Summary of Research on Site Response Analysis

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Abstract. A large number of seismic observation data and macroscopic survey of earthquake damage indicate that soil site may amplify the intensity of ground-motion and thus aggravate the damage to the structures on the soil site[1]. The influence of site response on ground motion is one of the most important topics in earthquake engineering. The methods of predicting the site effects can be divided into two groups with respect to theoretical methods and empirical methods. The theoretical methods of predicting site effects are to analyse the site response to ground motion based on the theory of seismic wave propagation in which the detailed soil information is required. Whereas the empirical methods predicting the site effects by empirical prediction model which is determined using observed seismic data or ground pulsation data. According to whether the reference site is introduced, the empirical methods can be further divided into the reference site method and the non-reference site method. This article introduces in detail the principles, advantages and disadvantages of various methods of analysing site effects, which is of reference value for further research on site ground motion response.

1. Introduction

Through the analysis of seismic observation data and the investigation of earthquake damage, we can know that the intensity of ground motion is closely related to the geological conditions of the shallow overburden layer, and the local site response may enlarge or reduce the intensity of ground motion, which directly affects the degree of earthquake damage[2]. As early as the 1906 San Francisco earthquake, researchers found that the damage degree of buildings on soft sediments was 5-10 times higher than that of similar buildings about a mile away but built on hard soil or rock[3]. In 1967, Venezuela earthquake (M = 6.5) caused a lot of casualties. The buildings in Karax City were seriously damaged, and the damage degree was related to the thickness of the overburden layer: the buildings on the shallow site were basically intact, and the damage rate of the buildings with the thickness of 160 ~ 230m reached 75%, however, the damage rate of the buildings with the thickness of 230 ~ 300m even reached 80% [4]. The 1989 Loma Prieta earthquake with Ms7.0 also shows that the soft soil site has a significant amplification effect on the ground motion[5, 6], the peak ground acceleration of bedrock site and soft soil site in San Francisco Auckland area are about 0.08g and 0.20g respectively. Compared with the bedrock site in San Francisco Bay, the seismic intensities of treasure island and Auckland soft soil site are more than three times larger[6, 7]. Obviously, the ground motion on the thick overburden layer in the San Francisco Bay area was amplified[8]. Similar phenomena is seen in the Mexico earthquake in 1985[9, 10], 1999 Chi-Chi earthquake in Taiwan[11, 12], Northridge earthquake in 1994[13, 14]and 2011 3.11 Great Tohoku Earthquake in Japan[15, 16]. Through the above macro seismic damage and the actual observation records, it is seen that the site effects on ground motion are significant, and the influence of site effect should be fully considered in the design of engineering structures[17].

2. Research status

Many scholars at home and abroad have carried out a lot of research work on site effects after wood realized that site conditions have an important impact on seismic damage by analysing the seismic damage data of San Francisco earthquake. Seed proposed the equivalent linearization method for site response analysis in 1968 and compiled the corresponding calculation program SHAKE[18]. SHAKE2000 is the most popular one-dimensional equivalent linearization program in the world. Academician Liao of China also studied the equivalent linearization program and gave the equivalent linearization program LSSRLI-1 for soil layer response analysis in China[19]. LSSRLI-1 is the preferred calculation method for soil layer seismic response analysis in seismic zoning and seismic safety evaluation of major projects in China. In view of the inaccuracy of the calculation results under the conditions of soft soil site and strong ground motion, Sugito compiled FDEL soil response analysis program considering the correlation

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between equivalent shear strain and frequency[20]. Yoshida [21]improved FDEL with different frequencies and different calculation formulas, which improved the problem of insufficient high frequency amplification to a certain extent. In view of the unsolved problems such as "short and thick" in the calculation results of ground motion of soft soil layer and the lack of high-frequency components in the equivalent linearization of hard soil, researcher Yuan[22] adopted a new direct frequency method to solve the dynamic shear modulus damping ratio and proposed a new generation of soil seismic response calculation method SOILQUAKE. Compared with SHAKE2000 and LSSRLI-1, SOILQUAKE has the same precision in hard field, significant advantage in soft field, and significant advantage in thick field.

