Research Article

The Characteristics of Seismic Response on Hard Interlayer Sites

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Based on the engineering geological data of a nuclear power plant site, nine engineering geological profiles were created with hard interlayers of different thicknesses. The equivalent linearization method of seismic motion segment-input used for one-dimensional nonlinear seismic response analysis was applied to study the effect of the interlayer thickness on the peak acceleration and the acceleration response spectra of the site seismic response. The results showed that there was an obvious influence of hard interlayer thickness on site seismic responses. With the increase of hard interlayer thickness, the site nonlinear effect on seismic responses decreased. Under the same thickness of the hard interlayer, the nonlinear effect of the site was strengthened with the higher input peak acceleration. In addition, the short-period acceleration response spectrum was found to be significantly influenced by the hard interlayer and showed that the longer the period, the less influence of the hard interlayer on the acceleration response spectrum coordinates. Moreover, the influenced frequency band was wider with the increase in the thickness of hard interlayer.

1. Introduction

The influence of site conditions on earthquake damage has been recognized widely [1–5]. For example, the 1906 San Francisco earthquake caused markedly severe damage on soft soil foundations throughout the city [6, 7]. During the 1975 Haicheng earthquake in China [1], the damage of brick chimneys in Yingkou city and Panjin district was equivalent to that of Haicheng County and Dashi-qiao, while the damage of typical brick houses in Haicheng County and Dashi-qiao was far more severe than that in Yingkou city and Panjin district; this difference was related to the thicker overburden layer in the former areas. During the 1976 Tangshan earthquake [1], the seismic damage of two areas in Tianjin was quite different. The survey results showed that the site of the area suffering lighter damage consisted of a soft intercalation of mucky clay at a depth of approximately 10 m. In particular, the earthquake that occurred in Mexico

on 19 September 1985 further demonstrated that site conditions have a significant impact on earthquake damage [8]. During this earthquake, Mexico City, which was 400 km away from the epicentre, suffered severe damage, far exceeding the damage that occurred in the area around the city. The analysis results showed that Mexico City is located in a deep and weak sedimentary basin, which caused the amplification of seismic motion and the lengthening of the duration of strong seismic motion. The destructive earthquakes that occurred in the last 2 decades [9], such as Nepal 2015, Chile 2010, Sichuan 2008, and Kocaeli 1999, proved that the influence of local site conditions on the earthquake damage is substantial when compared to travel path effects and the effects induced by the proximity of earthquake sources.

The damage of earthquake was found to be very selective of site conditions [10–14] which generally refer to local geological conditions, such as the near-surface soil layer,

topography, and fracture zones. Existing studies [10, 15–18] have shown that the impact of site conditions on seismic damage is due to their significant ground motion amplification or deamplification effect. The influence of the near-surface soil layer on seismic effects has attracted a lot of research due to its widespread impact and the large number of sites involved, and the research studies focused on the formation age [6, 7, 19–21], genetic type [22–25], thickness variability [26–28], structure [29–34], and dynamic characteristics of overlying soil layers [35–39]. Although many studies on site effects have been performed at home and abroad and the results are remarkable, there are few studies of the influence of hard interlayers on the site seismic response. In this paper, the one-dimensional seismic response analysis of a nuclear power plant site underlying a hard interlayer was performed to discuss the influence of the hard interlayer thickness on the site seismic response, in order to provide a basis on which the ground motion parameters for seismic design of similar sites will be determined. The site of this research is one of several soft soil sites in China's industry-specific projects for the further understanding of the impact of hard interlayers on ground motions. Thus, we confirm that the research in this manuscript has a certain reference value for understanding the characteristics of ground motions at similar sites.

