Nonlinear analysis on seismic response of a multi-geomorphic composite site

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Abstract: Based on the explicit FE method and parallel computing cluster platform of ABAQUS, a large-scale two-dimensional (2D) nonlinear analytical model for a multi-geomorphic composite site consisting of valley flat, terraces, undulating hilly terrain was established by considering the inhomogeneity of ground soils and influence of terrain change. Nonlinear seismic effect characteristics of the composite site were analyzed, including the peak ground acceleration (PGA), spectral acceleration, duration and acceleration transfer functions. The main results demonstrated that: (1) the PGA of different observation points on the ground surface vary with each other, which was caused by the terrain differences. For the same input motions, the ground surface PGA of valley flat area show obviously larger than that of the first terrace area. (2) the horizontal spectral acceleration of ground surface appears a double-peak or multi-peak phenomena, the spectra shape peak moves to a larger period in the floodplain area compared with that in first terrace area and the period difference comes to be from 0.05s to 0.25s. (3) the sensitive frequency band of seismic site response was 0.5Hz to 1.75Hz, when the frequency is lower than 0.2Hz or higher than 2Hz, the seismic amplification characteristics is not apparent.（4）PGA exhibits spatial variation characteristics which varies in both lateral and depth directions, and there is a non-monotonic decreasing characteristic with soil depth, greater motion amplification and focusing effect of some shallow soil layers were found. In some degree, the 2D results can reflect nonlinear site effect and the influence of lateral heterogeneity of soils on seismic wave propagation.

Key words: seismic site effect; multi-geomorphic units; soil nonlinear characteristics; focusing effect in soil amplification; PGA

1 INTRODUCTION

Seismic damage investigation and theoretical study has shown that the spread of seismic wave would be influenced by the change of geographic and geomorphic conditions, which may cause difference of seismic spatial distribution characteristics. It was found in seismic damage investigation of Tonghai earthquake in 1970, Yongshan-Daguan earthquake of Yunnan province in 1974 and Haicheng earthquake in 1975 that the top and its neighboring positions of low hill site or isolated mounds have a larger seismic response [1,2]. Previous literatures [3-6] had studied the effects of terrain conditions on the seismic ground motion, analytical solutions of different terrain problems such as arc mounds, depressed river alluvial, and side slope had been given. Wei Rulong et.al [7] had studied the seismic response of bank slope surface in the transition region between rivers and terraces, and it was found that there existed amplification phenomenon of surface ground acceleration. Also some literatures [8,9] had indicated that the seismic response differences caused by the difference of terrain should not be ignored.

As linear structures such as long-span bridge, pipeline projects and transmission tower (line) engineering have emerged in a large amount, the effect of topographical change on the seismic responses has been obtained more and more attentions[10-12], there is firm rules in the "code of seismic design of buildings" (GB50011-2001) that tell us we should pay high attention to the amplification effect on the design ground motion parameters caused by unfavorable location such as complicated terrain or obvious terrain changes.

The seismic response analysis results of site may provide scientific basis for the engineering seismic design, the ground seismic amplification coefficient should be evaluated in the seismic zoning work, it aims at selecting favorable locations in the seismic design of civil engineering. So far, the seismic zoning and seismic safety evaluation of engineering sites for key projects are always conducted by one dimensional (1D) site analysis method. However, it is unreasonable when it comes to large-scale complex site, in this case, it is necessary to use two or three dimensional (2D or 3D) models to analyze the seismic site effect. In addition, analysis assuming that the soil is linear or equivalent linear, homogeneous and elastic in engineering applications, may not reflect the real nonlinear of soils under great ground motion according to the propagation mechanism of seismic wave, besides, the homogeneous and elastic models may not indicate the influence of inhomogeneity of ground soils and fluctuation of topography to the seismic wave propagation. In previous studies, the site model was always greatly simplified, and the results are far from the truth.

Based on the explicit FE method and parallel computing cluster platform of ABAQUS[13], considering the nonlinearity and consumption characteristics of damping energy of soil, according to a actual site in Chuzhou city of Anhui province, China, the nonlinear scattering problem of valley flat and terraces under S wave is analyzed. Also nonlinear seismic effect characteristics of multi-geomorphic composite site are studied.

