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Original Article

Effect of Local Site Conditions on Earthquake Ground Motions in Hanoi: Results from Numerical Simulations

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Abstract: This paper presents some numerical simulation results on the influence of local site conditions on earthquake ground motions in Hanoi. Numerical simulation method through DEEPSOIL program was used in the study. Geological data of 600 groundwater survey and engineering geology boreholes in Hanoi as well as the acceleration records of Imperial Valley earthquake in 1979 with magnitude M = 6.5, hypocenter of 26.5 *km*, and PGA of 0.169 *g* were chosen as input data for the research. By analyzing geological conditions, tectonics, seismic characteristics of different soil types in Hanoi, a geological cross-section cutting through different engineering geology in Hanoi areas have been constructed. Numerical simulations of site effect at typical locations along the cross-section show: (i) The geological conditions on the surface of Hanoi clearly influence the earthquake ground motion, this is confirmed by the increase in the amplitude of the horizontal component of ground acceleration and the change of the strong vibrations from short to longer period. These effects obey a general rule, they become stronger when moving on the cross-section from west to east, corresponding to an increase in the thickness of the weak sedimentary layers covering the hard rock; and (ii) However, at the place where the weak and soft soil layer appear (LK50 borehole), despite of the vibrations that are still converted from short to longer periods, the amplitude of the PGA is strongly attenuated at the surface layer.

Keywords: Site effect, Hanoi, local site condition, numerical simulation, geological cross-section.

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1. Introduction

The formation of the Red River basin is considered as a results of the activity of the Red River Shear Zone (RRSZ). The Ailao Shan-Red River shear zone (Yunnan, China) running more than 1,000 *km* from eastern Tibet to Vietnam is the boundary of the Indochina plate and the South China plate. As shown in Figure 1, this shear zone divides into two main faults, the Song Hong and the Song Chay faults, which run across the Hanoi basin [1, 2]. As shown by previous geodynamic researches, at present the Song Hong and Song Chay faults are the active zones, which can create earthquake of magnitude up to M_s = 6.1 and produce intensity of VIII on the MSK-64 scale in downtown area of Hanoi city [3].

According to previous studies, Hanoi is located on an area with a weak ground consisting of thick sedimentary layers, complex geological structure and shallow aquifer belonging to the Holocene and Pleistocene epochs of Quaternary formations [4, 5]. Hanoi is a capital, cultural and political center of Vietnam. Over the past two decades, the infrastructure of Hanoi has developed very fast. Many mega structures, such as high-rise buildings, modern underground constructions, and subway systems have been built. The safety of construction works in the Hanoi city area when an earthquake occurs is a matter of concern to many scientists. Based on earthquakes, seismic tectonics, geotechnical, and hydrogeological data, Xuyen and colleagues have constructed the first map of seismic microzonation for Hanoi in 1990 [6]. In the following work, the microzonation map and site effect of Hanoi have been further improved by more details [7-9].

