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Discussion on the Site Effect Coefficient and Topographic Effect Coefficient of Ground Motion Peak Acceleration and Its Relationship

Aijuan Liu¹, Taiping Liu¹, Yulong Cui^{2*} and Hongchun Zheng¹

¹ China Three Gorges Corporation, Beijing, 10038, China

² School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan, Anhui, 232001, China

*Corresponding author's e-mail: ylcui@aust.edu.cn

Abstract. By summarizing the research results of the site effect coefficient and topographic effect coefficient of ground motion peak acceleration, we analyzed the ground motion site effect and topographic effect and concluded that the relationship between site effect and topographic effect was wane and wax and gradually transition. The amplification factor of the peak acceleration of the surface can be calculated by multiplying the site effect coefficient and the topographic effect coefficient. The article proposes to study the site effect coefficient and the topographic effect coefficient in two ways and obtain the function expression. In the introduction of V_s30 , the calculation method of the limits of two effect of V_s30 as the parameter is also proposed. Through the above methods, accurate ground motion peak acceleration can be obtained, which provides support for seismic design, ground motion attenuation relationship research and seismic geological disaster prevention.

1. Introduction

During the process of seismic waves passing from the source to the surface, the propagation medium gradually changes from the bedrock to the soft soil layer; after passing to the surface, it may encounter steep terrain, so the ground motion acceleration value changes, that is, generally an increase effect is produced on the basis of rock acceleration. The influence of the surface soil layer and the undulating terrain on the ground motion acceleration values is represented by the site effect and the topographic effect. However, the exact values of these two types of effects have not been obtained so far, and even whether the origins of the two are the same or whether there is an internal relationship between the two has not been discussed.

For the conceptual description of site effect and topographic effects, some literatures attribute topographic effects to local site effects [1]. In this paper, in order to make the concept clearer, re-discuss the definition of site effect and topographic effects. In general, the site effect refers to the influence of the cover layer on the ground motion parameters transmitted by the bedrock, especially for the deep soil layer, the amplification effect on the seismic wave is very obvious. In areas with deep overburden layers, the general terrain is relatively flat, and the influence of terrain on ground motion is not obvious. The topographic effect refers to the influence of different parts of the steep terrain on the ground motion parameters of the bedrock. In general, towering mountains are formed by geological movements and surface weathering erosion. The surface medium has a hard feature and is closer to the bedrock characteristics, so the site effect caused by the cover layer is less obvious than that of the



topography. In view of the definition of the two, the "Code for Seismic Design of Buildings" also made a statement that "the geomorphological conditions are considered in the topographical conditions and the site soil, and the concept of the geomorphic parts is no longer proposed"[2]. Therefore, the site effect described in this paper refers to the amplification effect of the surface cover layer on the seismic waves transmitted from the bedrock, which is mainly related to the geotechnical properties of the surface; the topographic effect refers to the amplification effect of the steep terrain on the seismic waves transmitted from the bedrock, which is mainly related to the terrain parameters such as slope height and slope.

The actual size of ground motion parameters is of great significance in the establishment of ground motion attenuation relationship and seismic calculation of buildings. There are many research literatures that describe the amplification of ground motion peak acceleration under the influence of site and topographic effects, but relatively accurate data results are not yet available. Determining the amplification effect of the site and the topographic acceleration of the ground motion peak acceleration requires more in-depth research. Finding a method to accurately calculate the peak acceleration of the ground surface has great significance for the study of ground motion parameters. This paper mainly summarizes the influence of site and terrain on the peak acceleration of ground motion, and summarizes the research results of site effect coefficient and topographic effect coefficient. The relationship between the two and the future research ideas provide support for seismic design, ground motion attenuation relationship research and seismic geological disaster prevention.

2. Research results of site effect coefficient and topographic effect coefficient

It has long been recognized that the site and terrain have a certain influence on the ground motion parameters and some regularity is obtained during the later test. However, the theoretical results that can be expressed in the form of coefficients and can be applied to the calculation of regional ground motion parameters are still relatively small.