Because the stress-strain relationship of soil is nonlinear and hysteretic when the shear strain is greater than 10^{-5}-10^{-4}[23-26], the equivalent linearization method can not truly reflect the nonlinear characteristics of soil. The calculation results are unreasonable when the ground motion is strong and the soil layer is soft. The nonlinear method takes the dynamic constitutive model of soil as the core, which truly reflects the dynamic characteristics of soil under earthquake and other dynamic loads. DEEPSOIL is the most widely used time-domain nonlinear program in the world.

Theoretically speaking, the time-domain fully nonlinear calculation method can reflect the whole process of ground motion, which is more in line with the actual situation. However, due to its relatively low calculation efficiency and involving the dynamic stress-strain constitutive relationship of soil, it is difficult to be popularized in practical engineering applications. The equivalent linearization method is still the most widely used and mainstream calculation method.

In recent years, with the development of strong motion observation technology, more and more strong motion records are collected in destructive earthquakes and applied to the research of site effect. Because it doesn't need too many assumptions and complicated calculation process and the data are from field observation, the results are more authentic, so the empirical method based on strong motion records is more and more recognized and widely used. According to whether the reference site is introduced, the empirical method can be further divided into the reference site method and the non-reference site method [27]. Borcherdt[28] proposed the reference site method for the first time, also known as the traditional spectral ratio method, which is one of the most common methods to study the site response. This method needs to select a site as the reference site, because it is theoretically considered that the site response at the ideal bedrock is constant and does not change with frequency. Therefore, the site of the outcrop bedrock station is usually selected as the reference site. The ratio of the observation value of the target site station to the observation value of the reference site station is used as the estimation of the site amplification effect. Andrews[29] proposed the linear inversion method by extending the traditional spectral ratio method and separated the source, propagation path and site response from the strong earthquake records at the same time through the generalized inversion technology. The linear inversion method is also one of the most popular methods. Traditional spectral ratio method and linear inversion method are two methods of reference field method. In practical application, it is difficult to find an ideal reference site, so many scholars have studied the non- reference site method. Moya and Irikura[30] put forward the reference event method. This method selects an event recorded by most stations and uses the known source model constraint for its source shape, that is, uses the reference event constraint rather than the reference site constraint to analyse the site response. The most widely used non-reference field method is HVSR method[31], i.e. horizontal vertical spectral ratio method. However, the amplification value of site response obtained by HVSR method is quite different from that obtained by other methods. It is generally considered that HVSR method is more reliable in estimating site predominant period[32].

3. Formatting the text

3.1. Theretical method

The existing seismic response analysis methods of soil layer can be roughly divided into equivalent linearization method in frequency domain and nonlinear method in time domain. Among them, the equivalent linearization method is widely used.

The stress-strain relationship of soil under the action of seismic wave is a complex hysteretic curve, and the size, shape and orientation of each loop are variable. The basic idea of the equivalent linearization method is to use an equivalent steady-state loop to approximately represent the average relationship of all loops. In the equivalent linearization method, an initial equivalent shear strain is given, and the shear modulus and damping ratio are determined according to the initial shear strain. The dynamic equation is solved according to the new shear modulus and damping ratio, and the above process is repeated until the error of two adjacent calculations reaches the allowable range.

The advantage of equivalent linearization are that the concept is simple and easy to understand, the soil calculation parameters are complete, and the amount of calculation is small. When the earthquake intensity is relatively small, the calculation results are basically consistent with the actual records. The disadvantages are: the equivalent linearization method can not reflect the real movement process of soil layer. When the earthquake intensity is large, the calculation error is large, and when calculating the soft soil site, the error is also large.

A large number of researchers have found the real evidence of site nonlinear response by using different methods[33-36], so the nonlinear properties of soil layer must be considered in the study of site effect. The nonlinear method assumes that the seismic shear wave propagates vertically through the horizontal soil layer, the particle only moves in the horizontal direction, and the stress-strain relationship of the soil layer is nonlinear. The nonlinear hysteretic constitutive model is used to simulate the dynamic stress-strain relationship of each soil layer. The representative program of nonlinear method is DEEPSOIL.

The advantage of non-linear method is that it can simulate the movement of soil layer. In the case of soft soil site and strong earthquake, it can get more accurate analysis and solve the problem of inaccurate high-frequency estimation results in the equivalent linearization method. The disadvantage is that the nonlinear analysis considers many factors and inputs many parameters, so it takes up a lot of memory in numerical calculation, and the accuracy of nonlinear method is related to the accuracy of soil constitutive model, so it is limited in practical application.

