



Study on the Contrast between Two Seismic Response Analysis Programs of Soil Layer

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PAPER INFO

Paper history:

Received 23 August 2018

Received in revised form 19 October 2018

Accepted 26 October 2018

Keywords:

Soil Analysis Program

Ground Motion

Soil Shear Strain

Response Spectra

Peak Acceleration

A B S T R A C T

56 ground motions of the bedrock and surface are selected from 28 stiff sites (site class I and site class II) of the KiK-net station. The peak acceleration, response spectra and shear strain of actual hard sites are calculated by using SHAKE2000 and LSSRLI-1. The similarities and differences between SHAKE2000 and LSSRLI-1 and their differences from measured records are analyzed. It provides a basis for improving the seismic response analysis method of soil layers. The results show that when the soil is not obviously nonlinear, most of the difference in PGA results calculated by SHAKE2000 and LSSRLI-1 can be ignored, and the maximum error of the calculated soil shear strain is also less than 20%. When the soil is highly nonlinear, only a few differences in PGA results can be ignored. The maximum error of shear strain of the soil is greater than 20%. The results of peak acceleration and response spectra calculated by SHAKE2000 and LSSRLI-1 differ greatly from the measured results in most cases. Nevertheless, the probability of having big difference and significant difference between LSSRLI-1 and measured response spectra is greater than SHAKE2000.

doi: 10.5829/ije.2019.32.01a.06

1. INTRODUCTION

As an essential part of seismic design, soil seismic response analysis directly affects the safety and cost of engineering structures under the earthquake [1-4]. At present, the estimation of soil ground motion is provided by the soil response analysis program. SHAKE2000 and LSSRLI-1 are the two kinds of soil reaction analysis programs which are widely used respectively in the West and China. SHAKE2000 is modified by SHAKE91, which is a kind of one-dimensional equivalent linear program. And it is also the most widely used one dimensional seismic response analysis program currently [5-8]. LSSRLI-1 [9] program has become the recommended soil reaction analysis program for seismic safety evaluation of engineering sites in China [10]. Besides, SHAKE2000 and LSSRLI-1 have the same assumption. That is, the equivalent shear modulus and damping ratio are used to replace the shear modulus and damping ratio under different strain amplitudes in the sense that the global

dynamic effect is approximately equivalent, and the nonlinear problem is transformed into a linear problem [11, 12]. Both SHAKE2000 and LSSRLI-1 assume that the actual site is horizontally stratified. The input seismic wave is a shear wave incident vertically upward from the bedrock. The shear wave input from the bedrock can be decomposed into a series of harmonic superposition by Fast Fourier Transform (FFT), and the response is obtained by Inversely Fast Fourier Transform (IFFT) after superposition. The equivalent linear soil response iteration is adopted in the calculation. The difference is that SHAKE2000 and LSSRLI-1 have different methods for calculating shear strain. SHAKE2000 adopts frequency domain solution and LSSRLI-1 takes both frequency domain solution and time domain solution into account when calculating shear strain.

At present, there are few works to verify the existing soil response analysis programs with actual site and its ground motion records. Wenhao et al. [13] selected four strong motion records of bedrock in a certain array of Tangshan as input ground motions to contrast the soil response analysis programs SHAKE91,

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and LSSRLI-1. According to his research, if the seismic intensity is not strong enough, the programs can meet the engineering requirements. Meanwhile, from the security and economic point of view, the LSSRLI-1 program is desired. Blind predictions of ground response at Turkey Flat vertical array site during the 2004 Park field earthquake were performed using a series of nonlinear and equivalent-linear ground-response analysis codes by Annie et al. [14]. However, both of them only used one site profile, lack of representativeness. Although these two programs are widely used, they are seldom adopted to calculate the ground motions from actual site. The main reason is that the actual borehole seismic records are rare in the past.

Many borehole seismic ground motions have being collected recently from the KiK-net network in Japan, which creates the condition for the seismic response analysis of the soil. While the existing researches have indicated that the results of LSSRLI-1 are unreasonable when the soil is soft or the input seismic motion is

strong. The results are reliable when the soil is chosen from stiff sites. In this paper, according to Chinese site classification principle [15], 28 stiff sites were selected (including site classes I and II) from the KiK-net stations. By analyzing 56 different actual seismic records, this paper compared the application of two programs in stiff sites, which provided the basis for the improvement of seismic response analysis method of soil [16-18].

