Factors Affecting Site Response to Multi-directional Earthquake Loading

J. Yang[1] and X.R. Yan[1]

ABSTRACT

This paper presents an investigation into various factors that may affect the ground response to multi-directional earthquake loading, focusing mainly on the behavior of vertical ground motion and its relation with the horizontal counterpart. The factors investigated herein include the intensity of input motion and the associated soil nonlinearity, the location of input motion (rock outcrop versus bedrock), the variation of water table, and the damping property of soil. Influence of these factors is studied on the characteristics of site amplification in both vertical and horizontal directions, the response spectra of vertical and horizontal ground surface motions, the spectral ratio between the two components (V/H) at the ground surface, and the distributions of stresses and strains in the ground. One of the main results is that varying water table can bring about a significant impact on vertical motion and the the relationship between vertical and horizontal motions. The surface response spectral ratio (V/H) can largely exceed the rule-of-thumb value 2/3 at low periods with lowering the water table, but does not appear to be substantially affected at long periods.

Key words: earthquakes; ground motion; site response; soil damping; soil nonlinearity

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INTRODUCTION

Evaluation of site response to earthquakes plays an important role in seismic design of engineering structures. Most of site response analyses have concentrated on horizontal ground motion, in which site response is regarded as the consequence of the vertical propagation of shear waves in a horizontally layered system. Although it has long been recognized that the ground is simultaneously subjected to shaking in both horizontal and vertical directions during a real earthquake, vertical ground motion, as compared with its horizontal counterpart, has received much less attention. As a result, knowledge with regard to the characteristics of vertical ground motion and, particularly, with regard to relating vertical and horizontal ground motions is rather limited. The common procedure for generating vertical design spectra, as documented in many seismic provisions and codes (e.g., UBC, 1997), is to simply multiply a factor (typically a value of 2/3) to the horizontal design spectra (Fig. 1). In other words, it is assumed that the response spectral ratio between vertical and horizontal motions is a constant less than 1 over the entire period of interest and for all site conditions.

However, several studies on ground motion records obtained in recent earthquakes have shown that the constant (V/H) ratio is not a good descriptor (e.g., Yang and Sato, 2000; Elgamal and He, 2004; Yang and Lee, 2007). The response spectral ratio (V/H) depends on a number of factors (e.g., site-to-source distance and source mechanism), and can be significantly greater than 2/3 at short periods in moderate and large earthquakes. In the most recent Wenchuan, China earthquake of

May 12, 2008, vertical ground acceleration as large as 0.633 g (*g* is the gravity) was recorded in the epicenter zone.

From a geotechnical engineering perspective, it is of particular interest to identify the influence of such factors as the intensity of earthquake motion, the location of input motion (or control motion), the depth of water table, and the damping property of soil on the behavior of vertical motion as well as its relation with the horizontal motion. This is precisely the purpose of the present study. In an earlier study by Yang and Yan (2009), a simple procedure was proposed for analysis of the ground response under both vertical and horizontal earthquake loading; validation of the analytical procedure against the downhole array records at the Turkey Flat test site in California showed reasonably good agreement between predictions and measurements. By using this newly developed procedure, a series of analyses have been carried out for a hypothesized site with the aim to explore several potential influencing factors. The main results derived from these analyses are presented in this paper.

HYPOTHESIZED SITE AND INPUT MOTION

The hypothetical soil site is shown in Fig. 2. The soil profile is 30 m deep comprising a surface sandy clay layer of 10 m and an underlying sand layer of 20 m. The water table is located at the depth of 5 m below the ground level. The mass density of the clay is assumed to be 1800 kg/m^3 and the density of the sand is 2000 kg/m^3. The shear wave velocity, V_s, varies from 170 m/s in the clay layer to 350 m/s in the sand layer.

Using the UBC site classification system, the site can be categorized to be a stiff-soil site. On the other hand, the compressional wave velocity, V_P, is assumed to vary from 360 m/s in the clay above the water level, to 1561 m/s in the clay below the water level, and to 1788 m/s in the sand. The location of bedrock is assumed to be at the depth of 30 m, with the shear wave velocity of 470 m/s and the compressional wave velocity of 2007 m/s.

The nonlinear behavior of the sandy clay in terms of the shear modulus reduction curve and the damping ratio curve is described using the proposal by Sun *et al*. (1988), while the nonlinear behavior of the sand is assumed to follow the curves developed by Seed and Idriss (1970). The input motions used in this study are shown in Fig. 3 in terms of acceleration time histories and response spectra at 5% damping. They are the north-south and up-down components of the acceleration records obtained at the Mount Wilson station during the 1987 Whittier Narrows earthquake in California. The peak horizontal acceleration appearing at 2.84 s is 1.482 m/s^2, and the peak vertical acceleration, 0.756 m/s^2, occurs at 3.08 s. As can be seen in Fig. 3(b), the spectral accelerations in both directions take the maxima at periods of approximately 0.16 s.

INFLUENCE OF INPUT MOTION INTENSITY

Among various measures of earthquake ground motion, peak acceleration has been widely used in engineering practice to characterize the intensity of seismic loading. To investigate its effect, the original horizontal and vertical acceleration records given in Fig. 3 are scaled simultaneously by multiplying factors of 0.5 and 2, respectively, to produce two more sets of acceleration records having different intensity levels. The three sets of records are referred to as Level 1, 2 and 3 hereafter. Analyses have been performed by subjecting the hypothesized soil profile to these three sets of accelerations, which were all specified at the rock outcrop (see Fig. 2).

Figure 4 shows the influence of motion intensity on the transfer functions for horizontal and vertical motions. It is clear that site frequencies in both components decrease with increasing intensity level or increasing peak acceleration. For Level 1 earthquake motion (the weakest case), the fundamental frequency is at 2.5 Hz for the horizontal component and 12.5 Hz for the vertical component. By comparison, they are reduced to be 2.2 and 11 Hz in the case of Level 3 earthquake motion. In the meantime, peak values of the spectral ratios in both components are reduced substantially when the intensity of input motion increases. For example, the vertical amplification at the fundamental frequency drops from approximately 25 at Level 1 motion to about 13 at Level 3; the horizontal amplification at the fundamental frequency varies from approximately 17 at Level 1 to less than 10 at Level 3 input motion.