2. Site Description and Input Ground Motions

2.1. Site Description. The site involved is a typical site for nuclear power plant site selection on soft soil site in China. It was found that there is a thick hard interlayer under the soft layer. Because of the importance of the project, it is necessary to study the influence of the hard interlayer on the seismic response of the site. For the confidentiality requirements of the nuclear engineering site, the specific location information is not convenient to disclose. The data derived from our in-situ tests and laboratory tests of the site are given in Table 1 and Figure 1. The site consists of a soft layer of silty clay and silty sand from the surface to a depth of 44.3 m, beneath which the hard interlayer composed of basalt and volcanic breccia continues to a depth of 198 m. Beneath the thick hard interlayer, a soft layer shows up again and extends to over 337.5 m with the measured shear wave velocity reaching 730 m/s at a depth of 337.5 m. According to the code for evaluation of seismic safety for engineering sites of China [40], the surface of the bedrock determined by drilling or the surface of the layer with the shear wave velocity not less than 700 m/s should be used as the input interface of ground motion for class-I site when establishing the one-dimensional site seismic response analysis model. Therefore, we chose the interface at the depth of 337.5 m as the interface of input ground motion, which is called the computational basis of the model.

It can be seen from Figure 1 that the shear wave velocity of the hard interlayers of the nuclear power plant site was about 1429 m/s–2499 m/s, which was more than twice that of underlying silty clay and overlying silty sand. From qualitative analysis point of view, the hard interlayer has a high wave impedance ratio relative to the underlying and

overlying soil layer, which will have a significant reflection effect on upward and downward ground motion, and the site amplification effect mainly depends on the overlying soil layer on the hard interlayer. In addition, the thick silty clay layer will show strong nonlinearity under the strong ground motion, and the thicker hard interlayer and soil layer will also have a significant impact on the lower-frequency ground motion.

2.2. Input Seismic Motion. The thick hard interlayer and soil layer of the analysis model will influence a wide frequency band of the site earthquake response, which means that not only the high-frequency seismic motion but also the low-frequency (long-period) seismic motion will be influenced. Therefore, the input seismic motions with a relatively wider band were selected. Based on this, the east-west acceleration record obtained from a near-field strong motion station in Qingping, Mianzhu (approximately 3 km from the fault), during the Wenchuan Ms8.0 earthquake was selected as the seismic motion input [41], and its peak acceleration is 824.1 gal. The input acceleration time history and the corresponding acceleration response spectra are shown in Figure 2. From Figure 2, it can be seen that the input seismic motions have a wider frequency band, especially the abundant long-period components with a response spectrum of 25.6 gal at the period of 20 s. To consider the influence of the hard interlayer on the seismic response of soil layers under different input ground motions, the peak accelerations of the actual ground motions were scaled to 50 gal, 100 gal, and 200 gal.

3. Site Seismic Response Results

One-dimensional analysis (i.e., assuming horizontal soil layers, boundaries of infinite lateral extension, and vertically propagating shear waves) has proved adequately to model the propagation of the seismic waves through the soil profile (e.g., [42, 43]). Then, the equivalent linear method for the one-dimensional site response analysis has been widely used in both research and engineering practices (e.g., [9, 17, 36, 42–44]) due to its simplicity, flexibility, and robustness. Based on this method, many calculation programs are implemented and improved day by day, such as the SHAKE91 [45], ProShake [46], DEEPSOIL [47], and our LSSRLI-1 [48, 49] which has the same basic theory, and the validity of LSSRLI-1 was verified and compared with that of SHAKE91 and DEEPSOIL by Ma and Ding [50]. Therefore, the one-dimensional seismic site response calculation of the nuclear power plant site underlying a hard interlayer in this paper will be carried out by our program LSSRLI-1. In view of the relevant literature available for the verification of procedure, this paper does not provide a detailed introduction.

3.1. One-Dimensional Site Seismic Response Analysis Model. As shown in Table 1, the soil profile consists of 17 major layers. For the application of the one-dimensional equivalent linear method, these major layers were further divided into

TABLE 1: Information regarding soil strata collected from drilling results.