2. CALCULATION CONDITIONS

Soil profiles of the selected 28 stations in this paper have a complete record of the underground and the surface rocks [19]. Drilling conditions and the equivalent shear wave velocity obtained according to relevant Chinese codes are shown in Table 1. The soil is layered every two meters. Besides, different kind of soils should be stratified.

TABLE 1. Information of station

Drilling number	The equivalent shear wave velocity (m/s)	Depth (m)	Geographic coordinates	
			Longitude	Latitude
KGWH03	600	100	134 °9'3.1"	34 °16'0.1"
KYTH04	220	100	135 °33'13.0"	35 °15'55.0"
MYGH06	200	100	141 °4'28.0"	38 °35'16.0"
IWTH18	180	100	141 °40'50.0"	39 °27'36.0"
GIFH22	270	100	137 °6'30.2"	35 °39'54.4"
IBRH14	180	100	140 °33'6.5"	36 °41'20.4"
IBRH19	100	210	140 °5'33.2"	36 °12'38.0"
NIGH10	430	100	139 °22'2.00"	37 °32'26.0"
SMNH10	500	200	133 °18'11.0"	35 °33'17.0"
SZOH38	300	200	138 °58'51.6"	35 °4'55.6"
TCGH14	275	100	139 °37'7.0"	36 °32'52.0"
EHHM01	420	100	132 °33'29.0"	33 °3'12.0"
FKSH09	244	200	140 °25'47.0"	37 °21'0.00"
HDKH04	210	220	142 °2'31"	42 °30'37"
IWTH09	440	100	141 °42'56.0"	40 °4'60.0"
IWTH12	312	100	141 °25'41.0"	40 °9'2.0"
KNGH18	349	100	139 °7'53.4"	35 °38'25.4"
MIEH03	286	100	136 °22'20.0"	34 °32'37.0"
MIEH05	240	100	136 °10'18.0"	34 °3'38.0"
MIEH09	327	100	135 °59'59.0"	33 °45'40.0"
NARH01	131	99	135 °39'12.0"	33 °57'49.0"
NIGH11	364	205	138 °44'50.0"	37 °10'11.0"
SMNH02	330	101	133 °5'17.9"	35 °13'13.1"
SMNH05	420	101	132 °38'30.1"	34 °51'58.0"
TCGH12	305	120	139 °59'15.0"	36 °41'34.0"
TKCH05	254	100	143 °37'19.0"	43 °7'7.0"
WKYH07	285	100	135 °26'32.6"	33 °41'12.0"
YMNH11	268	200	138 °58'50.9"	35 °37'17.4"

KiK-net strong-motion records were selected as the inputs. 21 seismic waves with different peak and spectra characteristics were selected as the bedrock input waves from site class I, and the peak acceleration of records is between 12gal and 192gal. 35 records with different peak and spectra characteristics were selected as the bedrock input waves from site class II, and peak acceleration is between 12gal and 370gal. In this paper, there are totally 336 sets of calculation conditions.

3. SELECTION OF NONLINEAR PARAMETERS

Since the nonlinear calculation parameters of soil are not provided in the actual investigation data, three kinds of nonlinear conditions, respectively defined as weakly nonlinear condition, mean value and strong nonlinear

condition, are used in the same profile. In this work, according to the uncertainty analysis of nonlinear dynamic shear modulus ratio and damping ratio of soil were applied [20]. The weak nonlinear condition means that the dynamic shear modulus ratio takes the maximum, while the damping ratio takes the minimum value. Mean value condition implies that both dynamic shear modulus ratio and damping ratio take the mean value. The strong nonlinear condition means that the dynamic shear modulus ratio takes the minimum, while the damping ratio takes the maximum value. G/G_{max} is the dynamic shear modulus ratio; λ is the damping ratio; γ is the shear strain. The relationship between the dynamic shear modulus ratio G/G_{max} as well as λ and shear strain γ of different soil types are shown in Table 2.