The above observations are mainly attributed, as will be shown later, to the following two effects. First, higher peak acceleration causes a higher hysteretic damping and therefore a larger reduction of site amplification. Second, higher peak acceleration results in larger strains and reduced moduli and thus lower frequency response.

Site amplification has sometimes been simply examined in practice by a factor which is defined as the ratio between the peak acceleration at the ground surface and the peak acceleration at the base of soil deposit (e.g., Idriss, 1990) Following this practice, the amplification factors for both horizontal and vertical motions are calculated for the three cases of intensity levels and summarized in Table 1. It is noted that the amplification factor for horizontal motion decreases with increasing intensity level. The amplification factor for vertical motion, however, is found to be an increasing function of the intensity level. This implies that the so-defined amplification factor, as compared with the transfer function given in Fig. 4, is not an appropriate indicator for soil nonlinearity involved with vertical motion.

As far as the ratio between peak vertical and horizontal accelerations (V/H) is concerned, it is interesting to note that the ratio increases with increasing intensity at the ground surface but decreases with increasing intensity at the base of the soil deposit. Consequently, the surface-to-base (V/H) ratio is an increasing function of the intensity of input motion.

The influence of the intensity of input motion on surface response spectra is shown in Fig. 5 for both horizontal and vertical motions. Again, the influence is observed to be significant on both components. In the case of Level 1 input motion, the peak spectral acceleration in the horizontal direction is approximately 1/3 of that under Level 3 input motion. Similarly, the peak spectral acceleration in vertical direction at Level 3 is about 5 times the peak value at Level 1 input motion. It is worth noting from Fig. 6 that, while the intensity of input motion has a profound influence on both individual components, its impact on the response spectral ratio between the vertical and horizontal motions (V/H) appears to be less significant. With increasing the motion intensity, a slight increase in the (V/H) spectral ratio occurs for periods lower than 0.2 s; for longer periods the influence becomes negligible and the (V/H) ratio is generally less than 2/3. In the period range of 0.05-0.2 s, the (V/H) ratio substantially exceeds 2/3 regardless of the intensity of input motion.

Shown in Fig. 7 are the variations with depth of peak accelerations in horizontal and vertical directions for the three intensity levels. The influence of the motion intensity on the profiles of peak stresses and peak strains is presented in Fig. 8. Generally, higher intensity level causes larger response in both components. It is to be noted that there is a dramatic variation in peak horizontal acceleration occurring at a depth of 5 to 10 m, while a high gradient of peak vertical acceleration appears at a depth of about 5 m. Significant variations in shear and normal strains are observed in similar zones. Recalling the soil profiles given in Fig. 2, the observed variations are considered reasonable.

Figure 9 presents the profiles of the degraded shear and constrained moduli and the shear-strain compatible damping ratio (ζ_h) under different intensity levels of input motion. It can be seen that the higher the input motion intensity, the smaller the moduli and the larger the damping ratio. With respect to the shear modulus, the influence of intensity tends to be appreciable in the sand layer below the depth of 10 m. The influence on the constraint modulus, however, becomes notable for soils below the depth of 5 m. This is consistent with the previous observation on the variation of normal strain, and is thought to be associated with the variation of the compressional wave velocity and Poisson's ratio with depth.

INFLUENCE OF LOCATION OF INPUT MOTION

In site response analysis there are generally two options to input earthquake motion: one is to specify the motion at a rock outcrop, as done in the above case analyses, and the other is at the bedrock or soil-rock interface (Fig. 2). In the former case the incident waves are equal in amplitude with the reflected waves at the rock outcrop, as required by the free-stress condition. In the theoretical procedure used herein, this case is handled by introducing a radiation dashpot at the soil-rock interface, with the damping coefficients determined from the properties of the bedrock. For the later case, the response of the site can be established directly by solving the displacement-force equation as described by Yang and Yan (2009). Since there has been confusion with the bedrock and outcrop inputs, an effort is made here to clarify this issue by examining the difference in ground response for two cases: in one case the earthquake motion is input at the rock outcrop and in the other case the same motion is input at the bedrock.

Using the acceleration records given in Fig. 3 as the bedrock and outcrop input respectively, the response spectra of ground surface motions were calculated and are compared in Fig. 10. In both plots the curves for the case of outcropping input are denoted as "outcropping" while the curves generated from the case of bedrock input are labeled as "bedrock". Shown in Fig. 11 are the profiles of peak accelerations in both directions for the two cases. The results for stresses and strains in the two cases are presented in Fig. 12.

The overall observation on these figures is that, compared with the case of outcropping input, the response of the site to the same earthquake motion but input at the bedrock is stronger in both vertical and horizontal directions. Accordingly, in the case of bedrock input more significant modulus reduction and higher damping are observed (Fig. 13). These observations are reasonable because in the outcropping case, perfect reflection occurs due to the free stress conditions (i.e. reflected waves are equal to incident waves), whereas in the bedrock case part of the incident waves are transmitted into the soils resulting in the reflected waves of being less than the incident waves. More detailed discussion on the relation between bedrock motion and outcropping motion can be referred to Yang and Yan (2009).

Moreover, the difference in the modulus reduction and damping ratio will bring about changes in site frequencies in both horizontal and vertical components. For example, the fundamental frequency of the vertical motion in the case of bedrock input is about 94% of that in the case of outcropping input. It should be noted that the change of input motion position will not cause difference in the transfer function for either component if the nonlinear behavior of the soil is not taken into account.

With respect to the response spectral ratio (V/H) at the ground level, Fig. 14 shows that the ratio is substantially increased at short periods (less than 0.2 s) but slightly decreased at periods longer than 0.2 s when the location of input motion changes from rock outcrop to the base of the soil deposit.

Table 2 gives peak values of the horizontal and vertical surface accelerations in the two cases of input motion position. Note that the influence of input motion position is more significant for vertical motion than for horizontal motion; this is also observed on Fig. 10. As for the ratio between peak vertical and peak horizontal accelerations at the ground surface, the results show that it increases from 0.5 for outcropping input to 0.98 for bedrock input.