2.1. Research results of site effect coefficient

The influence of site conditions on peak acceleration is a very complex problem. The essence is to estimate the influence of different site conditions on the input seismic wave intensity. Lu Y.J. found that the site effect of peak acceleration was related to many factors, such as the average shear wave velocity of the site, the input ground motion intensity of the bedrock and the thickness of the rock layer [3]. Chen X.L. and Feng Xi J. both obtained the data results of the amplification factor of the research site [4-5].

It is currently expressed in the form of coefficients and can be applied to regional-wide continuous site effects. The research results mainly use V_{s30} as an independent variable. Table 1 shows the results of the existing site effect coefficient function expression research.

Table 1. Function relation formula of coefficient of site effect already existed

Num	author	Formula	Data sources
1	Jiang Z.J. et al.[6]	$\ln(F_{PGA}) = c_1 \left(\ln \frac{V_{s30}}{V_{ref}} \right)^2 + c_2 \ln \frac{V_{s30}}{V_{ref}} + c_3 + \eta + \zeta$	Strong motion records of main shock and aftershocks of Wenchuan earthquake and some strong motion records from NGA
2	Jiang Z.J. et al.[7]	$\ln(F_{PGA}) = c \times \ln \left(\frac{V_{s30}}{V_1} \right) + (a_1 \times e^{a_2 \times V_{s30}}) \times \ln \left[\frac{PGA_{ref} + f_3}{f_3} \right]$	105 sites borehole data and 897 strong motion records in Sichuan area
3	Shi D.C. et al.[8]	$\log(F_{PGA}) = 1.46 - 0.455 \times \log(V_{s30}) + \sigma$	Shear wave velocity data and strong motion records from K-net and Kik-net Network

Num	author	Formula	Data sources
4	Wang L. et al.[9]	$F_{PGA} = 2.5322[\log(Vs30)]^2 - 15.124\log(Vs30) + 22.37$	Strong earthquakes recorded by the Wenchuan earthquake and the Lushan earthquake

In addition to the $Vs30$ as an independent variable, the F_{PGA} ground motion amplification factor in Equation 1 and Equation 2 is also related to the peak acceleration of the bedrock, and gives different regression coefficients under different site characteristics. Equation 3 and Equation 4 express their relationship with the site amplification factor only with $Vs30$ as a single independent variable.

In the case of the site $Vs30$, using the empirical relationship model formula 1 to formula 4 to analyze the site amplification effect of the bedrock ground motion acceleration, we can estimate the peak acceleration amplification factor. This can reflect to some extent the actual magnitude of the ground motion acceleration from the bedrock to the surface.

For the accuracy of Equation 1 to Equation 4, it can be judged by calculating the site effect coefficient of the actual area. In the literature [10], the site effect coefficient of the slope from Xiluodu to Xinshi Town in the lower reaches of the Jinsha River was calculated by Equation 1. The magnitudes of the 6.9 and 7.3 earthquakes were 1.02~1.37 and 1.02~1.35, respectively. The Equation 3 is used to calculate the site effect coefficient for the same study area in the literature [10]. The maximum value could reach 2~3, and the calculation results of different formulas were quite different. Combined with the research results of Lu Y.J. [3], it can be inferred that equation 1 and equation 2 consider the information of bedrock acceleration, characteristic period of surface rock and soil and $Vs30$ in the fitting process. Therefore, it is possible to more accurately express the amplification effect of ground motion acceleration at different sites during the earthquake. At the current level of research, the impact of the site on ground motion cannot be fully represented by $Vs30$ alone as a single variable. The topographic effect coefficients in equations 1 and 2 are related to a number of parameters, which in principle are more in line with the actual situation.

2.2. Research results of topographic effect coefficient

At present, there are three methods for studying ground motion topographic effects at home and abroad and obtaining test results on the coefficient of variation: actual surface monitoring, physical simulation and numerical simulation.

(1) Actual surface monitoring. The influence of terrain on ground motion parameters was obtained during the Wenchuan earthquake. For example, the peak acceleration ratio of the ground motion of the peak and the foot of Xishan Park in Zigong was up to 1.768 [11-12]; the peak acceleration ratio of ground motion of the peak and the foot of Dourui Mountain was up to 1.82 [12]; the peak acceleration ratio of the ground motion of the peak and foot of Wenxian County was up to 1.5 [13].