2 THE SITE MODEL AND INPUT SEISMIC WAVE

The Chuzhou city of Anhui province, China, which is located in the east of Langya Mountain was taken as the site prototype. The site area is about 95km^2, see in Fig.1. In the north of the site, there is a branching river from the west to the east, from which we can find that there are obvious landforms of valley flat; in the south, there are first terrace and undulating hilly terrain. The spatial distribution of soil presents obvious nonlinearity.

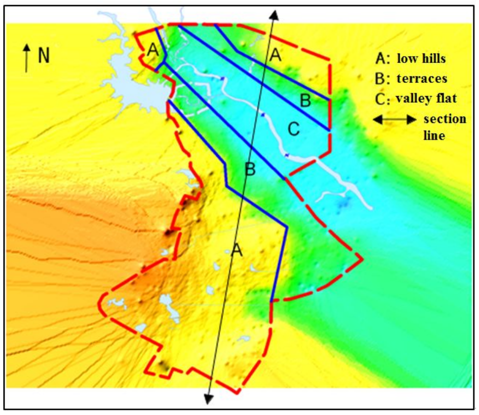


Fig.1 Topography and section location

According to the geotechnical engineering investigation materials and wave velocity data, a large –scale section across valley flat, terrace and undulating hilly terrain is selected, and the corresponding section model is established for the 2D analysis of nonlinear seismic effect characteristics of multi-geomorphic composite site. See in Fig.2, in which, the serial numbers on the ground surface represent the positions of observation points. And the elevation of terrace and low hills come to be 30-50m, the upper portion of the site is clayey soil and the lower portion is gravel soil. The exposed elevation of the valley flat is about 10m, and the upper portion is silty clay, the middle portion is sludge and mucky soil, also, the lower portion is gravel layer.

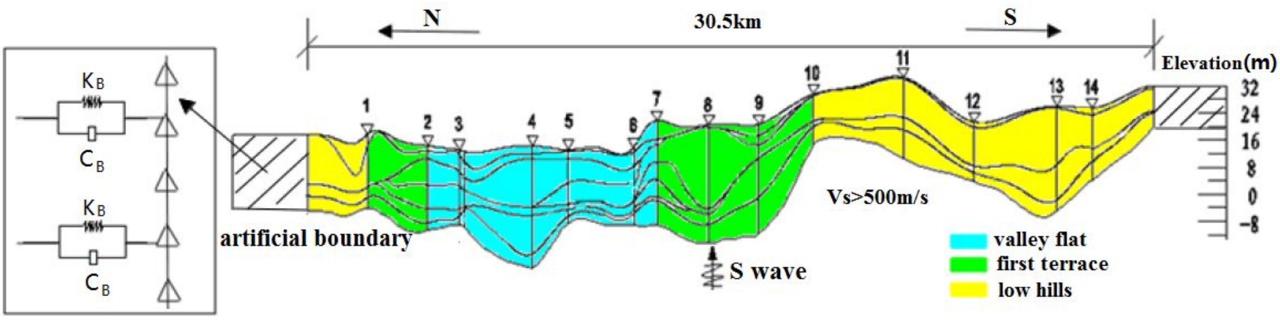


Fig.2 The profile and calculation area

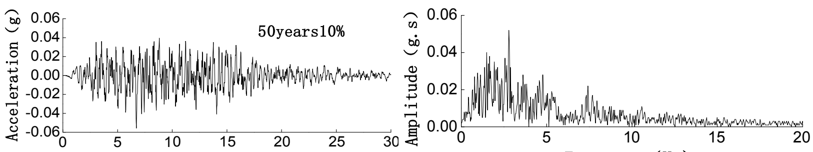
Form the ground surface to the bedrock, the site soil distribution comes to be: filling soil, clay, mucky silty clay, fine sand, medium-coarse sand and gravel, the same kind of soil in different geomorphic unit have different soil property. Table 1 shows the dynamic triaxial test results of the typical site.