No.	Depth (m)	Soil property	Thickness (m)	Density (t/m^3)	Category number
1	3.9	Silty clay	3.9	1.81	1
2	13.4	Silty sand	9.5	1.93	2
3	17	Silty clay	3.6	1.93	3
4	21	Silty clay	4	1.89	4
5	25.2	Silty clay	4.2	1.89	5
6	32	Silty clay	6.8	1.89	4
7	38	Silty clay	6	2.04	6
8	42.7	Silty clay	4.7	1.96	7
9	44.3	Silty sand	1.6	1.92	8
10	92.9	Basalt	48.6	2.51	18
11	198	Volcanic breccia	105.1	2.51	18
12	204	Silty clay	6	2.06	9
13	216	Silty clay	12	2.02	10
14	279	Silty clay	63	2.07	11
15	309.8	Silty clay	30.8	2.05	12
16	311.1	Silt sand	1.3	2.06	13
17	337.5	Silty clay	26.4	2.06	14
18	—	Silty clay	—	2.55	19

FIGURE 1: Shear wave velocity of the nuclear power plant site derived from the controlled borehole field test.

FIGURE 2: (a) Input acceleration history. (b) The response spectra of input acceleration.

TABLE 2: Analysis models and the corresponding soil mechanical parameters.

Sublayers	Soil property	Depth (m)	Thickness (m)	Shear wave velocity (m/s)	Density (t/m ³)	Category number
1	Silty clay	3.9	3.9	105	1.81	1
2		7.0	3.1	156	1.93	2
3	Silty sand	10.0	3.0	254	1.93	2
4		13.4	3.4	289	1.93	2
5		17.0	3.6	264	1.93	3
6	Silty clay	21.0	4.0	224	1.89	4
7		25.2	4.2	218	1.89	5
8	Silty clay	29.0	3.8	229	1.89	4
9		32.0	3.0	277	1.89	4
10		35.0	3.0	312	2.04	6
11	Silty clay	38.0	3.0	333	2.04	6
12		42.7	4.7	347	1.96	7
13	Silty sand	44.3	1.6	357	1.92	8
14		48.0	3.7	1249	2.51	18
15	Basalt	52.0	4.0	1332	2.51	18
16		56.0	4.0	1427	2.51	18
17		60.0	4.0	1428 (466)	2.51 (1.96)	18 (7)
18	Basalt (silty clay)	65.0	5.0	1470 (470)	2.51 (1.96)	18 (7)
19		70.0	5.0	1470 (474)	2.51 (1.96)	18 (7)
20	Basalt (silty clay)	74.2	4.2	1481 (477)	2.51 (1.96)	18 (7)
21		80.0	5.8	1874 (482)	2.51 (1.98)	18 (15)
22		85.0	5.0	2272 (486)	2.51 (1.98)	18 (15)
23	Basalt (silty clay)	90.2	5.2	2499 (491)	2.51 (1.98)	18 (15)
24		92.9	2.7	1500 (493)	2.51 (1.98)	18 (15)
25	Volcanic breccia (silty clay)	99.0	6.1	1463 (498)	2.51 (1.98)	18 (15)
26		105.0	6.0	1463 (503)	2.51 (1.98)	18 (15)
27		111.0	6.0	1463 (508)	2.51 (1.98)	18 (15)
28	Volcanic breccia (silty clay)	117.0	6.0	1552 (513)	2.51 (1.98)	18 (15)
29		123.0	6.0	1552 (518)	2.51 (1.98)	18 (15)
30		129.0	6.0	1552 (524)	2.51 (1.99)	18 (16)
31	Volcanic breccia (silty clay)	135.0	6.0	1588 (529)	2.51 (1.99)	18 (16)
32		141.0	6.0	1588 (535)	2.51 (1.99)	18 (16)
33		147.0	6.0	1588 (540)	2.51 (1.99)	18 (16)
34		153.0	6.0	1588 (546)	2.51 (1.99)	18 (16)
35	Volcanic breccia (silty clay)	159.0	6.0	1552 (551)	2.51 (1.99)	18 (16)
36		165.0	6.0	1552 (557)	2.51 (1.99)	18 (17)
37		171.0	6.0	1552 (563)	2.51 (1.99)	18 (17)
38		177.0	6.0	1605 (569)	2.51 (1.99)	18 (17)
39	Volcanic breccia (silty clay)	183.0	6.0	1605 (574)	2.51 (1.99)	18 (17)
40		189.0	6.0	1552 (580)	2.51 (1.99)	18 (17)
41		195.0	6.0	1552 (586)	2.51 (1.99)	18 (17)
42		198.0	3.0	1552 (589)	2.51 (1.99)	18 (17)
43		204.0	6.0	601	2.06	9
44		210.0	6.0	603	2.02	10
45		216.0	6.0	605	2.02	10
46		222.0	6.0	608	2.07	11
47	Silty clay	228.0	6.0	608	2.07	11
48		234.0	6.0	608	2.07	11
49		240.0	6.0	635	2.07	11
50		246.0	6.0	635	2.07	11
51		252.0	6.0	635	2.07	11
52		260.0	8.0	667	2.07	11