Since the measured results are mixed with the comprehensive influence of the site and the terrain on the seismic waves, the number of monitoring data is small, which is difficult to analyze and obtain the general expression of the topographic effect coefficient. Therefore, the current actual surface monitoring method is difficult to use for the estimation of coefficient function expression, which can only be used as a regular cognitive means.

(2) Physical simulation. The physical simulation technology developed in recent years has made the shaking table test an important means of laboratory research on earthquakes. Many scholars have used the vibration table to complete the model test for different types of slopes. The conclusions of the study fully reveal the significant influence of the terrain on the ground motion parameters in the earthquake [14-20]. These research results have obtained a series of numerical results of amplification factors, but the research focus of each model is different, and most of them are for the study of single slope. Therefore, it is difficult to derive a topographic effect coefficient function expression suitable for various slopes.

(3) Numerical analysis. Zhou X.T. used FLAC3D to carry out a large number of numerical

simulations [21]. The results showed that the slope acceleration coefficient could reach 4.49. For the influence of terrain expressed in functional form on ground motion parameters, only Bouchuvalas used numerical simulation to analyze the influence of a large number of terrain conditions on ground motion parameters and summarizes certain rules [22]. And the law is expressed as equation (5) with the terrain magnification factor as a parameter.

$$F = 1 + \frac{0.225 \left(\frac{H}{Vs30 \times T} \right)^{0.4} \left(\frac{I^2 + 2I^6}{I^3 + 0.02} \right)}{1 + 0.9\xi} \quad (5)$$

In the literature [23], the topographic effect coefficient of the slope from Xiluodu to Xinshi Town in the lower reaches of the Jinsha River was calculated by the equation (5), and its value ranged from 1 to 1.45, which confirms that the value does not exceed the conventional range of values and is reasonable.

It can be seen from the above research results that the site effect and the topographic effect have different research systems, and the corresponding coefficient expression function can be obtained. In theory, the coefficient function expression greatly improves the research accuracy of the site and topographic effects, so that as long as the main parameters such as the site $Vs30$ and the bedrock ground motion are known, the ground motion acceleration value transmitted to the surface can be calculated accordingly.

At present, the ground motion site effect and topographic effect use two different research ideas and there are no mature and universal research results. Therefore, how to combine the two to obtain more accurate ground motion parameters considering both the site impact and the terrain impact requires more research.

3. The relationship between site effect and topographic effect in ground motion attenuation and calculation methods in seismic specifications

3.1. Calculation method of ground motion attenuation relationship on site effect

One of the methods for obtaining the peak acceleration distribution in the region is to calculate according to the ground motion attenuation relationship. Many countries in the world have made attenuation equations for their respective regions based on the corresponding ground motion data records. The next generation attenuation relationship study (NGA west) in the western United States represents the research frontier of ground motion attenuation relationships. In the existing peak acceleration attenuation relationship results, the early results mainly consider the magnitude of the epicentral distance, and do not include the impact of the site and terrain; newer research results incorporate site influences into the components of the formula, such as the C-B model established by Campbell [24]. In the attenuation relation expression, $Vs30$ is used as a variable, and the influence part of the site is considered together with other influencing factors in the form of sum.

3.2. Calculation method for two effects of code for seismic design buildings

3.2.1. Code for calculation method of site effects

In the codes for seismic design of various countries, although they all recognize the importance of considering the influence of the site, they have not found a satisfactory implementation method. Taking the code for seismic design buildings as an example, the codes for seismic design recommended by NEHRP in the United States use the two site coefficients of F_a and F_v , and consider the influence of site conditions on the peak acceleration and characteristic period of ground motion. The US ASCE-7 uses the surface 30m average shear wave velocity $Vs30$ as the index to classify the site classification and gives the site effect coefficient of each classification. In China's current code for seismic design buildings, only the adjustment of the response spectrum characteristic period to the site conditions is considered, and the amplitude of the ground motion is not adjusted.