Table 1 Dynamic triaxial test results of the typical site

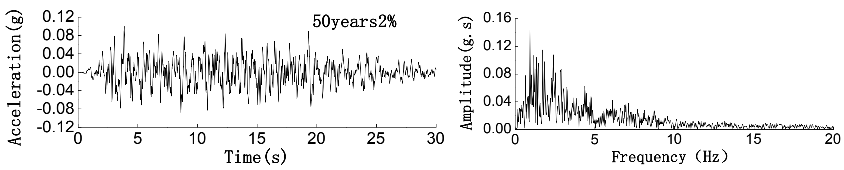
Soil type	Density kg/m^3	Parameter	Shear strain (10^{-4})							
			0.05	0.1	0.5	1	5	10	50	100
fine sand	1960	G/Gmax	0.9933	0.9851	0.9241	0.8576	0.5444	0.3738	0.1066	0.0563
		λd	0.0040	0.0050	0.0213	0.0306	0.0741	0.0944	0.1238	0.1291
clay	1990	G/Gmax	0.9975	0.9951	0.9760	0.9531	0.8025	0.6702	0.2890	0.1689
		λd	0.0303	0.0373	0.0602	0.0736	0.1135	0.1325	0.1670	0.1751
silty clay	1950	G/Gmax	0.9983	0.9966	0.9831	0.9668	0.8533	0.7441	0.3677	0.2253
		λd	0.0329	0.0402	0.0638	0.0776	0.1193	0.1402	0.1821	0.1932

The modified Davidenkov dynamic viscoelastic constitutive model [14] is taken to simulate the dynamic characteristics of the site soil and subroutines of soil dynamic nonlinear constitutive relationship are compiled using the FORTRAN language, besides, the UMAT/VUMAT connector of ABAQUS is used in the integration of the subroutines of dynamic constitutive relationship model into the ABAQUS software. Seismic wave energy would transmit toward into the far-field sites, thus it requires that there are no reflections on the truncated boundary or at least the boundary is close to non-reflective. In Fig.2, vertical constraints are set also horizontal viscous dampers and linear springs on the both sides of the soil calculation region are adopted. And the reference [15] is useful for the values range of spring rate KB and damping coefficient CB. The calculation cut-off frequency is selected as 20Hz, considering the wavelength varies with depth which is related to the cut-off frequency, the vertical grid size is selected as 1/8~1/10 of the wavelength, that is 0.5~1.2m, besides, according to the horizontal heterogeneity, the horizontal grid size is selected as 5~8m.To ensure accuracy and reduce calculating time, we adopt mainly quadrilateral finite elements in meshing the model, and also use few triangular elements for assistance. The total number of the elements of the site model is 95414, and the corresponding degrees of freedom are 190818. The parallel computing and dynamic explicit algorithm are adopted to analyze the nonlinear seismic effect characteristics of the large-scale composite site.

Based on the seismic hazard analysis of this site, two seismic wave respectively in two intensity levels （with exceeding probability of 10% and 2% in 50 years）are selected as the input ground motions, the corresponding PGA of the input ground motion is 55cm/s^2 and 100 cm/s^2， for convenience sake，the seismic waves are named W1-55，W1-100，W2-55and W2-100，The acceleration time course of the input waves and the corresponding Fourier spectra are shown in Fig.3 and Fig4.

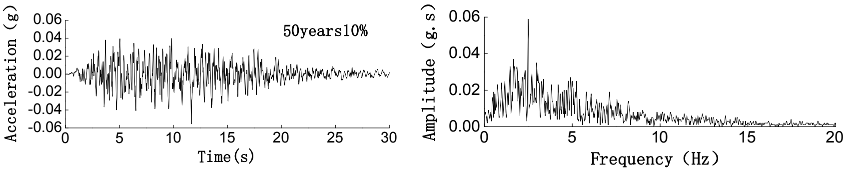


（a）W1-55

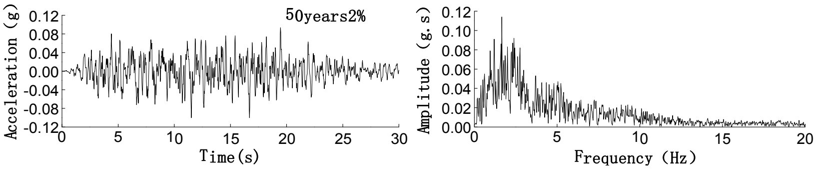


（b）W1-100

Fig 3 The acceleration time course of the input wave W1 and the corresponding Fourier spectrums