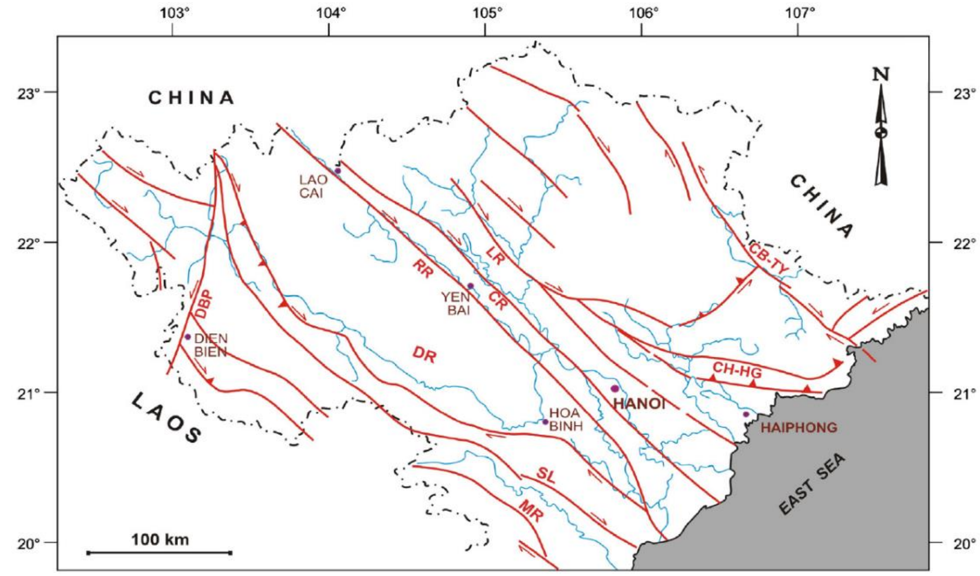


Figure 1. The map of northern Vietnam with some major faults (RR: Red River, DR: Da River, CR: Cai River, LR: Lo River, MR: Ma River, DBP: Dien Bien Phu, CB-TY: Cao Bang- Tien Yen, CH-HG: Chi Linh - Hong Gai). Adapted from Tran Dinh To et al., 2013 [10]. Adapted with permission.

In theory, earthquake in Northern of Vietnam can have a magnitude of up to M_s = 7.0 and the hypocenter can be around 15-25 *km*, seriously threatening Hanoi areas [11, 12]. Therefore, seismic hazard assessment in Hanoi is always the most attractive problem to study by many researchers. With the crucial position and the weak geological condition of Hanoi capital, in this work we choose another way of assessment, which is to evaluate the effects of local site conditions in Hanoi city by earthquake.

There are many examples of local geological conditions that have had a major impact on human and property losses when earthquakes occur. For example, in 1985, the Michoacán earthquake (M_w = 8.1) happened at distance 400 *km* far from the Mexico City.

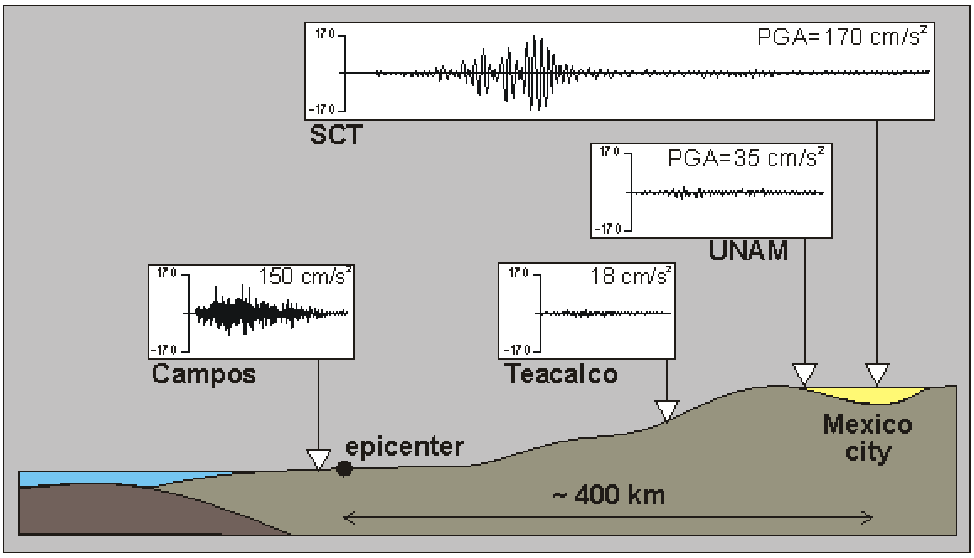


Figure 2. Site effects in Mexico city: recordings from the 1985 earthquake
Adapted from Semblat J.F. and Pecker A., 2009 [13]. Adapted with permission.

Theoretically, vibrations when propagating will decrease in energy with distance. However, the PGA (Peak Ground Acceleration) at the SCT station (PGA = 170 cm/s^2) in Mexico City was even bigger than in the Campos station that is nearby the epicenter (PGA = 150 cm/s^2). The ground motion was amplified, and the period became longer than the original ones [13]. The reason is mostly due to local site conditions of Mexico City, which is situated in the Mexican basin with alluvium and thick clay sediments. Therefore, in the case of Hanoi city with moderate seismicity and weak soil ground, the influence of the site effect should be paid more attention.

2. Database and Method

Database

Data of 600 boreholes in Hanoi areas were supplied by Bui Du Duong, Phi Hong Thinh, and Do Anh Chung, among them 18 boreholes were selected for the numerical simulations. The input data were borehole number; borehole locations; borehole coordinates; elevation of the borehole; depth of the borehole; ground water depth in the borehole; soil descriptions, thickness of layers, densities and SPT values in the borehole.