TABLE 2: Continued.

Sublayers	Soil property	Depth (m)	Thickness (m)	Shear wave velocity (m/s)	Density (t/m ³)	Category number
53	Silty clay	264.0	4.0	667	2.07	11
54		267.0	3.0	667	2.07	11
55		270.0	3.0	688	2.07	11
56		273.0	3.0	688	2.07	11
57		276.0	3.0	688	2.07	11
58		279.0	3.0	688	2.07	11
59		282.0	3.0	706	2.05	12
60		285.0	3.0	706	2.05	12
61		288.0	3.0	706	2.05	12
62		291.0	3.0	706	2.05	12
63		294.0	3.0	706	2.05	12
64		297.0	3.0	706	2.05	12
65		300.0	3.0	715	2.05	12
66		303.0	3.0	715	2.05	12
67		306.0	3.0	715	2.05	12
68		309.8	3.8	715	2.05	12
69	Silt sand	311.1	1.3	715	2.06	13
70	Silty clay	315.0	3.9	715	2.06	14
71		318.0	3.0	730	2.06	14
72		321.0	3.0	730	2.06	14
73		324.0	3.0	730	2.06	14
74		327.0	3.0	730	2.06	14
75		330.0	3.0	730	2.06	14
76		333.0	3.0	730	2.06	14
77		337.5	4.5	730	2.06	14
78	Computational basis of the model			730	2.55	19

TABLE 3: The dynamic nonlinear parameter of different soil categories.

Category number	Soil layer	Modulus ratio or damping ratio	Shear strain γ (10^{-4})							
			0.05	0.1	0.5	1	5	10	50	100
1	Silty clay	$G/G_{\max}$	0.992	0.984	0.924	0.859	0.633	0.463	0.147	0.079
		λ	0.019	0.030	0.046	0.058	0.092	0.112	0.169	0.184
2	Silt sand	$G/G_{\max}$	0.992	0.984	0.925	0.861	0.664	0.497	0.165	0.090
		λ	0.004	0.007	0.025	0.036	0.074	0.120	0.239	0.273
3	Silty clay	$G/G_{\max}$	0.996	0.992	0.960	0.924	0.661	0.493	0.163	0.089
		λ	0.005	0.009	0.032	0.047	0.065	0.103	0.192	0.215
4	Silty clay	$G/G_{\max}$	0.993	0.987	0.937	0.881	0.718	0.560	0.203	0.113
		λ	0.004	0.007	0.028	0.045	0.060	0.098	0.204	0.236
5	Silty clay	$G/G_{\max}$	0.991	0.983	0.919	0.870	0.762	0.678	0.316	0.188
		λ	0.005	0.009	0.032	0.047	0.055	0.091	0.193	0.224
6	Silty clay	$G/G_{\max}$	0.994	0.989	0.946	0.897	0.728	0.572	0.211	0.118
		λ	0.005	0.009	0.030	0.041	0.062	0.086	0.189	0.228
7	Silty clay	$G/G_{\max}$	0.990	0.980	0.905	0.827	0.702	0.601	0.232	0.131
		λ	0.005	0.009	0.032	0.047	0.061	0.099	0.198	0.226
8	Silt sand	$G/G_{\max}$	0.989	0.978	0.947	0.906	0.822	0.716	0.371	0.227
		λ	0.005	0.009	0.032	0.037	0.054	0.083	0.186	0.282
9	Silty clay	$G/G_{\max}$	0.992	0.985	0.938	0.896	0.801	0.703	0.321	0.191
		λ	0.005	0.009	0.032	0.044	0.063	0.085	0.172	0.208
10	Silty clay	$G/G_{\max}$	0.993	0.986	0.943	0.905	0.834	0.763	0.439	0.281
		λ	0.005	0.010	0.034	0.048	0.068	0.081	0.157	0.179
11	Silty clay	$G/G_{\max}$	0.995	0.991	0.955	0.915	0.746	0.595	0.227	0.128
		λ	0.002	0.004	0.018	0.031	0.056	0.094	0.203	0.238
12	Silty clay	$G/G_{\max}$	0.996	0.991	0.958	0.919	0.813	0.685	0.303	0.179
		λ	0.002	0.004	0.018	0.030	0.050	0.083	0.180	0.211