INFLUENCE OF WATER LEVEL

The analysis of Yang and Sato (2000) on the downhole array records at a reclaimed site in Kobe, Japan has indicated that the variation of water table plays an important role in the amplification of vertical ground motion. To further investigate this effect, three cases of water levels are examined in parallel in this section (Fig. 15): the first case is for water level at the surface (i.e. WL=0 m), the second case is for water level at 5 m below the surface (i.e. the case discussed previously), and in the third case the depth of water table is at 10 m. Note that in the three cases the profiles of the shear wave velocity (V_s) are assumed to be identical but the profiles of the compressional wave velocity (V_P) vary with the change of water table. In the case of WL=0 m, V_P is assumed to vary from 1561 m/s in the clay layer to 1785 m/s in the underlying sand, whereas in the case of WL=10 m, it is assumed to vary from 360 m/s in the clay to 1785 m/s in the sand layer.

The above assumption for the variations of V_P and V_s is based on the results of the studies by Yang and Sato (2000) and Yang *et al*. (2004), which indicate that the presence of ground water has a significant influence on the compressional wave velocity but little influence on the shear wave velocity and that a dramatic change in the compressional wave velocity may occur at the location of water table.

Figure 16 compares vertical ground surface motions computed for the three water levels in terms of the acceleration time histories. Shown in Fig. 17 is the influence of water level on the surface response spectra and the transfer function for vertical motion. Clearly, the variation of water table brings about a profound effect on the behavior of vertical motion. The transfer function will be shifted to the low frequency end when the water table is lowered. For example, the fundamental frequency is found to be at 13.4 Hz when the water table is at the ground surface, but it drops to 7.4 Hz when the depth of water table becomes 10 m. In the meantime, lowering water table brings about a much stronger amplification of vertical motion, as can be seen from Fig. 17(a). The peak spectral acceleration in the case of WL=10 m is about 3 times that in the case of WL=0 m.

With respect to the relation between vertical and horizontal motions, Fig. 18 shows that the variation of water table can also significantly affect the response spectral ratio (V/H) at the ground surface. For water level at the surface, the (V/H) spectral ratio is generally below the value of 2/3 in the whole range of period. If the water level is lowered to the depth of 10 m, the ratio will increase sharply for periods shorter than about 0.2 s, with the peak value of as large as 2.3. On the other hand, the influence of varying water table is found to be slight for the spectral ratio (V/H) at periods longer than 0.6 s.

Shown in Fig. 19 are distributions with depth of the peak vertical acceleration and vertical velocity under different water levels. High gradients are found to occur at the depth that is close to the water table. Taking the case of WL=10 m as an example, peak vertical acceleration is increased only by 26% when seismic waves travel from the base to the depth of 10 m; but it is increased by 200% when the waves further propagate from the depth of 10 m to the ground surface. This result highlights the importance of varying water table in vertical site amplification, and is in agreement with the observation on the downhole array records in the Kobe earthquake (Yang and Sato, 2000).

For ease of reference, Table 3 summarizes the peak values of vertical surface accelerations under different water levels. It is worth noting that the peak vertical acceleration at WL=10 m is about 2.6 times that at WL=0 m. The peak acceleration ratio (V/H) accordingly increases from 0.37 in the case of WL=0 m to 0.96 at WL=10 m.

INFLUENCE OF DAMPING RATIO

The damping property of soils associated with shear wave propagation has been studied extensively (e.g., Sun *et al*., 1988; Vucetic and Dobry, 1991; Ishihara, 1996). Current knowledge of soil damping with respect to the propagation of compressional waves is however very limited, although several attempts have been made to discuss the combined loading effect (e.g., Zhang and Aggour, 2004). In the previous case studies, the damping ratio for vertical motion (ζ_v) was assumed to be identical with the damping ratio for horizontal motion (ζ_h), which was derived from the horizontal site response analysis through iterations. It is necessary to examine the potential effect of damping ratio, ζ_v , on the vertical site response. For this purpose, two more cases of vertical damping, $\zeta_v = 0.5\zeta_h$ and $\zeta_v = 2\zeta_h$, are assumed for the reference soil profile given in Fig. 2.

The surface response spectra of vertical motion under three damping ratios are presented in Fig. 20(a). The transfer functions for vertical motion under the three damping ratios are presented in Fig. 20(b). As expected, an increase in damping ratio (ζ_v) results in a greater reduction in vertical amplification. In the case of low damping ratio, i.e. $\zeta_v = 0.5\zeta_h$, the vertical amplification at the fundamental frequency is as large as 37; but it is reduced to be less than 10 when $\zeta_v = 2\zeta_h$. On the other hand, the influence of vertical damping ratio on the surface response spectra appears to be minor for the entire range of periods. Accordingly, the surface response spectral ratio (V/H) is not significantly affected by the variation of vertical damping (Fig. 21).

The influence of damping ratio on peak vertical acceleration and velocity at ground surface is summarized in Table 4. It is noted that when the damping ratio is decreased from $2\zeta_h$ to $0.5\zeta_h$, the peak acceleration ratio (V/H) is increased by 10%, from 0.48 to 0.54.

IMPLICATIONS FOR PRACTICE

The results presented in the preceding sections indicate that the current practice to produce vertical response spectra for seismic design is not adequate as the response spectral ratio (V/H) is influenced by a number of geotechnical factors, in addition to source mechanism and site-to-source distance. In particular, the behavior of vertical motion can be significantly affected by the variation of water table or the associated variation in compressional wave velocity, which may occur in certain circumstances such as change of seasons. It is thus necessary to examine the water table conditions in interpreting vertical earthquake motion recordings. A good example can be referred to the study of Yang and Sato (2000).

The results presented here also have useful implications for the applications of the site-evaluation technique known as (H/V), which is based on the interpretation of recordings of microtremors or weak ground motions in both horizontal and vertical components and has drawn an increasing interest in practice (e.g., Mucciarelli *et al*., 2003).