Method

To simulate the influence of ground conditions during earthquakes, the methods Shake91 and DEEPSOIL as described by Hashash et al. were applied [14, 15]. In brief, the model is considered as consisting of many semi-infinite horizontal layers (N layers). These layers lie on the lower half of the homogeneous space called the bottom layer. The layers in the model are homogeneous and isotropic. They are described by their thickness, density, damping ratios of soil, and shear modulus.

The method considers the response of shear waves propagating vertically from underlying rock formation (the base rock motion or the rock outcrop motion). The process of calculating the wave propagation equation can be done in both the time and the frequency domain. DEEPSOIL will read the input motion to find out the maximum acceleration; calculate the predominant period, maximum stresses and strains in the middle of each sublayer; compute the new motions at the top of any sublayer in the model.

By the program one can plot the corresponding simulated acceleration spectrum for each soil layer in the model, the amplification function between any two sublayer~~s~~, the Fourier amplitude ratio (surface/input) vs frequency, the PGA profile, the displacement profile and export the output data to a spreadsheet file.

In this work, the calculation of the wave propagation equation was done in the frequency domain using the strong motion of Imperial Valley earthquake in 1979 as input motion.

3. Results and Discussion

Construction of a geological cross-section

In a previous study in 2018, we used borehole data and DEEPSOIL program to primarily assess the local site effects for several areas in Hanoi [16]. However, the results were not enough for a seismic hazard assessment of Hanoi because the number of the boreholes were too small.

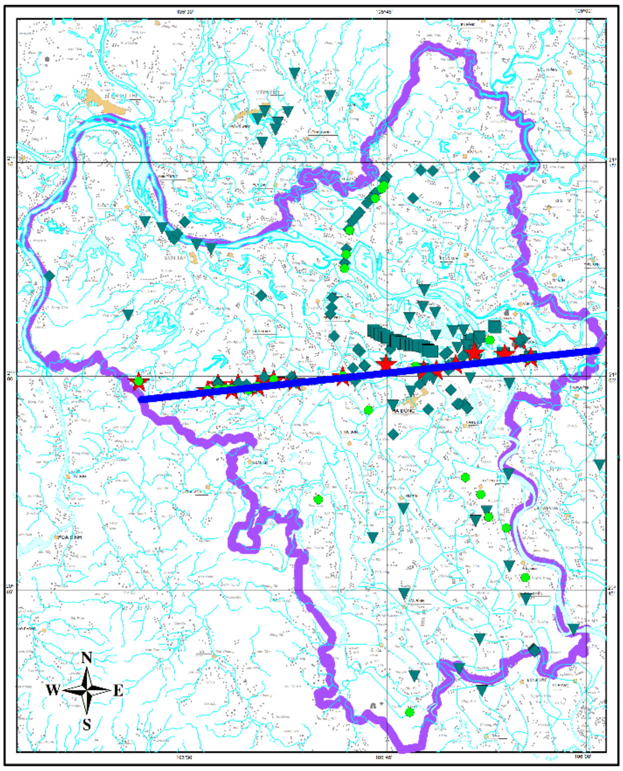


Figure 3. The location of the investigated boreholes in Hanoi area.

In this work, we collected data from more than 600 boreholes in Hanoi area. Based on analysis of the geological conditions, tectonics, seismic characteristics of different soil types in Hanoi, a structural seismic cross-section cutting through different engineering geology in Hanoi was constructed (the blue, thick horizontal line in Figure 3). The geological cross-section was selected to reflect the basic properties of the Hanoi area in general and northern Vietnam, in particular. In this profile, 18 boreholes were chosen with full characteristics of Hanoi geology (Table 1).