（a）W2-55



（b）W2-100

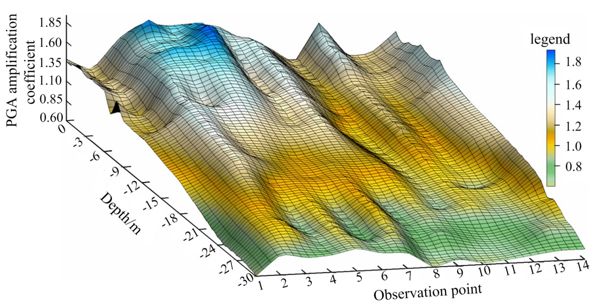
Fig 4 The acceleration time course of the input wave W2 and the corresponding Fourier spectrums

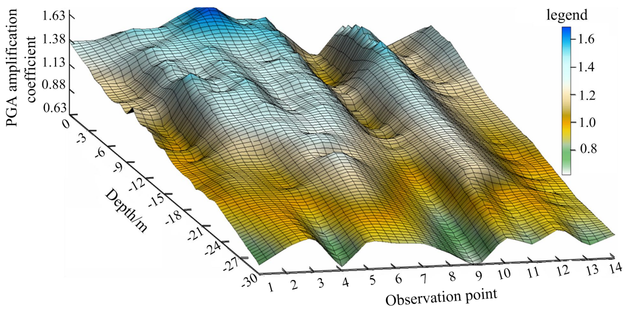
3 NUMERICAL CALCULATION RESULTS

When analyzing the seismic response characteristics of the site, it is not comprehensive to evaluate only using single index. In this paper，comprehensive analysis of seismic amplitudes，spectra and ground motion duration were conducted to study the seismic response characteristics of the site.

3.1 Variation characteristics of PGA

Based on the above calculation model, the PGA characteristics with depth were obtained, and Fig.5 gives the PGA amplification coefficient of different observation points, from which we can find that: (1) Compared with the input ground motion， the peak acceleration of soils near the ground surface show an obvious amplification phenomenon , the seismic amplification effect of soils deeper than 15m seem weakened with the growth of depth, and gradually the amplification factor of PGA become smaller than 1.0. (2) The PGA display a non-monotonic decreasing characteristic with depth and a greater focusing effect of some particular soil layers, and this is more common in valley flat area, such as the observation points No.3 to 7. (3) As it's a multi-geomorphic composite site, the PGA amplification coefficient of each observation point varies from each other for the reason of topographic change. For example, the PGA of observation points No.3 to 7 in valley flat （slope toe, the corresponding bedrock is flat）is larger than that of observation points No.8,9,11,12 and 13, which may be caused by the geological differences and terrain fluctuation.



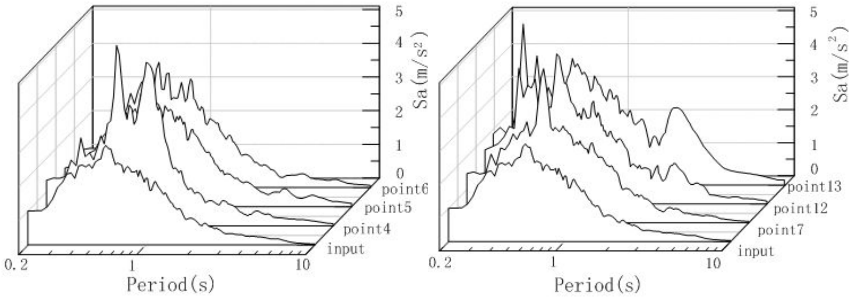


（a）average value of different conditions (50 years 10%) （b）average value of different conditions (50 years 2%)