Since there is possibility that vertical motion at the ground surface can become comparable to or even larger than its horizontal counterpart in magnitude, it is necessary to take into account a wider range of magnitudes of vertical motion in seismic analysis and design of engineering structures. Several recent studies have shown that the effect of vertical motion should not be simply disregarded (Ling and Leshchinsky, 1998; Mylonakis and Gazetas, 2002; Yang, 2007).

Owing to the simplifications introduced in the present modeling procedure, the effects on ground motions due to very strong nonlinear soil response, in particular that associated with soil liquefaction (e.g., Yang *et al.*, 2000), may not be well accounted for. In these situations more sophisticated procedures such as fully-coupled, elasto-plastic, 2D or 3D finite element programs can be sought to investigate the ground motion characteristics. However, it is to be recognized that these analyses usually involve with great difficulty and uncertainty in determination of the parameters of constitutive models for soils, rendering them unsuitable for routine engineering practice.

CONCLUSIONS

An attempt has been made in this study, by using a simple analytical procedure developed by Yang and Yan (2009), to investigate potential factors that may influence ground response to vertical and horizontal earthquake loading. Particular attention has been paid to the behavior of vertical ground motion and its relation with the horizontal counterpart, on which current understanding is very limited. The main results of the present study can be summarized as follows.

(a) Site frequencies for both vertical and horizontal motions decrease with increasing the intensity of input motion, accompanied by a significant reduction of site amplification at these frequencies. This is due primarily to high hysteretic damping and reduced moduli associated with strong earthquake motion.

(b) While the intensity of input motion has a profound influence on the characteristics of individual components of ground motions, its impact is however less significant on the response spectral ratio between the vertical and horizontal motions (V/H) at the surface.

(c) The amplification factor, simply defined as the ratio between peak accelerations at the surface and at the base of soil deposit, is not an appropriate indicator for soil nonlinearity involved with vertical ground motion.

(d) Compared with the case of rock outcropping input, the response of the site to the same earthquake motion specified at the bedrock is stronger in both vertical and horizontal directions. Vertical ground response appears to be affected more significantly by the location of input motion than the horizontal one.

(e) The variation of water table can bring about a significant impact on vertical ground response. When the water table is lowered, site frequencies for vertical motion will be shifted to the low frequency end and the surface response spectra will exhibit higher peak values.

(f) The surface response spectral ratio (V/H) increases substantially at low periods with lowering the water table, but is not affected significantly at long periods (greater than 0.6 s). The peak value of the spectral ratio (V/H) tends to largely exceed the rule-of-thumb value 2/3 when the water table is lowered.

(g) The vertical amplification at site frequencies decreases with increasing the damping ratio for vertical motion, but the influence of damping ratio appears to be minor on the response spectra of vertical surface motion and on the response spectral ratio (V/H) at the surface.

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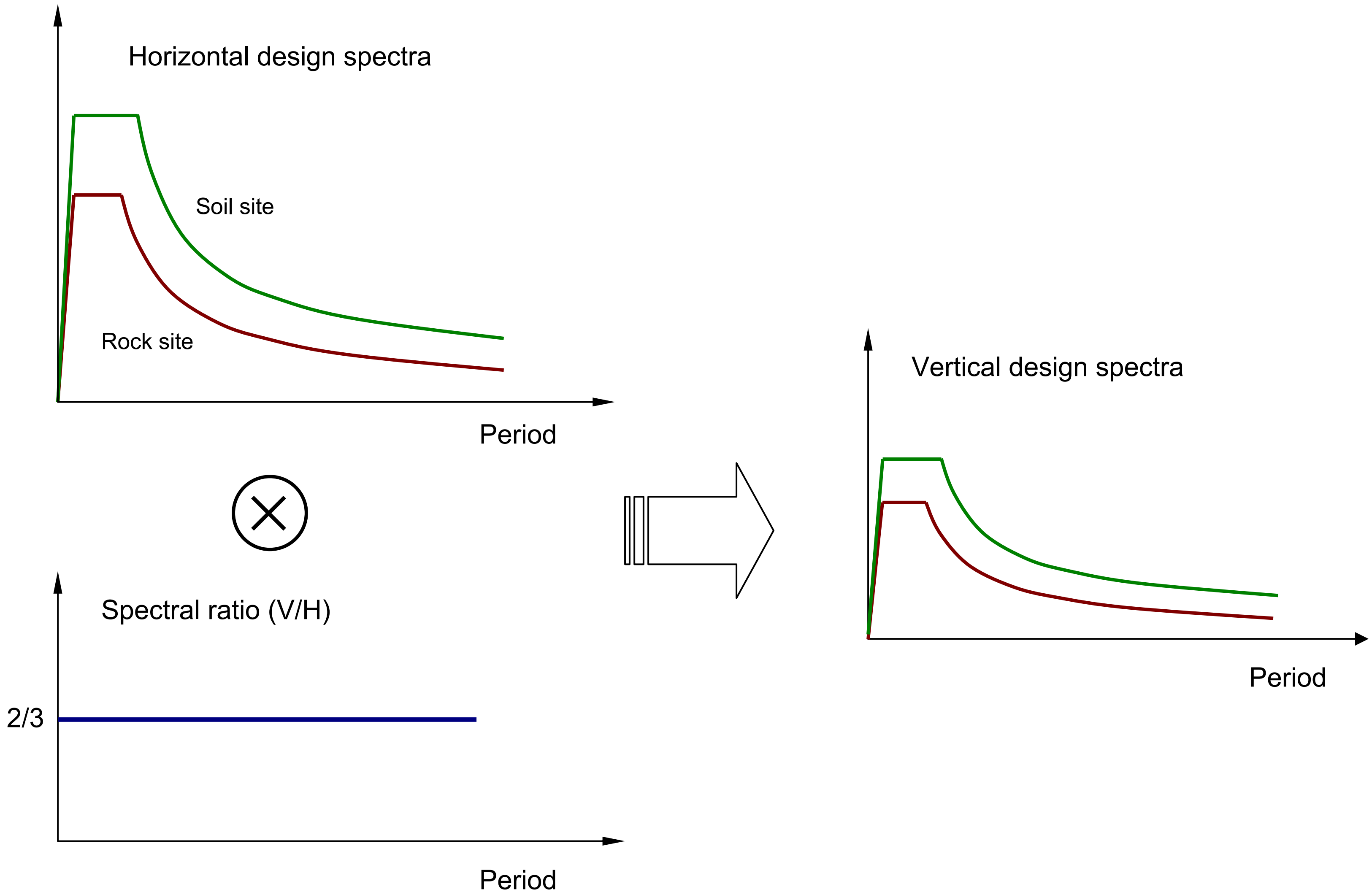