TABLE 2. Nonlinear calculation data of soil

Soil classification	Nonlinear conditions		Shear strain $\gamma/10^{-4}$							
			0.05	0.1	0.5	1	5	10	50	100
Clay	Weak nonlinear	G/G_{max}	0.9984	0.9965	0.9813	0.963	0.8377	0.7205	0.34	0.2048
		λ	0.005	0.008	0.0161	0.0224	0.0582	0.0744	0.1082	0.1192
	Mean nonlinear	G/G_{max}	0.9936	0.9852	0.9265	0.8668	0.5863	0.4272	0.1949	0.0767
		λ	0.026	0.0321	0.0522	0.0867	0.1385	0.1586	0.1949	0.2033
	Strong nonlinear	G/G_{max}	0.9578	0.9093	0.6499	0.4788	0.1133	0.06	0.008	0.004
		λ	0.0668	0.087	0.128	0.158	0.222	0.2388	0.267	0.28
Silty clay	Weak nonlinear	G/G_{max}	0.9987	0.997	0.9839	0.9679	0.8568	0.7493	0.3739	0.2299
		λ	0.004	0.007	0.0133	0.0237	0.0581	0.0669	0.086	0.0943
	Mean nonlinear	G/G_{max}	0.9933	0.985	0.925	0.8611	0.5663	0.4028	0.1253	0.0677
		λ	0.0168	0.0212	0.0387	0.0518	0.11	0.1312	0.1637	0.17
	Strong nonlinear	G/G_{max}	0.9688	0.9325	0.7173	0.5567	0.1995	0.1107	0.0243	0.0123
		λ	0.062	0.072	0.099	0.1293	0.1992	0.2168	0.264	0.2733
Silt	Weak nonlinear	G/G_{max}	0.999	0.9976	0.9873	0.9283	0.7199	0.5621	0.2041	0.1136
		λ	0.003	0.006	0.0152	0.0192	0.0387	0.0506	0.075	0.077
	Mean nonlinear	G/G_{max}	0.9889	0.9775	0.8946	0.8232	0.5299	0.3792	0.123	0.067
		λ	0.0171	0.0226	0.0416	0.0573	0.0999	0.1228	0.1485	0.1572
	Strong nonlinear	G/G_{max}	0.923	0.872	0.577	0.48	0.13	0.069	0.0038	0.0019
		λ	0.0601	0.07	0.089	0.116	0.1652	0.1952	0.2405	0.257
Sand	Weak nonlinear	G/G_{max}	0.9978	0.9952	0.9742	0.9492	0.7875	0.6493	0.27	0.1561
		λ	0.001	0.002	0.01	0.018	0.045	0.0503	0.0627	0.0664
	Mean nonlinear	G/G_{max}	0.976	0.9544	0.8389	0.8008	0.3985	0.2763	0.0868	0.0431
		λ	0.0135	0.0176	0.0346	0.0467	0.0844	0.0983	0.1175	0.1212
	Strong nonlinear	G/G_{max}	0.9	0.837	0.66	0.594	0.174	0.1031	0.031	0.0108
		λ	0.052	0.061	0.086	0.099	0.1613	0.1893	0.232	0.2464
Silty soil	Weak nonlinear	G/G_{max}	0.9984	0.9963	0.9803	0.9611	0.8304	0.7098	0.3283	0.1964
		λ	0.0058	0.0085	0.0235	0.0305	0.066	0.083	0.117	0.126
	Mean nonlinear	G/G_{max}	0.9722	0.9526	0.8397	0.8041	0.4377	0.3099	0.1262	0.0659
		λ	0.0191	0.0246	0.0477	0.068	0.1329	0.1641	0.1993	0.2091
	Strong nonlinear	G/G_{max}	0.9	0.864	0.63	0.46	0.1	0.079	0.017	0.008
		λ	0.054	0.067	0.102	0.13	0.1904	0.2141	0.2608	0.278

For a drill section, under the same ground motion, the peak of surface acceleration and the maximum shear strain of soil as well as acceleration response spectra are obtained using the two kinds of programs, SHAKE2000 and LSSRLI-1. The results of the above two programs are analyzed and then compared with the actual measured records. The input data of each program include earthquake waves, the equivalent shear wave velocity, the depth of the soil layer, the dynamic shear modulus and the damping ratio and the shear strain.