3.2. Empirical method

3.2.1 Traditional spectrum ratio method

The traditional spectrum ratio method, also known as the reference field method, was first proposed by Borcherdt[28] and is currently one of the most common methods for studying site response. The traditional spectral ratio method needs to select a station located at the outcrop bedrock as the reference station. Since it is assumed that the site response of the ideal bedrock position is a constant that does not change with frequency, the difference between the target station and the reference station is the local site response value. The traditional spectral ratio method has a clear physical basis and can well identify the predominant period of the site. The spectrum value recorded during the earthquake can be written as:

$$O_{ij}(f) = S_i(f) \cdot P_{ij}(f) \cdot G_j(f) \quad (1)$$

path item $P_{ij}(f)=R_{ij}^{-1}\exp(-\pi f R_{ij}/Q(f)\cdot V_s)$, $S_i(f)$ is the source spectrum of the i-th earthquake; $G_j(f)$ is the ground motion response spectrum of the j-th station. $P_{ij}(f)$ is the propagation path term between the i-th earthquake and the j-th station; R_{ij} is the focal distance from the i-th earthquake source to the j-th station; $O_{ij}(f)$ is the ground motion observation spectrum (acceleration spectrum, velocity spectrum or displacement spectrum) of the i-th earthquake recorded by the j-th station; $Q_s(f)$ is the frequency-dependent S wave quality factor; Since the reference station is selected at the adjacent bedrock station, It is believed that $P_{ij}(f) \cong P_{ir}(f)$.

The traditional spectrum ratio method is to calculate the Fourier spectrum ratio of S wave between the j-th station and the reference station r in the same earthquake

$$\frac{O_{ij}(f)}{O_{ir}(f)} = \frac{S_i(f)\cdot P_{ij}(f)\cdot G_j(f)}{S_i(f)\cdot P_{ir}(f)\cdot G_r(f)} \quad (2)$$

Because the same earthquake has the same source term and ignores the influence of the propagation path term near the reference station, the above formula can be written as follows:

$$\frac{O_{ij}(f)}{O_{ir}(f)} = \frac{G_j(f)}{G_r(f)} \quad (3)$$

The traditional spectral ratio method can well estimate the site amplification effect when the reference site is near the studied soft soil field and the site response of the reference site is a constant that does not change with frequency[27, 37-41]. Considering the amplification effect of free surface on seismic wave, some scholars set the site response as 2 [42-44]. However, it is difficult to find an ideal site as a reference site due to weathering in practical applications[45, 46], and the selected reference site will have site amplification that varies with frequency. Therefore, the estimation of site amplification by using the reference site method will be inaccurate due to the site amplification of the reference site itself. Steidl et al. [45] put forward a method which is helpful to find the ideal reference field, that is, to select the seismic station at the bottom of the deep well as the reference station. They think that the site at the bedrock has no amplification effect on the seismic wave, and the ratio of Fourier spectrum recorded on the well to that recorded underground can be used to characterize the site amplification. Many countries and regions (such as the United States, Japan, China, etc.) have set up many arrays, which makes it possible to use underground stations as reference sites to estimate site amplification.

3.2.2 Generalized Inversion Technique

Andrews[29] developed the linear inversion method based on the traditional spectral ratio method through the generalized inversion technique. This method can separate source term, propagation path and site response from strong earthquake records at the same time. Different from the traditional spectral ratio method, the effect of propagation path term is not ignored. Tomotaka and Iwata[47] improved it to make it more reasonable and widely used in the world.