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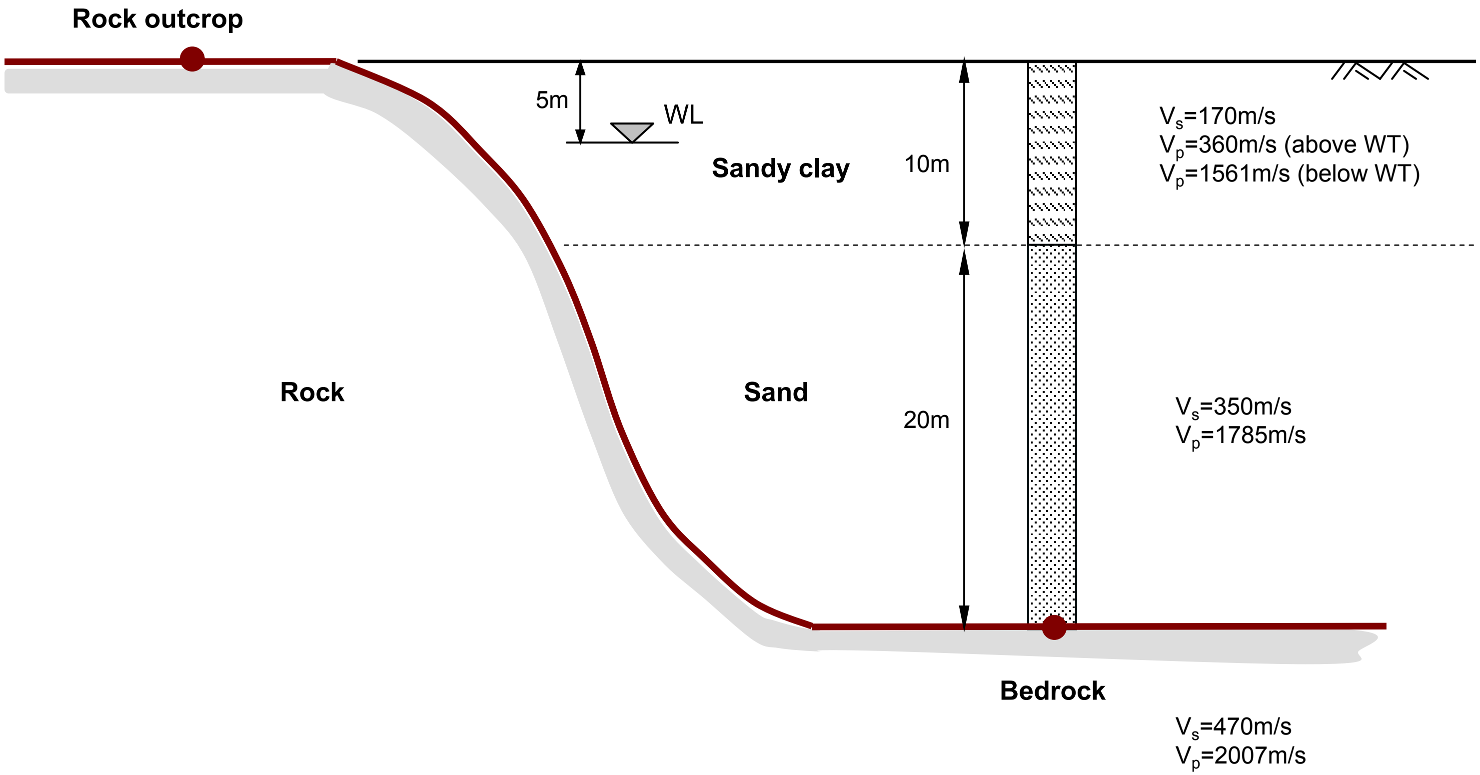

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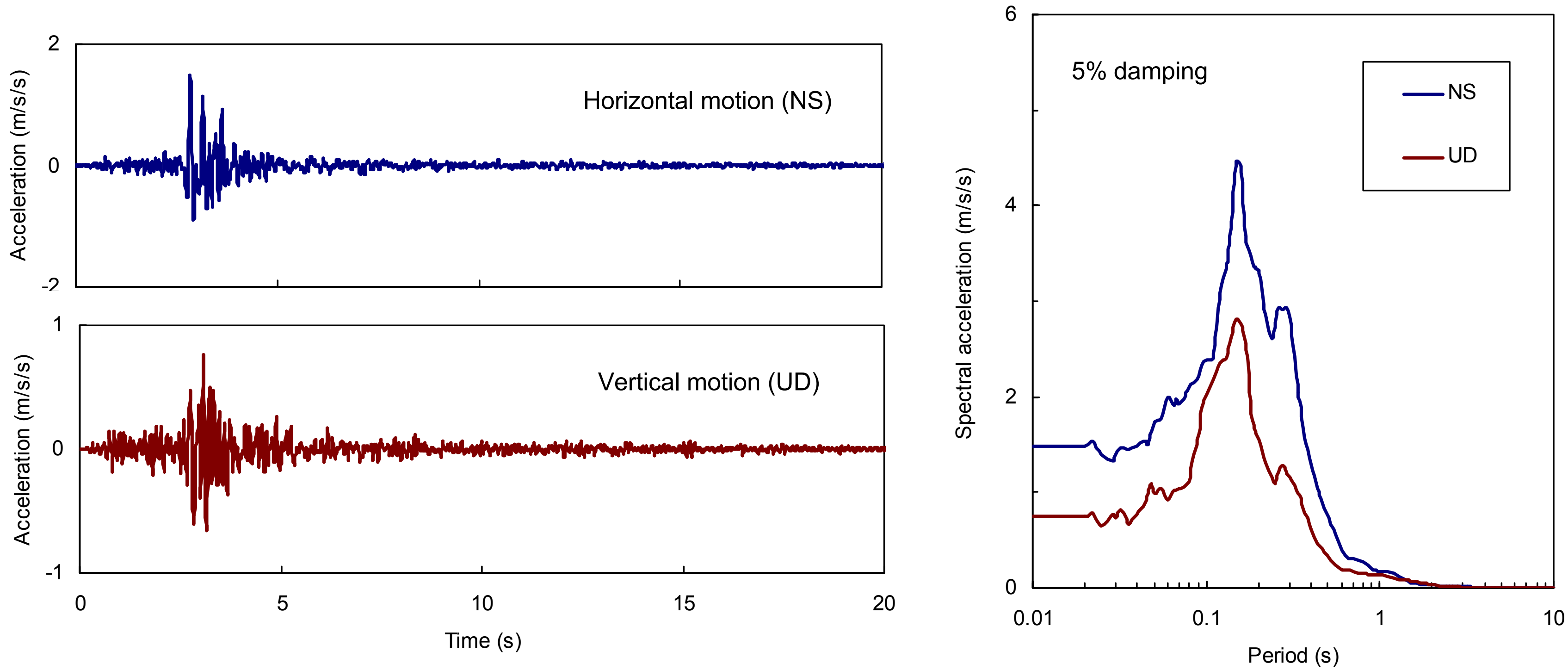