4. PEAK ACCELERATION OF GROUND SURFACE

In the contrast analysis, it is assumed that the peak error is negligible if less than 20%. The above condition is defined as a boundary. The error of peak acceleration between SHAKE2000 and LSSRLI-1 is showed in Figure 1. The error of peak acceleration between the calculated and the measured is shown respectively in Figure 2. The results are amended referencing to the seismic intensity scale of China [21]. In the statistics of this paper, error of peak acceleration less than 10% is defined as "the individual", the error between 10 and 50% is defined as "the minority", the error between 50 and 70% is defined as "the majority", the error between 70 and 90% is defined as "the big most", the error over 90% is defined as "the overwhelming majority".

Seeing from both Figures 1 and 2, in site classes I and II, the overwhelming majority of peak acceleration errors calculated by SHAKE2000 and LSSRLI-1 can be ignored when the soil is weakly nonlinear. While the big most can be ignored when the soil is mean value condition or strongly nonlinear condition. For the measured surface acceleration, only a little difference of the measured results and the calculated by the two programs can be ignored. Though the results of the two programs are different from the actual results, relatively

speaking, the calculated results of SHAKE2000 are better than LSSRLI-1.

5. ACCELERATION RESPONSE SPECTRA

Based on measured response spectra, response spectra calculating by SHAKE2000 and LSSRLI-1 and the measured response spectra are compared in Table 3. In this table, the maximum error less than 20% of the response spectra is defined as "the negligible", the maximum error between 20 and 50% is defined as "a little different", the maximum error between 50 and 80% is defined as "a big different", and the maximum error over 80% is defined as "a significant different". Comparisons of response spectra between calculated and the measured records from MYGH06 station and NIGH11 station are respectively shown in Figures 3 and 4.

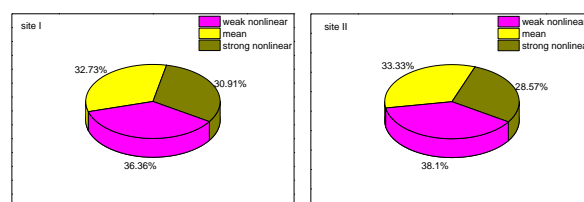


Figure 1. The peak acceleration errors of SHAKE2000 and LSSRLI-1

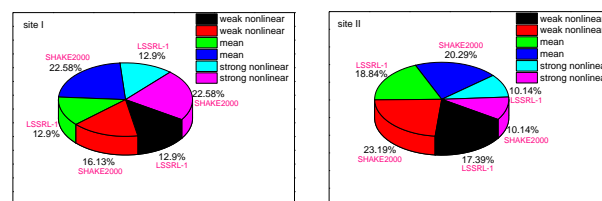


Figure 2. The peak acceleration errors of the calculated and the measured conditions

TABLE 3. The difference between the calculation results and the record results

Site Category	Difference Degree (%)		LSSRLI-1 Event			SHAKE2000 Event		
			Weak Nonlinear	Mean Nonlinear	Strong Nonlinear	Weak Nonlinear	Mean Nonlinear	Strong Nonlinear
I	the negligible	0-20	48	43	43	62	57	48
	a little different	20-50	38	38	28	38	38	43
	a big different	50-80	14	19	24	0	5	9
	a significant different	80-100	0	0	5	0	0	0
II	the negligible	0-20	37	34	24	31	34	27
	a little different	20-50	48	37	49	49	46	49
	a big different	50-80	6	20	9	11	11	12
	a significant different	80-100	9	9	18	9	9	12