Fig.5 The profile of PGA with depth

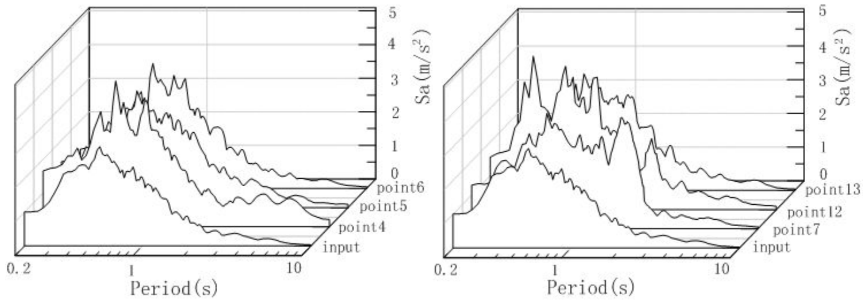
3.2 Seismic spectra

Fig.6 and Fig.7 give the acceleration response spectra of observation points under different seismic excitation. From which, we can find that the horizontal acceleration response spectra present a double- or multi- peak phenomenon under different seismic wave. No matter in which geomorphic unit, the horizontal acceleration is largely amplified in period of 0.4s-1.2s. Parts of the observation points (No.7-10 in terrace) present another peak of acceleration response spectra in period of 1.2s-1.5s. from the comparison between Fig.6 (under seismic wave W1) and Fig.7 (under seismic wave W2), we fan find that the acceleration response spectra characteristics have something to do with the characteristics of input ground motions, in this paper, the seismic wave W1 is relatively more abundant in low-frequency component than seismic wave W2, and the ground motion amplification effect under W1 seem larger than that under W2.



（a） valley flat （b） terrace

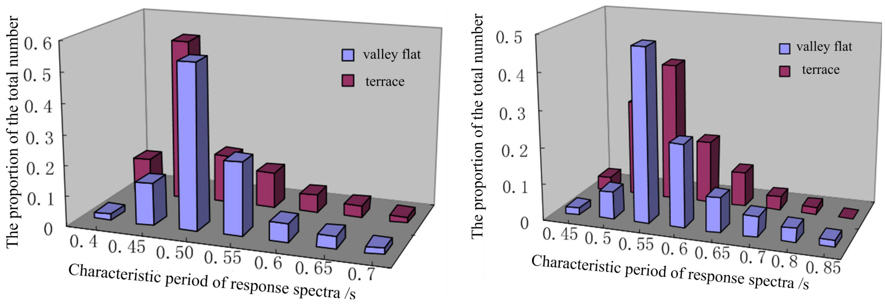
Fig.6 Acceleration response spectra of observation points(under W1)



（a） valley flat （b） terrace

Fig.7 Acceleration response spectra of observation points(under W2)

Fig.8 shows characteristic periods of ground surface acceleration response spectra, and it can be found that characteristic periods of valley flat are on the whole larger than that of terrace, the characteristic period of valley flat ranges from 0.50 to 0.55s under input motion with peak acceleration of 55cm/s^2 , and under the same condition, the correspondingly ranges from 0.45 to 0.50s in terrace. the period difference between terrace area and valley flat area comes to be from 0.05s to 0.25s.



（a） 50 years 10% （b） 50 years 2%

Fig.8 The characteristic periods of response spectra

Fig.9 shows Fourier spectrum ratio (the ratio of acceleration response Fourier spectrum value of each observation point to the acceleration Fourier spectrum value of input ground motion) under different frequency. The results show that the acceleration response Fourier spectrum of each observation point is amplified in different degree compared with the acceleration Fourier spectrum value of input ground motion. the Fourier spectrum ratio curve is steady under frequency of 0.2Hz and 0.25Hz, that is the acceleration response Fourier spectrum value of each observation point has little difference with that of input ground motion. When it comes to the frequency range of 0.5Hz-1.75Hz， the Fourier spectrum ratio curve present multi-peak phenomenon, which indicates that the seismic site effect is significant. However, when the frequency is larger than 2Hz, the site amplification effect seems weakened, and the Fourier spectrum ratio curve becomes more and gentler with the increasing of frequency. The site effect of observation points（No.2-7）in valley flat become obvious when the frequency is larger than 0.75Hz. and when it is in the frequency range of 0.75Hz-1.50Hz， the seismic amplification effect comes to be the most obvious. However, the observation points(No.10-14) in low hills present a noticeable seismic response when the frequency is relative small（about 0.25Hz）, and the seismic amplification effect comes to be the most obvious. In the frequency range of 0.2Hz-1.7Hz.thus, we can find that the low hills area has a lower sensitive frequency than that of the valley flat area.