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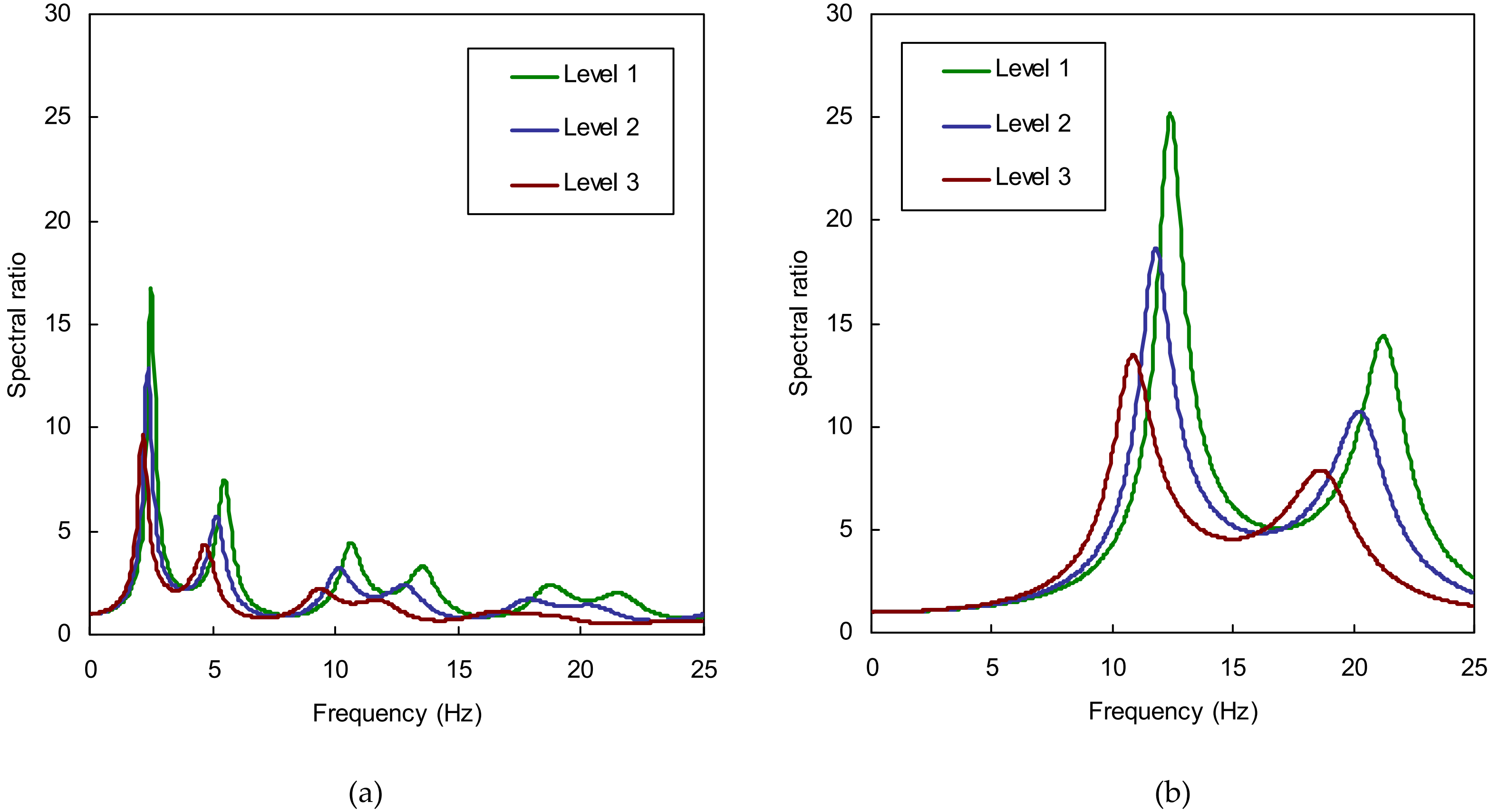