Table 1. The location of the boreholes in seismic cross-section from Western to Eastern of Hanoi

No.	Borehole	Latitude	Longitude	Distance (*km*)	Location of the borehole
1	628	20.994226	105.438726	Starting point of the line	Yen Trung, Thach That, Hanoi
2	625	20.983919	105.525122	9.08	Hoa Lac, Thach That, Hanoi
3	VBPC CL-LK3	20.991603	105.538140	1.63	Bac Phu Cat flyover bridge, Hanoi
4	633	20.985349	105.555481	1.98	Dong Truc, Thach That, Hanoi
5	CVGI CT-GP1	20.991767	105.563565	1.10	Vuc Giang I bridge, Hanoi
6	636	20.988772	105.587974	2.56	Ngoc Liep, Quoc Oai, Hanoi
7	CDS-14	20.999061	105.596226	1.43	Ngoc Bai, Thang Long express way, Hanoi
8	641	20.996252	105.608135	1.28	Tam Quang, Ngoc Liep, Quoc Oai, Hanoi
9	HKC-CS04	20.995198	105.633837	2.67	Dong Mo bridge, Hanoi
10	612	21.000718	105.694375	6.31	An Thuong, Hoai Duc, Hanoi
11	LK56	21.014739	105.748885	5.87	Tay Mo, Mieu Nha, Hanoi
12	LK-P3	21.00749	105.79597	4.94	Hoang Minh Giam over bridge, Hanoi
13	LK51	21.007757	105.811574	1.63	Quan Nhan, Trung Hoa, Thanh Xuan, Hanoi
14	LK50	21.014747	105.835938	2.65	De La Thanh, Trung Phung, Dong Da, Hanoi
15	LK5DT	21.028599	105.859531	2.90	Chuong Duong Do, Hoan Kiem, Hanoi
16	M2	21.026685	105.897367	3.93	Co Linh, Long Bien, Hanoi
17	HK19	21.042436	105.916375	2.64	Phuc Loi, Long Bien, Hanoi
18	LK3P16	21.022676	105.930190	2.62	Thach Ban, Long Bien, Hanoi

The first borehole in Yen Trung, Thach That (Hanoi) is located near the border of Hanoi city and Hoa Binh province. At this location, the sediment is thin and the data of boreholes showed that the bedrock is very near the ground surface, at around 30 *m*. The depth of bedrock increases along the profile toward the center of Hanoi city (Figure 4). From borehole 9th, the layer of sand and gravel appear and the depth of the bedrock is around over 40 *m*. In boreholes 13, 14 and 15 layers of silt appear under the cover layer. In this area the depth of the rock layer is larger 100 *m*. At the depth from 60 *m* to 80 *m* the layers are composed of very dense blackish grey to blueish grey sandstone and siltstone.

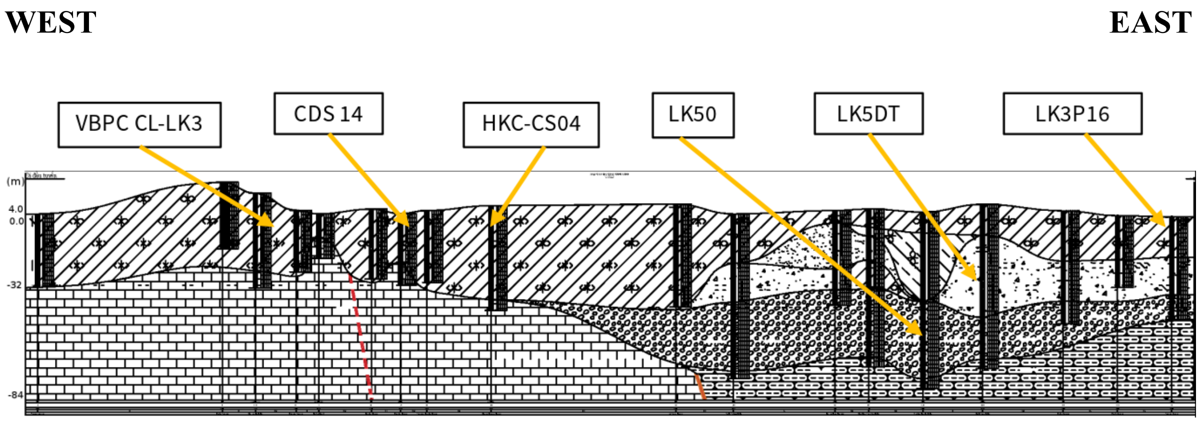


Figure 4. The geological cross section in the West-East direction through Hanoi city.

Cover layer: Cultivated soil, clay, silt, or silty sand

Very dense multicolor, multi-mineral gravel and cobble.