From the variation of ground motion parameters from bedrock to class II sites, the empirical relationship between the ground motion peak accelerations of Class I sites (ground rock sites) and Class II sites (average sites) is given by equation (6) during the current Chinese ground motion parameter zoning map compilation. The "*China Earthquake Parameter Zoning Map*" stipulates that the peak acceleration of ground motion of I₀, I₁, III, and IV sites can be adjusted according to the peak ground acceleration of the ground motion of Class II sites[25].

$$k_s = \begin{cases} 1.25 & a \leq 62.5 \\ 1.25 - \frac{(a-62.5)}{1250} & 62.5 < a \leq 375 \\ 1 & a > 375 \end{cases} \quad (6)$$

3.2.2. Code for calculation method of topographic effect

The Topographic effect is described in the *Code for Seismic Design of Buildings* as a magnifying effect of local prominent terrain on ground motion parameters. The magnification factor of the seismic influence coefficient at the top of the locally prominent topography is summarized by the height difference of the prominent terrain, the tangent of the slope angle, and the relative distance of the site edge to highlight the edge of the terrain. Since the local prominent terrain may be a mountain ridge, a mountain ridge or a cliff, a steep ridge, etc., the situation is relatively complicated, and it is difficult to specify the amplification effect of various ground motion parameters. The amplification factor listed in the article is based on the results of the macro seismic damage survey and the results of the two-dimensional seismic response analysis. The article states that the coefficient has a maximum increase of 0.6, which was amended to be a mandatory provision after the 2008 Wenchuan earthquake.

In addition, Li Y.M. and Peng Y.D. further analyzed and gave corresponding coefficient value methods for the ground motion amplification effect of the slope segment not covered by the code[26-27].

3.3. Discussion in this section

From the ground motion attenuation relationship and seismic design specifications to the consideration of site effect and topographic effect, although the corresponding coefficients have been introduced, the significance of the site effect coefficient and the topographic effect coefficient defined in this paper is not the same. Although the adjustment factors for the site effect are given in the seismic design codes of various countries, they are all based on the safety considerations of the upper buildings, which are mainly based on experience. The actual and reliable site effect study should establish a downhole array for strong earthquake observations, which is obtained by comparing the strong earthquake records of bedrock and surface soil layers in the deep underground, but it is only implemented in a few countries and regions due to its difficulties.

The effective ground motion attenuation relationship can lead to a relatively reliable peak acceleration distribution map, thereby guiding regional geological disaster prevention and other work. From the perspective of the existing ground motion attenuation relationship considering the site and topographic effects, it is still not possible to achieve a relatively accurate degree. At present, there have been many research results on the attenuation relationship of bedrock ground motion. Therefore, the distribution of regional ground motion parameters can also be achieved by multiplying the adjustment coefficient by the ground motion ground motion distribution. For example, the literature [10] and the literature [23] multiply the site and topographic effect coefficients by the peak acceleration distribution of the bedrock to obtain the regional surface peak acceleration, and the results show reasonable. Therefore, in-depth study of the site effect coefficient and the topographic effect coefficient can be used to estimate the ground motion parameters, and can also provide reference and basis for the formulation of the correlation coefficient in the code.

4. Relationship between site effect coefficient and topographic effect coefficient

The site effect and topographic effect are the two main factors that change the peak acceleration of the ground motion bedrock. Because they are all distributed on the earth's surface, there is a certain relationship between them. Exploring the basic theoretical connection between the two is very meaningful for more in-depth judgment of the magnitude of the peak acceleration of the surface.

The relationship between site effect and topographic effect was wane and wax and gradually transition. In the alpine valley area, the ground motion parameter amplification mainly comes from the influence of steep terrain; in the plain area, the ground motion amplification mainly comes from the influence of deep overburden. From the alpine valley to the plain, the topographic effect is gradually weakened, and the topographic effect coefficient is gradually reduced from a larger value to 1; the site effect is gradually increased, and the site effect coefficient is gradually increased from 1 to a larger value.

From the plain to the alpine valley, the site effect is gradually weakened, and the site effect coefficient is gradually reduced from a larger value to 1; the topographic effect gradually increased, and its topographic effect coefficient gradually increased from 1 to a larger value. In the intermediate state of gradual transition from one effect to another, the site effect and the topographic effect coexist.