The ground motion observed on the surface is the product of the source, path and site in the frequency domain

$$O_{ij}(f) = S_i(f) \cdot P_{ij}(f) \cdot G_j(f) \quad (4)$$

Among them, $O_{ij}(f)$ is the Fourier spectrum of the ground motion observed by the j-th station in the i-th earthquake. $S_i(f)$ i s the source spectrum of the i-th earthquake; $G_j(f)$is the site response of the j-th station; $P_{ij}(f)$ is the path effect from the j-th station to the i-th earthquake epicenter.Assuming that the source is a point source, the attenuation of ground motion can be divided into two parts composition: Geometric diffusion and Inelastic loss; So $P_{ij}(f) = R_{ij}^{-1}\exp(-\pi f R_{ij}/Q(f)\cdot V_s)Q(f)$; V_s is the shear wave velocity of the medium. Therefore, equation (4) can be expressed as follows:

$$O_{ij}(f) = S_i(f)\cdot G_j(f)\cdot R_{ij}^{-1}\cdot \exp(-\pi f R_{ij}/Q(f)\cdot V_s) \quad (5)$$

After taking logarithm, the above formula can be expressed in the form of linear addition

$$ln\left(O_{ij}(f)\right) + lnR_{ij} = ln(S_i(f)) + ln\left(G_j(f)\right) - \pi f R_{ij}/Q(f) \quad (6)$$

Equation (6) is actually a system of linear equations, which contain i+j+1 unknowns. The least square solution can be obtained by singular value decomposition.

The advantage of the linear inversion method is that the quality factor QS of S wave and the ground motion response of the site can be obtained simultaneously. Because the linear inversion method also needs to select the reference site, the selection of the reference site limits the wide application of the linear inversion method.

3.2.3 reference event method

In view of the limitation of selecting a single station, Aaron, Moya and Kojiro [30] proposed a reference event method, that is, to analyse site response with reference event constraint instead of reference site constraint. The calculation idea of reference event is as follows:

The Fourier spectrum ratio of the same earthquake recorded by two stations is

$$\frac{O_{ij}(f)}{O_{ir}(f)} = \frac{G_j(f)R_{ij}^{-1}\,exp(-\pi f R_{ij}/Q(f)V_s)}{G_r(f)R_{ir}^{-1}\,exp(-\pi f R_{ir}/Q(f)V_s)} \quad (7)$$

The above formula can be changed to

$$O_{ir}^{ij}(f) = G_r^{j}(f)R_{ij}^{ir}\,exp(-\pi f(R_{ij}-R_{ir})/Q(f)V_s) \quad (8)$$

where $O_{ir}^{ij}(f)$ is the ratio of the observed spectra of the ith event at the jth site with respect to the divisor site r, and $G_r^{j}(f)$ is the ratio of the site effects. Taking logarithms on both sides,

$$ln[G_r^{j}(f)] - \frac{\pi f(R_{ij}-R_{ir})}{Q(f)V_s} = ln[O_{ir}^{ij}(f)R_{ir}^{ij}] \quad (9)$$

The above formula can be written in the form of matrix

$$[\boldsymbol{A}] \bullet [\boldsymbol{x}] = [\boldsymbol{b}] \quad (10)$$

The above formula can be written as

$$\ln[G_j(f)] - ln[\,G_r(f)] - \frac{\pi f(R_{ij}-R_{ir})}{Q(f)\beta} = ln[\,O_{ir}^{ij}(f)R_{ir}^{ij}] \quad (11)$$

However, formula (11) is lack of constraints. If the constraints are not added, the site response can not be obtained. The reference event method is to select the reference item as an event rather than a station. The source model Si (f) is used to constrain the source shape of the reference event. If most stations record a certain seismic event, and the seismic moment and corner frequency of the event are known, the event is selected as the reference event. For the reference event method, the following formula has two unknowns $G_j(f)$ and $Q(f)$.

$$O_{ij}(f) = S_i(f)G_j(f)R_{ij}^{-1}\,exp(-\frac{\pi R_{ij} f}{Q_s(f)V_s}) \quad (12)$$

Take the logarithm of both sides of the pair

$$\ln[G_j(f)] - \frac{\pi f R_{ij}}{Q(f)\beta} = ln[\,O_{ij}(f)R_{ij}] - ln[\,S_i(f)] \quad (13)$$

Modify the formula **[A] [x] = [b]** to include (11) and (13), we get:

$$\begin{bmatrix}\boldsymbol{A}\\ \boldsymbol{c}\end{bmatrix}[\boldsymbol{x}] = \begin{bmatrix}\boldsymbol{b}\\ \boldsymbol{d}\end{bmatrix} \quad (14)$$

The solution method is the same as the linear inversion method.

The reference event method assumes a source model as the source spectrum shape of the reference event to obtain the site response amplification value and Q_S value. However, the accuracy of calculation results is limited by the correctness of source model selection.