Medium dense fine sand

Sandstone, siltstone

Dense to very dense sand mixed gravels

Moderaterly to highly crack limestone

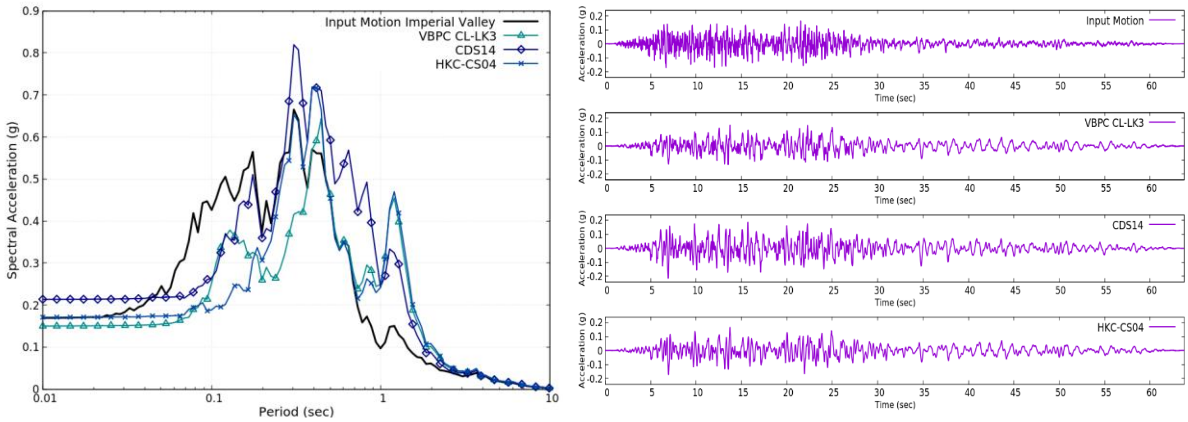
With input data described above, we constructed a geological cross-section for Hanoi in the West to the East direction (Figure 4). This geological cross-section is typical not only for Hanoi, it also conforms with the natural geology and geography of Northern Vietnam, which is developing in the direction from West to East (The terrain is gradually sloping from West to East). This geological cross-section clearly distinguishes the following areas: the hard rock area near the surface in the west; the transition zone (containing the Red River fault) with deeper bedrock and additional layers of dense to very dense blueish grey, yellowish brown, whiteish grey medium to coarse sand mixed gravels; and the central Hanoi area with sedimentary layers, such as silt, sand, very dense gravel and cobble, very dense blackish grey, blueish grey sandstone and siltstone. For simplification, in the construction of this cross-section we have combined several thin and small geological layers into larger ones.

Simulation results

From a number of seismograms supported by the DEEPSOIL program, we chose the strong motion of Imperial Valley earthquake in 1979 for analysis. With the earthquake magnitude *M* of 6.5, hypocenter of 26.5 *km*, and PGA of 0.169 *g*, it is considered comparable with condition of seismogenic source zone in Hanoi [3].

Based on the sedimentary characteristics, for analysis we have divided the constructed cross-section into two main areas, a western and an eastern one.

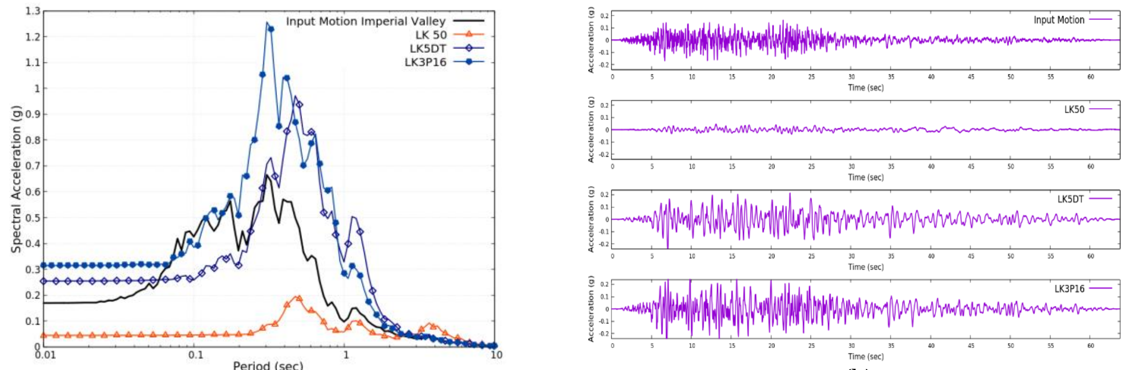
The western part of the cross-section includes the boreholes VBPC CL-LK3 in Bac Phu Cat and CDS-14 and HKC-CS04 in Quoc Oai, Hanoi. These boreholes are characterized by self-weathering sediments from the rocks in the same area (edQ). The eastern part of the cross-section includes the boreholes LK51 at Trung Hoa, Thanh Xuan district, LK50 at Trung Phung, Dong Da district, and LK3P16 at Thanh Tri, Long Bien district, Hanoi. These boreholes have diverse sedimentary layers. Their origin is from ancient rivers and lakes (amQ). The results of the analysis are shown in Figure 5.