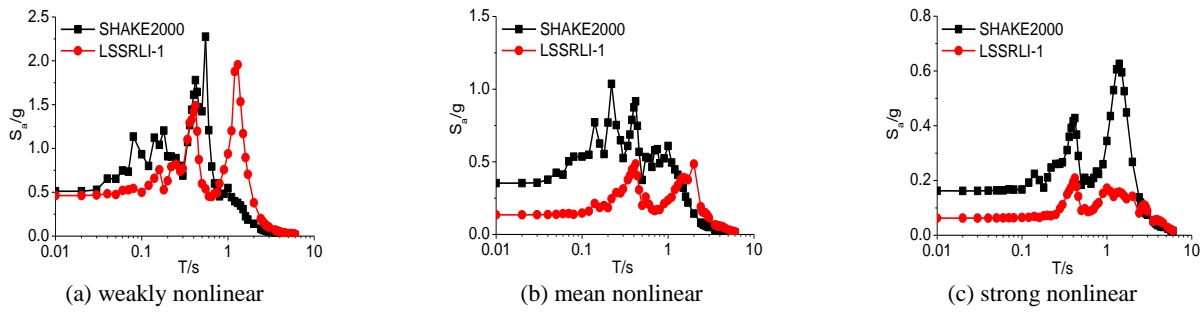


Figure 3. Comparison of response spectra between calculated and the measured records (MYGH06 station)

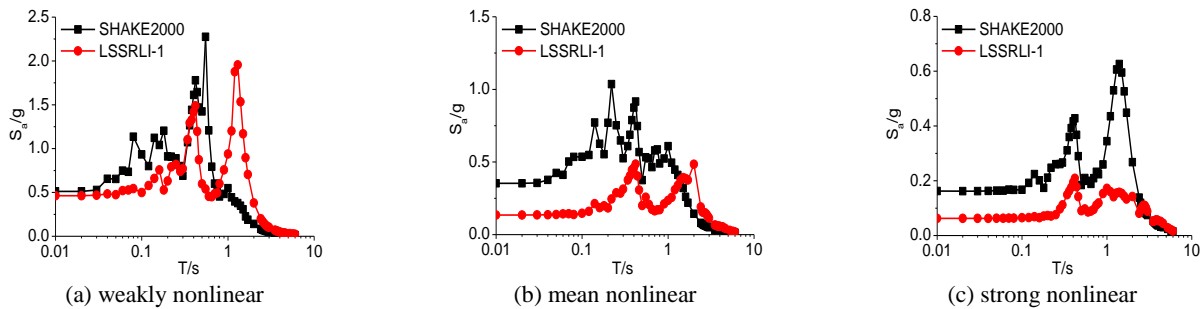


Figure 4. Comparison of response spectra between calculated and the measured records (NIGH11 station)

The difference between calculated response spectra and measured response spectra is given by spectral ratio $R(T)$.

$$R(T) = \ln[S_{a,p}(T)] - \ln[S_{a,m}(T)] \quad (1)$$

where, $S_{a,p}(T)$ is the calculated response spectra, $S_{a,m}(T)$ is the measured response spectra.

In site class I, the error between the LSSRLI-1 and the actual measured response spectra is more obvious than that of SHAKE2000. As shown in Table 3, the big different error of LSSRLI-1 is more than that of SHAKE2000. When the soil is strongly nonlinear condition, the error between the LSSRLI-1 and the actual measured response spectra has the situation of significant differences, while the error between the SHAKE2000 and the actual measured response spectra doesn't have the situation of significant differences. In site class II, the big different error of LSSRLI-1 is also more than that of SHAKE2000. The errors between the two programs and the actual measured response spectra both have the situation of significant differences. However, the difference of LSSRLI-1 is serious than that of SHAKE2000. Figures 1 and 2 further show that the difference between the SHAKE2000 and the actual measured response spectra is smaller than that between LSSRLI-1 and the measured results, especially when the soil is strongly nonlinear condition.

6. SHEAR STRAINS OF THE SOIL LAYER

In order to ascertain the difference between the two equivalent linear programs, shear strains of the soil layer calculated by the two programs under the same conditions are compared in this paper. The shear strain is calculated at the surface of every soil layer. It is the maximum shear strain. In site classes I and II, the maximum shear strain errors less than 20% calculated by SHAKE2000 and LSSRLI-1 are shown in Figure 5. While Figures 6 and 7 present the comparison of calculated shear strain between SHAKE2000 and LSSRLI-1.

As shown in Figure 5, in site class I, the shear strain error calculated by SHAKE2000 and LSSRLI-1 is less than 20% in most cases.