TABLE 3: Continued.

Category number	Soil layer	Modulus ratio or damping ratio	Shear strain γ (10^{-4})							
			0.05	0.1	0.5	1	5	10	50	100
13	Silt sand	$G/G_{\max}$ λ	0.992 0.001	0.985 0.003	0.934 0.012	0.897 0.018	0.831 0.035	0.757 0.050	0.453 0.104	0.293 0.120
14	Silty clay	$G/G_{\max}$ λ	0.989 0.017	0.978 0.025	0.913 0.041	0.876 0.044	0.782 0.053	0.701 0.066	0.413 0.128	0.262 0.189
15	Silty clay	$G/G_{\max}$ λ	0.992 0.005	0.984 0.009	0.923 0.032	0.884 0.047	0.703 0.071	0.611 0.088	0.239 0.175	0.136 0.206
16	Silty clay	$G/G_{\max}$ λ	0.993 0.002	0.986 0.005	0.935 0.022	0.886 0.038	0.713 0.075	0.624 0.093	0.249 0.198	0.142 0.242
17	Silty clay	$G/G_{\max}$ λ	0.990 0.021	0.980 0.032	0.907 0.061	0.862 0.078	0.712 0.118	0.607 0.143	0.236 0.179	0.134 0.198
18	Volcanic breccia	$G/G_{\max}$ λ	0.990 0.004	0.970 0.006	0.900 0.019	0.850 0.030	0.700 0.075	0.550 0.090	0.320 0.110	0.200 0.120
19	Computational basis of the model	$G/G_{\max}$ λ	1.000 0.050	1.000 0.050	1.000 0.050	1.000 0.050	1.000 0.050	1.000 0.050	1.000 0.050	1.000 0.050

TABLE 4: Information of the hard interlayer of analysis models.

Analysis models	Sublayers (44.3 m–198 m)									Thickness of hard interlayer (m)
	14–16	17–18	19–21	22–24	25–26	27–29	30–33	34–37	38–42	
Model 1	Basalt				Silty clay					11.7
Model 2	Basalt				Silty clay					20.7
Model 3	Basalt				Silty clay					35.7
Model 4	Basalt				Silty clay					48.6
Model 5	Basalt				Volcanic breccia			Silty clay		60.7
Model 6	Basalt				Volcanic breccia			Silty clay		78.7
Model 7	Basalt				Volcanic breccia			Silty clay		102.7
Model 8	Basalt				Volcanic breccia			Silty clay		126.7
Model 9	Basalt				Volcanic breccia					153.7

sublayers which were all assigned the same dynamic soil properties as the main layer. The thicknesses of the sublayers were chosen so that the site seismic response stability requirements of the time-domain method [51] in the LSSRLI-1 site seismic response calculation would be satisfied. Then, the one-dimensional analysis model for the equivalent linear method for site response analysis based on the partition of the major layers was established. Table 2 shows the composition of the one-dimensional analysis models, and the dynamic nonlinear parameter of different soil categories derived from the laboratory cyclic tests used in the analysis models is shown in Table 3.