At present, the site effect and topographic effect are studied separately as different earthquake phenomena, and whether there is a relationship between the two has never been comprehensively discussed. However, seismic waves travel from the epicenter to the surface and are subject to magnitude changes due to site and terrain. The site and terrain are expressed as two conceptual concepts of shallow surface media and morphologies, both of which have the same origin, that is, they are produced by surface changes during the long geological time. Therefore, the influence of both of them on seismic waves should also be intrinsically linked.

At present, how to combine the two to obtain a more accurate peak acceleration of the surface has not yet matured theoretical results. Ashford combined the formula for the field and topographic effects as: $Aa = (1 + At)(1 + As) - 1$, where, Aa is the surface magnification factor, At is the terrain magnification factor, and As is the site magnification factor[28]. In this paper, the combined effects of site and topographic effects are calculated according to the Ashford formula and the coefficient multiplication algorithm. The site effect coefficient uses Equation 1[6], and the topographic effect coefficient uses Equation (5)[22].

The calculation results show that the Ashford formula calculation results in a large number of data with a surface magnification factor less than 1, which is not consistent with the general phenomenon that the bedrock acceleration is amplified during the propagation process; the results of the surface magnification factor obtained by multiplying the field magnification factor and the terrain magnification factor are both greater than 1 and less than 2, which are in line with conventional values. In addition, Wang L. also concluded that "the amplification ratio of PGA under the action of topography and soil layer is approximately equal to the product of the topographical and soil PGA amplification ratios under their respective actions"[9].

When a variety of factors work together, when the force performance of the material is affected and changes occur, the practice of multiplying the influence coefficients is also used in multiple specifications.

For example, the internal force amplification factor of the conversion member in the *Introduction on the Revision of Technical Specification for Concrete Structures of Tall Building* considers the internal force amplification factor, the weak layer amplification factor and other adjustment factors of the seismic action[29]; the strength of the concrete structure and the masonry structure are mostly adopted by the mode of influence coefficient multiplication.

5. Suggestions for future research directions

According to the discussion of the relationship between the site effect coefficient and the topographic effect coefficient, it is suggested to study the site effect coefficient and the topographic effect coefficient in two lines for the future research direction. When studying the field effect coefficient, the surface is regarded as a flat state without any undulations, and only the influence of the variation of

the propagation medium of the seismic wave on the seismic wave parameters during the process from the epicenter to the surface is considered; when studying the topographic effect coefficient, the epicenter to the surface is regarded as a uniform medium, that is, the site parameters are set to bedrock, and the medium does not change during the process of setting the seismic wave to the surface, only the influence of surface topography on the seismic wave parameters is considered. After the two coefficients are expressed in a functional form, the product of them can be used as the amplification factor of the ground motion parameters under the influence of the actual site and the terrain.

For the research methods of two coefficient function expressions, relying on actual monitoring means requires a large amount of data, and the number of actual results is difficult to meet the research requirements. It is suggested that numerical simulation can be used as a research method and the statistical results of monitoring data can be used as verification. According to the different influencing factors, the site effect is mainly caused by the change of the propagation medium, and the topographic effect is mainly caused by the surface morphology. For the independent variable of the coefficient function expression, the site effect coefficient is mainly the average shear wave velocity V_{s30} of the surface 30 meters, and the topographic effect coefficient is mainly the slope related parameters such as slope angle, slope height, terrain gradient or V_{s30} . The ground motion parameter surface value should consider the combined effect of the site and topographic effect. The ground motion surface amplification factor can be expressed by the product of the site effect coefficient and the topographic effect coefficient.

In the future, we should gradually establish the functional expression of the coefficient as the research direction, and gradually establish the continuity function relationship between the site effect coefficient and the surface soil layer parameters, the terrain effect coefficient and the surface topographic parameters, thereby establishing a comprehensive relational expression that includes both the field effect and the terrain effect. Therefore, more accurate ground motion parameter values suitable for the research site are obtained in the seismic hazard assessment and seismic design.

6. Discussion of V_{s30}

6.1. The concept of V_{s30}

The average shear wave velocity of the soil layer within 30 m below the surface is expressed as V_{s30} . Stratigraphic properties within a depth of 30 m below the surface are key factors affecting seismic effects[30]. Therefore, it is generally regarded as the most important independent variable in the functional expression of the site effect coefficient. Namely, V_{s30} is a direct parameter for expressing the characteristics of the surface soil layer or the site conditions.