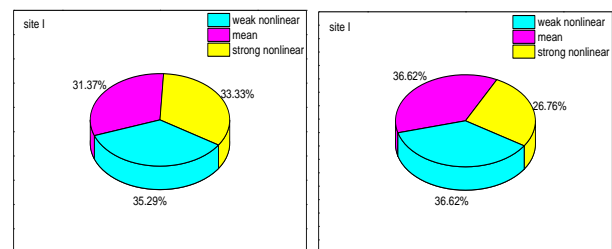


Figure 5. The error of maximum shear strain between SHAKE2000 and LSSRLI-1

Occasionally, however, the difference of shear strain is obvious. Besides, the shear strain of LSSRLI-1 is significantly higher than that of SHAKE2000, as shown in Figures 6 and 7. In site class II, when the soil is weakly nonlinear condition or mean value condition, the error of maximum shear strain calculated by SHAKE2000 and LSSRLI-1 is less than 20% in most cases. When the soil is strongly nonlinear condition, the error is less than 20% in some cases.

It is obvious that MYGH06 station is site class I. However, the shear strain calculated by SHAKE2000 and LSSRLI-1 is significantly different. This result overturns the previous statement that the results calculated by the two programs had little difference. The difference between the two programs in calculating shear strain may be the reason for the diversity in calculation results of shear strain. However, the methods for calculating shear strain between the two programs need to be further studied.

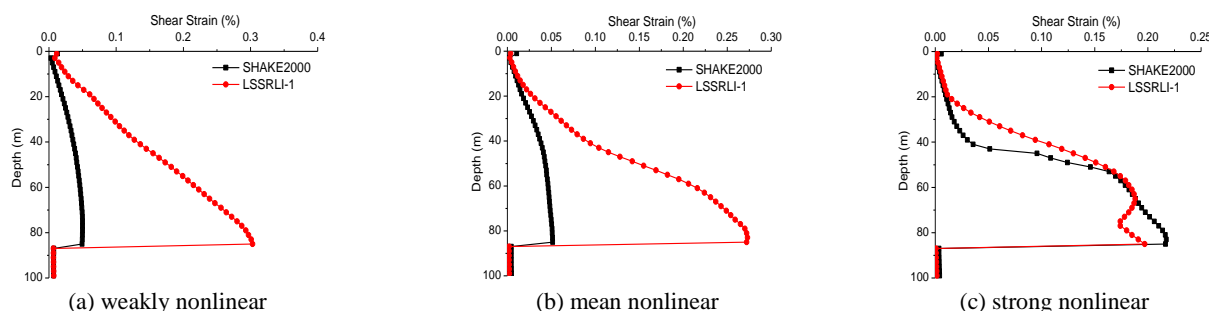


Figure 6. The comparison of calculated shear strain between SHAKE2000 and LSSRLI-1 (MYGH06 station)

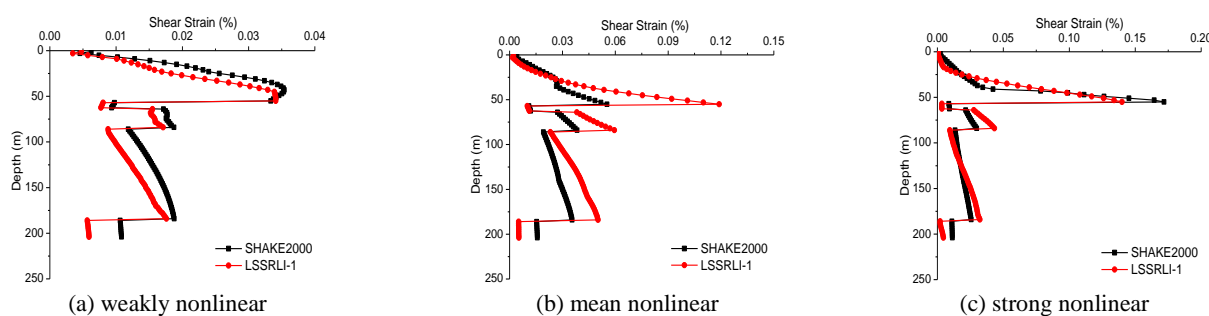


Figure 7. The comparison of calculated shear strain between SHAKE2000 and LSSRLI-1 (NIGH11 station)