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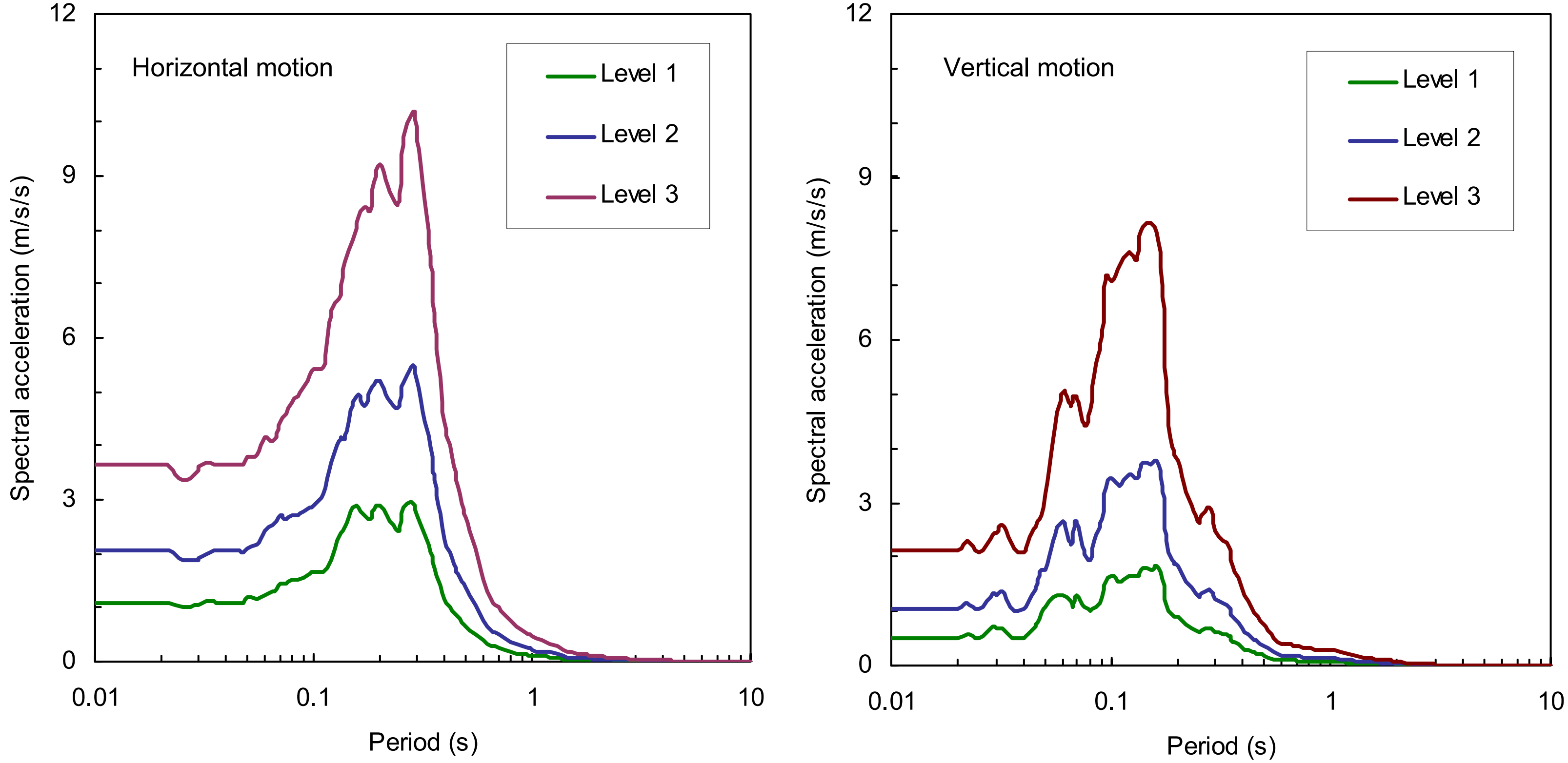

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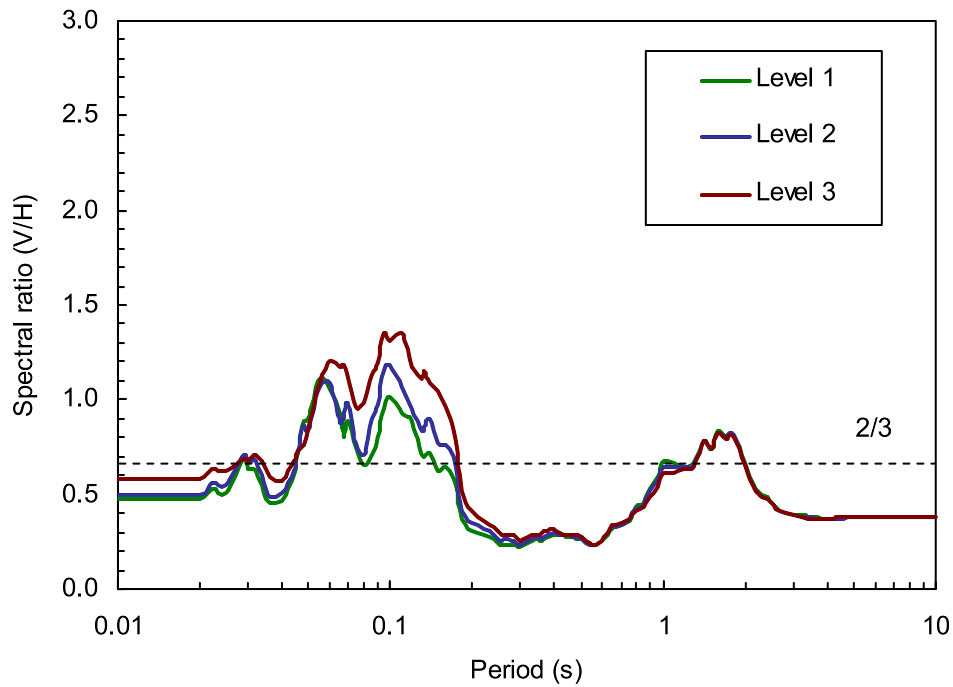