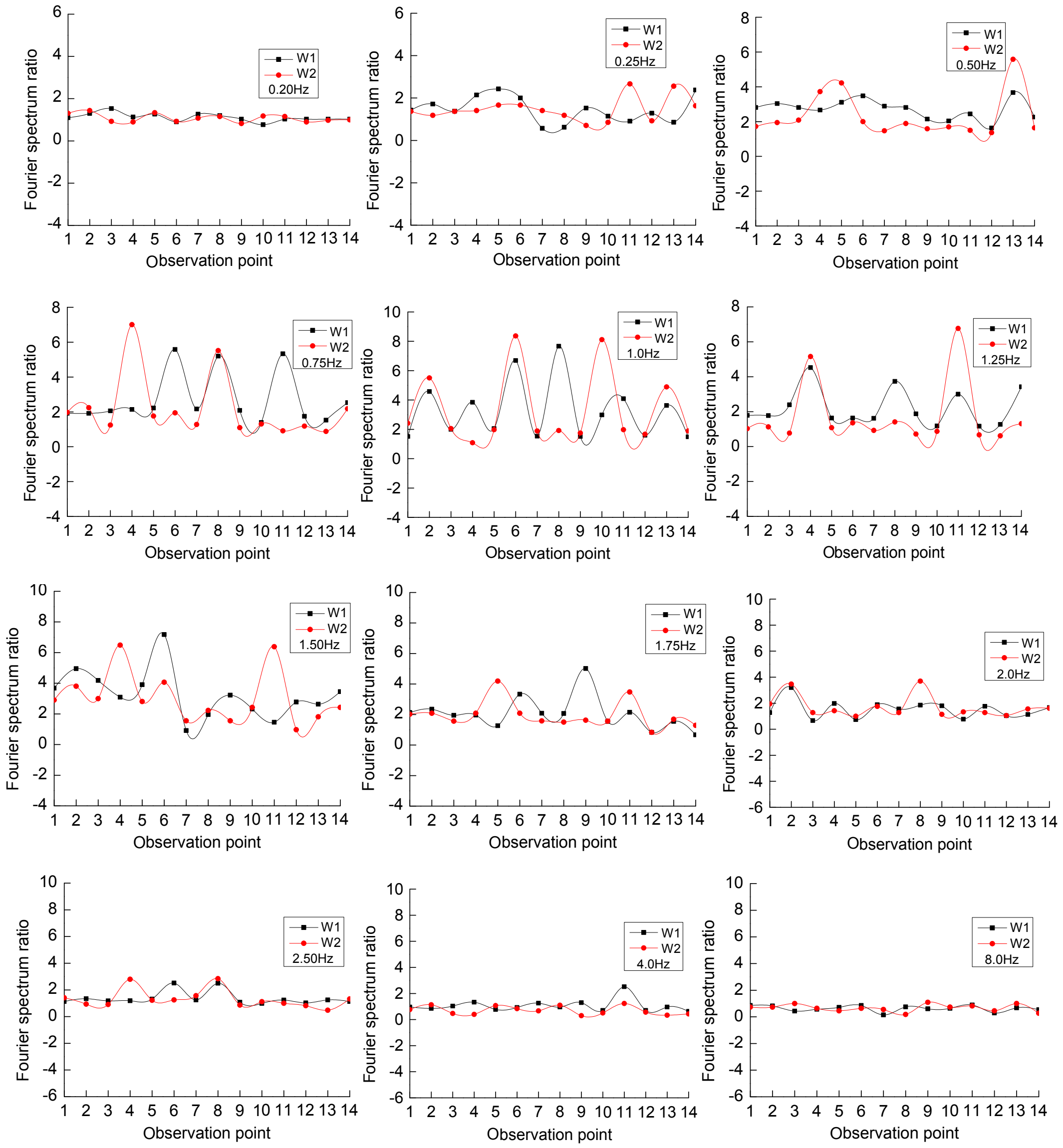


Fig.9 Acceleration Fourier spectrum ratio under different frequency

3.3 Seismic duration

The seismic disasters caused by earthquake motion is relative to both the seismic motion intensity and seismic duration, thus, it is necessary to consider the influence of the seismic duration besides the seismic response strength. However, so far， the definition of seismic duration is not unified.

