is made input to the appendage structure which is attached to the floor. The method stated in this paper saves the time historical computation.

Fig.9 illustrates the procedure newly developed to simulate the floor response spectrum of the appendage structure. η_p is obtained in the box (1), which is same procedure as the case for the building structure of the multi-degrees-of-freedom system. In the box (2) the amplification factor allocated to the appendage system for the respective modes of vibration of the building structure is estimated. The amplification factor of the appendage to the first and the second mode of the building structure can be given by the table same as the spectrum shown in Fig.3. It is given in term of the parameters T_m/T_g , T_p/T_g , h_m , h_b and γ . The allocated amplification factor is derived by F_{Am}/F_A where F_{Am} is the amplification factor of the appendage structure and F_A is that of the building structure. The effect of the composition due to the first and the second ground predominant period is introduced by the principle of SRSS. This is performed for the respective modes of vibration.

In the box (3) the participation function is introduced and the same principle is applied for summing the effect of the respective modes, and the allocated amplification factor of the j th mass to the first mass is estimated. If the amplification factor of the building structure of single-degree-of-freedom is multiplied by the allocated factor to be concerned with, the amplification factor of the appendage structure is obtained. The floor response spectrum is estimated by varying T_m .

Fig.10 compares the estimated spectrum of the appendage structure to the first and the second mass with those for El Centro. The natural period of the first mode T_{b1} is taken as $T_{b1}=0.2s$. The peaks at $T_{b1}=0.2s$ means that T_m , T_b and T_g are set equal. In the range of shorter period the levels of the spectrum due to two methods are almost equal. In the range of longer period the amplification factor for the appendage attached to the upper mass is estimated larger than that for the earthquake motion. It is probable to be estimated over by the principle of SRSS because it is not satisfied by the empirical law. It would be necessary to keep on noticing this by increasing the example in future.

Fig.11 shows another example for $T_{b1}=0.5s$. T_{b1} is obtained as $T_{b1}=0.204s$. This is the case that the first natural period of the building structure is made equal to the longer ground predominant period. The second natural period of the structure is by chance nearly equal to the shorter ground predominant period. Good agreement is also obtained where the natural period of the appendage is made equal to that of the first natural period of the building structure. The spectrum shows another small peak where the natural period of the appendage structure is equal to the second natural period of the building structure. The tendency that the amplification factor of the appendage attached to the first mass of the building becomes larger than that to the second mass is similar. The estimated spectrum by

the method fit well with that by the earthquake motion in its magnitude and shape as well as the case for the principal peak.

The agreement of the estimated spectrum with that by the earthquake motion shown in Fig.10 and Fig.11 should be mentioned conspicuously good taking it into consideration that the estimate due to the developed method is made without performing the time historical computation except the spectrum for the single-degree-of-freedom system.

5. Conclusions

The following conclusions can be obtained from the investigation.

- 1) The simple method to estimate response spectrum based on the standard spectrum which is statistically evaluated due to random vibration theory was developed. It was first applied to the analysis of the building structure represented by single-degree-of-freedom system and the building-appendage structure represented by two-degrees-of-freedom system, and was extensively applied to the analysis of building structure described by multi-degrees-of-freedom system and the appendage structure attached to this multi-degrees-of-freedom system. It was shown that the spectrum by this method could well estimate that by the earthquake motion.
- 2) The response characteristic of the appendage structure has been evaluated by the so called floor response spectrum which requires time historical computation. It was made obvious that the method saved the time historical computation in estimating the floor response spectrum analysis. At the moment the response spectrum analysis on the basis of the time historical computation is performed as for the analysis of the building structure of the single-degree-of-freedom system. If the spectrum of the single-degree-of-freedom system is described by a standard or averaged one, the other spectrum for the complex system would be obtained only by the procedure developed in the paper. This also has advantage that the estimated spectrum naturally provides the statistically averaged characteristic instead that the spectrum by the time historical computation gives fluctuation. The method would be effective in providing the seismic coefficient simply and reliably in the procedure of the practical aseismic design.

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Fig.1 Model scheme of structure and ground characteristic system to be analyzed

Fig.2 An example of standard response spectrum of the building structure estimated for the simulated earthquake

Fig.3 An example of standard response spectra of the appendage structure estimated for the simulated earthquake

Fig.4 Flow chart of the simple method for the building structure

Fig.5 Comparison of the response spectrum of the building structure by the simple method with that by the earthquake motion

Fig.6 (a) Model scheme of the building structure of two-degree-of-freedom
(b) Mode shape of the first natural period

Fig.7 Flow chart of the simple method for the building structure of multi-degrees-of-freedom

Fig.8 Comparison of the response spectrum by the simple method with that by the earthquake motion for two-degrees-of-freedom

Fig.9 Flow chart of the simple method for the appendage structure attached to the building structure of two-degrees-of-freedom

Fig.10 Comparison of the response spectrum by the simple method with that by the earthquake motion for the appendage structure ($T_{b1}=T_{g1}$)

Fig.11 Comparison of the response spectrum by the simple method with that by the earthquake motion for the appendage structure ($T_{b1}=T_{g2}$)