6.2. Relationship between V_{s30} and terrain

The value of V_{s30} is related to the type of geotechnical soil. The variation of topography can reflect the difference of geotechnical properties in the near surface. For example, high and steep mountains indicate the presence of rock or hard soil, and flat plains and basins indicate a softer soil layer. The study by Matsuoka et al. also found that V_{s30} has a good correlation with topographic gradient, landform and elevation[31]. In order to obtain the V_{s30} value lacking the measured data area, Wald and Allen proposed a method for calculating V_{s30} using the site terrain gradient G by comparing the correlation between the terrain gradient and V_{s30} [32-33].

In order to obtain a continuous function relationship between V_{s30} and terrain gradient, Liu A.J. performed a quadratic and quadratic regression analysis on the terrain gradients G and V_{s30} in the Wald table, which solved the problem of calculating the V_{s30} value of the regional site and achieved good results[23].

Therefore, V_{s30} can also be used as an indirect parameter to express surface topography. The topographic effect coefficient function expression can also use V_{s30} as a terrain variable.

Therefore, V_{s30} can also be used as an indirect parameter to express surface topography. The topographic effect coefficient function expression can also use V_{s30} as a terrain variable. In addition to

the actual measurement of V_s30 , the accurate value can be obtained. For large-area sites without measurement conditions, especially in mountainous areas, the digital elevation model can be used to obtain the slope angle and other information, and then the relationship between the terrain gradient G and V_s30 is used to evaluate each other[10]. For the V_s30 in the plain area, the national geological department can establish a national V_s30 distribution map for engineering and technical personnel in the form of a national ground motion parameter zoning map.

7. Limits between site effect and topographic effect

The relationship between site effect and topographic effect should be wane and wax. For the two parameters with this relationship, there must be two nodes with equal parameters, which can be used as the boundary between the site effect and the topographic effect. On both sides of the node, one of the effects is dominant. According to the discussion of V_s30 , the function expressions of the two factors of the site effect coefficient and the topographic effect coefficient can all take V_s30 as an independent variable. Therefore, the site effect coefficient with V_s30 as the basic variable has a data relationship with the topographic effect coefficient. When the value of V_s30 is equal to the site effect coefficient and the topographic effect coefficient, the boundary between the two effects with V_s30 as the judgment parameter can be obtained.

Some of the site effect coefficients expressed in functional form are shown in Equation 1 to Equation 4 and the topographic effect coefficients are shown in Equation (5). Since the different statistical methods and fitting processes are used, the respective functions do not have similar expressions. Since both ends of the formula have different independent variable forms, it is found that Equations 1 to 4 cannot be combined with the formula (5) to solve the V_s30 in the trial calculation. That is, the limit of V_s30 cannot be solved.

8. Conclusions and suggestions

(1) There are many research literatures that describe the amplification law of the ground motion peak acceleration under the action of site and topographic effects, but the relatively accurate data results are still not available. Further research is needed to determine the impact of the site and terrain on the peak acceleration of ground motion.

(2) The relationship between site effect and topographic effect was wane and wax and gradually transition.

(3) Under the influence of the site and terrain on the peak acceleration of the bedrock, the amplification factor after the peak acceleration is transmitted to the surface can be expressed by the product of the site effect coefficient and the topographic effect coefficient.

(4) It is recommended to study the site effect coefficient and the topographic effect coefficient in two ways. When studying the site effect coefficient, the surface is regarded as a flat state without any undulations, and only the influence of the variation of the propagation medium on the seismic wave parameters during the process of the seismic wave passing from the epicenter to the surface is considered; when studying the topographic effect coefficient, the epicenter to the surface is regarded as a uniform medium, and only the influence of the topography on the seismic wave parameters after the seismic wave is transmitted to the surface is considered.

(5) When studying the site effect coefficient and the topographic effect coefficient, it is suggested that the numerical method can be used as the research method and the statistical result of the monitoring data can be used as the verification to obtain the function expression.

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