For considering the influence of the hard interlayer on the site seismic response, the underlying silty clay (given in the brackets in Table 2) was used to replace the basalt and volcanic breccia to change the hard interlayer thickness so as to establish analytical models containing a hard interlayer of a different thickness, as shown in Table 4. The model 9 corresponded to the actual soil layer profile, while the thickness of the hard interlayer of model 8 is 126.7 m with the original volcanic breccia of layers 14 to 42 was replaced by silty clay. The mechanical parameters corresponding to the replacement silty clay are also given in the brackets in Tables 2 and 3, which were derived from the drilling data of the borehole nearby. The details of the remaining analysis

FIGURE 3: Sample points and regression curve.

models are provided in Table 4. The shear wave velocities of the replacement silty clay layer were determined according to equation (1), which was based on the statistical regression of the in-situ test shear wave velocity data. The statistical data

TABLE 5: The horizontal peak acceleration on the top of the hard interlayer and on the site surface under different input seismic motion levels.

Models	50 gal input peak acceleration		100 gal input peak acceleration		200 gal input peak acceleration	
	On the top of hard interlayer	On the site surface	On the top of hard interlayer	On the site surface	On the top of hard interlayer	On the site surface
Model 1	32.3	68.4	65.4	124.4	121.8	245.2
Model 2	32.4	64.3	64.8	122.8	116.5	235.0
Model 3	31.3	61.2	60.9	114.0	104.8	217.2
Model 4	29.5	61.3	57.0	106.7	96.0	206.5
Model 5	28.1	58.9	54.0	102.8	93.4	197.7
Model 6	25.3	58.9	48.0	116.5	90.0	199.9
Model 7	28.2	68.9	54.0	139.0	92.6	213.9
Model 8	26.1	80.3	46.8	150.2	98.1	250.8
Model 9	32.8	89.6	61.5	170.2	101.0	293.1

FIGURE 4: (a) Ratios of the peak accelerations on the site surface to those of the input seismic motions (S/I) and ratios of the peak accelerations on the top of the hard interlayer to those of the input seismic motions (T/I). (b) Ratios of the peak accelerations on the site surface to those on the top of the hard interlayer (S/T).

sampling point and the regression relationship are shown in Figure 3.

$$V_s = 420.8e^{0.0017H}, \quad (1)$$

where H represents the depth.

3.2. Site Response with Different Thicknesses of the Hard Interlayer. Table 5 lists the horizontal peak accelerations on the top of the hard interlayer and on the site surface, respectively. It can be seen that, under the same input seismic motions, the peak accelerations on the top of the hard interlayer were less than the input peak acceleration, while the peak accelerations on the site surface were greater than the input acceleration peak. From Table 1, a soft layer with a

thickness of about 44.3 m was found to be between the hard interlayer and the site surface. These results indicate that the hard interlayer has obvious isolation effect on ground motion while the soft soil layer overlying the hard interlayer has a significant amplification effect on the seismic motion.

We further calculated the ratio between the input peak accelerations, the peak accelerations on the top of the hard interlayer, and the peak accelerations on the site surface of each model. The results (as shown in Figure 4) show that, under the same input seismic motion, the ratios of the peak accelerations on the top of the hard interlayer to the input peak accelerations (denoted as T/I) were smaller than 1.0 and the ratios of the peak accelerations on the site surface to the input peak accelerations (denoted as S/I) were greater than 1.0, which indicates that the overlying soil layers on the

FIGURE 5: Continued.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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