3.2.4 HVSR method

Nakamura [31] proposed a method to estimate site response using Rayleigh waves of land pulsation, i.e. horizontal / vertical spectral ratio technique, which has been widely used in site amplification research. Lermo [48] extended this H/V method to seismic S-wave, and developed the theoretical background for using SV wave numerical simulation technology. HVSR method does not need site parameters [49] and can estimate site effects by using background noise or seismic records. Therefore, HVSR method is widely used because of its high cost-effectiveness[50].

The principle of HVSR method is as follows

$$HVSR(f) = \frac{H(f)}{H_b(f)} \bullet \frac{H_b(f)}{V_b(f)} \bullet \frac{V_b(f)}{V(f)} = \frac{HVSR_b(f)}{SBSR_V(f)} \bullet SBSR(f) \quad (15)$$

Where $HVSR_b(f)$ represents the spectral ratio of the horizontal and vertical directions of the borehole. $H(f)$ represents the Fourier spectrum in horizontal direction, $V(f)$ represents the Fourier spectrum in vertical direction, and b represents the borehole.

Nakamura made two assumptions when he proposed HVSR method: 1. In bedrock, the wave propagation is uniform in all directions, that is, the horizontal and vertical spectrum are equal ($HVSR_b(f)$= 1). 2. The second assumption is that the vertical component of seismic wave is not affected by local site effect, that is, $V_b(f)$=$V(f)$ or $SBSR_V(f)$ = 1, so HVSR can represent the horizontal site amplification.

Since HVSR method was put forward, it has been widely used in engineering because of its simplicity and practicality. However, this method and its two prerequisites have been the object of controversy for researchers at home and abroad in recent years. Many studies [51] confirmed that $HVSR_b$ can be approximated by a constant close to unity. However, some demonstrated that $SBSR_V(f)$ = 1 does not hold at most sites, so prominent vertical amplification ($SBSR_V$) is the main reason for the underestimation of HVSR to SBSR at relatively high frequencies. Therefore, it is generally believed that HVSR method can obtain a reliable estimation of the site predominant period. Chávez-García ,Domínguez, and Rodríguez [32] pointed out that HVSR can provide reliable predominant frequency results only when the impedance ratio is large; but when the site response is caused by more complex local geological conditions, the results of HVSR are very unreliable and its applicability is questioned.

4. Conclusion

Site seismic response is one of the most important research topics in seismic engineering. The damage degree of building structures on different sites is different under the same earthquake. The study of site effect can be divided into theoretical method and empirical method. On the basis of known detailed soil parameters, theoretical methods establish a calculation model based on seismic wave propagation theory to solve the ground motion response. The existing seismic response analysis methods of soil layer can be roughly divided into equivalent linearization method in frequency domain and nonlinear method in time domain. Among them, the equivalent linearization method is the mainstream calculation method which is widely used, but the equivalent linearization method is a rough estimate of the nonlinear characteristics of soil, which can not fully reflect the real motion state of soil under the action of ground motion. To solve this problem, it is necessary to analyse the nonlinear seismic response of soil layer, the core of which is to develop a simple and practical soil dynamic constitutive model.

The empirical method is to estimate the site amplification effect by using the actual ground motion observation data or the ground pulsation data. According to the need of introducing reference site, the empirical method can be divided into reference site method and non-reference site method. The traditional spectral ratio method and linear inversion method are two methods of reference field method. The traditional spectral ratio method has clear physical meaning and simple calculation, but its practicability is limited by the reference site. The advantage of the linear inversion method is that it can reflect the crustal quality factor and site effect at the same time, and calculate the predominant period of the site. However, due to the difficulty of selecting the reference site, its application is limited. As a non-reference site method, reference event method uses reference event constraints to analyse site effects. HVSR method is widely used because of its simplicity and practicality. However, many studies have found that the results of site magnification calculated by HVSR method are quite different from those calculated by other methods, and HVSR method is usually used to estimate the predominant period of sites.

In recent years, with the continuous construction of vertical drilling array in China, a large number of strong earthquake observation data have been accumulated, which lays a good data foundation for the further study of site seismic response. Site response analysis can provide a scientific basis for seismic safety evaluation of engineering sites, seismic fortification of buildings and the revision of codes.

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