there are three major categories of standards: the first standard is based on the absolute value of ground motion acceleration; the second one is based on the relative value of ground motion acceleration, the third one is based on the seismic accumulated energy, in this paper, the second standard is adopted, that is the duration time in the acceleration time history curve from the first time to the last time that the acceleration comes to be 1/5 of PGA.

Fig.10 gives the duration time of ground surface acceleration in different positions in the site under different seismic waves. The position of observation point has an important effect on the duration time， which may also indicate that the local terrain changes have influence on the seismic site response. The acceleration duration time is significantly prolonged in some positions. For example, the acceleration duration time of observation points 8-9（in the transition region between valley flat and low hills）are obviously longer than that of the other positions. Besides, the input ground motion characteristics has something to do with the acceleration duration time. In general, the acceleration duration of each observation point seems in uniform distribution under seismic wave W1, and the amplitude of fluctuation is small, however, when under seismic wave W2, the acceleration duration time distribution seems fluctuated.

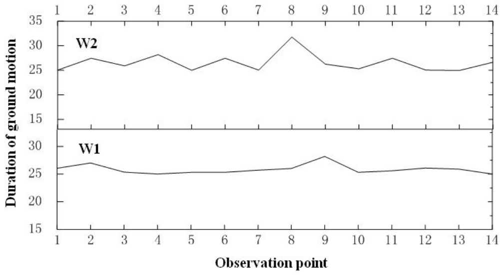


Fig.10 Duration time of ground motion

4 CONCLUSIONS

Taking the seismic microzonation site in Chuzhou city of Anhui province as the prototype, based on the explicit FE method and 32 CPU parallel computing cluster platform of ABAQUS, considering the inhomogeneity of ground soils， a large-scale refined two-dimensional(2D) FE nonlinear analytical model for a multi-geomorphic Composite site that consists of valley flat， terraces， undulating hilly terrain and monadnock was established. The SH wave is taken as the bedrock earthquake motion and nonlinear seismic effect characteristics of the composite site were analyzed, which may provide some scientific basis for engineering practice. The main conclusions are as follows:

(1) The PGA of different observation points on the ground surface vary with each other, which is caused by the terrain differences. When it's under the same input ground motion, the ground surface PGA of valley flat show obviously larger than that of the first terrace.

(2) The horizontal acceleration response spectrum of ground surface appears a double-peak or multi-peak phenomenon, the spectra shape peak moves to a larger period in the floodplain area compared with that in first terrace area and the period difference comes to be from 0.05s to 0.25s.Moreover, the acceleration response spectrum is related with the input ground motion.

(3) The amplification effect and focusing effect of seismic motion are more obvious in specific frequency band(0.5Hz-1.75Hz), when the frequency is lower than 0.2Hz or higher than 2Hz, the seismic amplification characteristics is not apparent；to the valley flat ，the sensitive frequency comes to be 0.75Hz-1.50Hz. while the sensitive frequency of low hills is 0.25Hz-1.75Hz.

（4）The location of observation point has influence on the acceleration duration， the changing terrain may cause difference of seismic motion duration， besides， the motion duration, in some way, is dependent on the input ground motion characteristics.

The large-scale two dimensional nonlinear analysis models, in a sense, may reflect the propagation characteristic of seismic wave, which may also indicate the amplification effect and focusing effect of seismic motion in specific frequency. To the multi-geomorphic composite site which is with nonlinear soil distribution and changing terrain, the one-dimensional equivalent linearization model is not suitable.

The above conclusions are obtained by the given model condition, and the seismic site response is relative with many factors such as geographic and geomorphic conditions, soil properties, input ground motion and so on. It is a complex process to study the ground motion distribution of a composite site. Further research should be conducted to improve the understanding of the seismic site effect, which may provide a basis for the seismic design of major construction project in composite site.

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