(a) (b)

Figure 5. Simulation results of site effect in the Western part of Hanoi: a) Spectral acceleration of the boreholes VBPC CL-LK3, CDS14 and HKC-CS04; b) Acceleration of input motion Imperial Valley 1979 and new acceleration at boreholes VBPC CL-LK3, CDS14 and HKC-CS04.

Simulation results for the VBPC CL-LK3, CDS14 and HKC-CS04 boreholes (Figure 5) show that their simulated spectral accelerations varied only little compared to that of the input motion. At high frequencies, the amplitude in spectral acceleration is slightly lower than the input acceleration. This is physically consistent because the energy is lost during wave propagation. In contrast, in the low frequency part, the signal is amplified by the structure of the soil layers, the energy gain by site effect is proportional to and complementary to the energy loss due to wave propagation, so that the amplified signal is approximately equal to Imperial Valley motion. This little variation is explained by the geological structure of the western part of the cross-section in Bac Phu Cat and Quoc Oai areas, where the thin sediments formed on the bedrock by its weathering are composed of very dense sand, gravel, or very stiff clay. Only in the case of the CDS14 borehole, the PGA value is larger than the input motion. Although the surrounding area has a good foundation, at the CDS14 position, there are thick clay layers on the bedrock interspersed with clay mud near the surface. This is the factor that makes the spectral acceleration of the surface layer amplified compared to the spectral acceleration of input motion.



(a) (b)

Figure 6. Simulation results of site effect in the Eastern part of Hanoi: a) Spectral acceleration of the boreholes LK50, LK5DT and LK3P16; b) Acceleration of input motion Imperial Valley 1979 and new acceleration at boreholes LK50, LK5DT and LK3P16.

The boreholes LK50, LK5DT and especially LK3P16 (in Thach Ban, Long Bien district) are very typical for the local site conditions in the center of Hanoi city. Their sediments are composed of deposits of loose-to-medium cohesionless soil, surface alluvium layer, and sensitive clays, which were left behind by dead rivers and lakes. Simulation results in Figure 6a show that at these boreholes the site effect can be observed very clearly (the lines with circle and square markers). Especially, the accelerations obtained at Thach Ban, Long Bien district (borehole LK3P16) and Hai Ba Trung district (borehole LK5DT), locations with week soil ground, show all characteristics of the site effect, such as amplified amplitude of the ground motion and prolonged shaking duration (Figure 6b). In this area, the results for the LK50 borehole is an exception with PGA value of only 0.195 *g* compared to 0.665 *g* of the input motion. This is explained by the anomalous geological structure at this location, where there is a very thick layer of mud at a depth of 15.5 *m* to a depth of 43.5 *m*.

4. Conclusions

In this study, with a large number of borehole data, we were able to construct a geological cross-section for Hanoi area. Numerical simulation results obtained from data of the boreholes along this cross-section afforded detailed and accurate information on the Shear wave velocity and unit weight, therefore allowed us to come to the conclusion: (i) The geological conditions on the surface of Hanoi have clearly influenced the earthquake ground motion, which is shown by the increase in the amplitude of the horizontal component of ground acceleration and the change of the strong vibrations from short to longer period. These effects obey a general rule: they become stronger when moving on the cross-section from west to east, corresponding to an increase in the thickness of the weak sedimentary layers covering the hard rock; and (ii) At the place where the weak and soft soil layer appears (LK50 borehole), despite of the vibrations that are still converted from short to longer periods, the amplitude of the PGA is strongly attenuated at the surface layer.

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