7. CONCLUSIONS

This paper is based on 56 different actual seismic records of 28 stiff sites at KiK-net station. The soil dynamic shear modulus and damping ratio are divided into three kinds of operating conditions, which are weakly nonlinear condition, mean value nonlinear condition and strongly nonlinear condition separately. The results of the two programs SHAKE2000 and LSSRLI-1 are compared. The conclusions are drawn as follows:

(1) When the soil is weakly nonlinear condition, the error of peak acceleration calculated by SHAKE2000 and LSSRLI-1 can be ignored in most cases. When the soil is mean value or strongly nonlinear condition, the error can be ignored in some cases. For peak acceleration, only a few differences between the two programs and the measured results can be ignored.

But the results of SHAKE2000 are better than LSSRLI-1.

(2) In site class I, the probability of having a big difference between LSSRLI-1 and the measured response spectra is significantly higher than that of SHAKE2000. While when the soil is strongly nonlinear condition, the difference between LSSRLI-1 and the measured response spectra is obvious, but the difference between SHAKE2000 and the measured response spectra is not obvious. In site class II, the probability of having a big difference between LSSRLI-1 and the measured response spectra is also significantly higher than that of SHAKE2000. What's more, there are significant differences between the two programs and the measured response spectra, but the probability of having a significant difference between SHAKE2000 and the measured response spectra is lower than that of LSSRLI-1, especially for the strongly nonlinear soil.

(3) For shear strains of soil layer, when the soil was weakly or mean value nonlinear condition, the shear strain error calculated by SHAKE2000 and LSSRLI-1 is less than 20% in most cases. When the soil was strongly nonlinear condition, the shear strain error calculated by the two programs is less than 20% in most cases in site class I, while the error was less than 20% in some cases in site class II. For shear strains of soil layer, the shear strain of LSSRLI-1 is universally higher than that of SHAKE2000. The shear strains calculated by the two programs have some differences in a few cases. Occasionally, however, the difference is obvious.

8. ACKNOWLEDGEMENTS

The author would like to express her sincere appreciations for Shandong Provincial Natural Science Foundation, China (ZR2018PEE020) and Youth talent innovation project of Binzhou University (BZXYQNLG201701) for their supports.

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PAPER INFO

چکیده

Paper history:

Received 23 August 2018

Received in revised form 19 October 2018

Accepted 26 October 2018

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Response Spectra

Peak Acceleration

۵۶ حرکت زمین از بستر سنگ و سطح از ۲۸ محل سفت (سایت کلاس I و سایت کلاس II) از ایستگاه KiK-net انتخاب شده است. شتاب پیک شتاب، طیف پاسخ و فشار برشی از مکان های سخت واقعی با استفاده از SHAKE2000 و LSSRLI-1 محاسبه می شود. شباهت ها و تفاوت های بین SHAKE2000 و LSSRLI-1 و تفاوت های آنها از مستندات اندازه گیری شده مورد تجزیه و تحلیل قرار گرفته است. این مبنایی برای بهبود روش تجزیه و تحلیل پاسخ لرزه ای لایه های خاک است. نتایج نشان می دهد که وقتی خاک به طور آشکار غیر خطی نیست، بیشترین تفاوت در نتایج PGA محاسبه شده توسط SHAKE2000 و LSSRLI-1 می تواند نادیده گرفته شود و حداکثر خطا در محاسبه فشار برشی خاک نیز کمتر از ۲۰٪ است. هنگامی که خاک بسیار غیر خطی است، تنها چند تفاوت در نتایج PGA می تواند نادیده گرفته شود. حداکثر خطای فشار برشی خاک بیش از ۲۰٪ است. نتایج طیف های شتاب و واکنش محاسبه شده توسط SHAKE2000 و LSSRLI-1 از نتایج اندازه گیری در اکثر موارد بسیار متفاوت است. با این وجود احتمال تفاوت بزرگ و تفاوت معنی دار بین LSSRLI-1 و طیف پاسخ اندازه گیری بیشتر از SHAKE2000 است.

doi: 10.5829/ije.2019.32.01a.06