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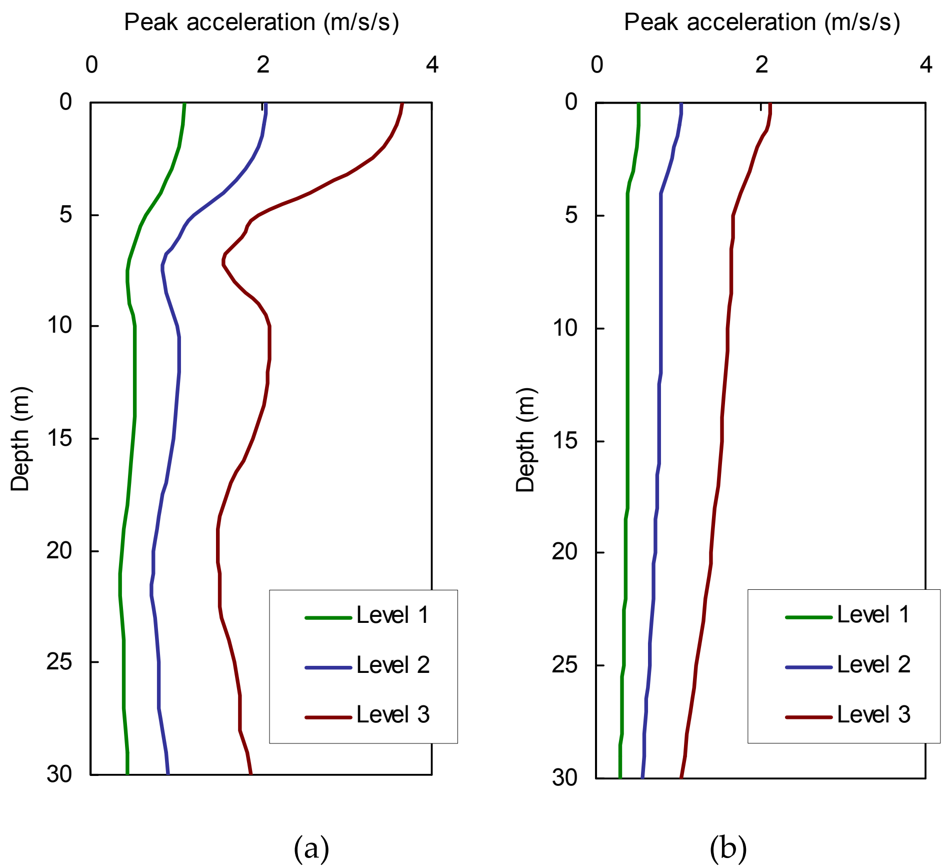

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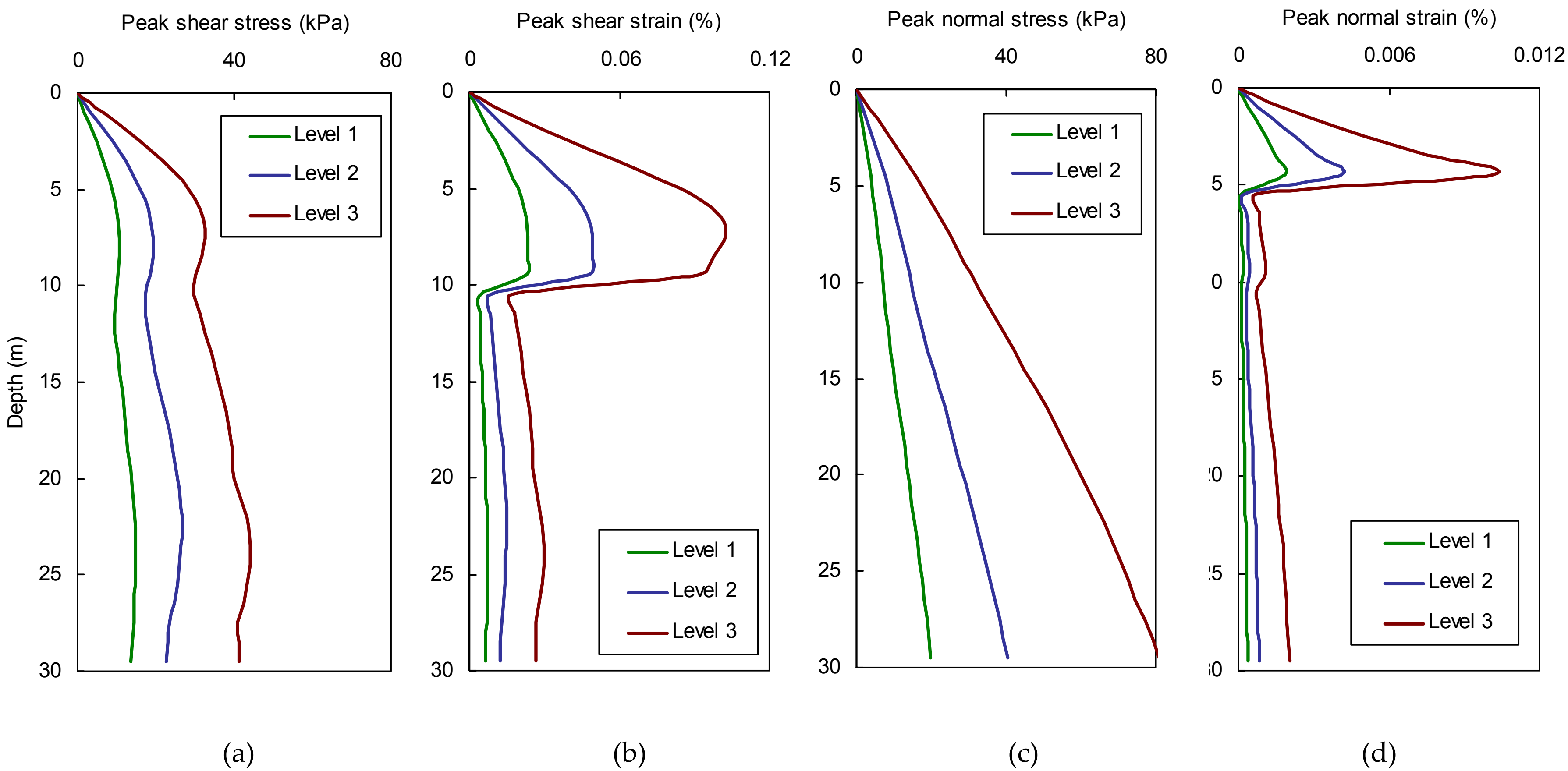

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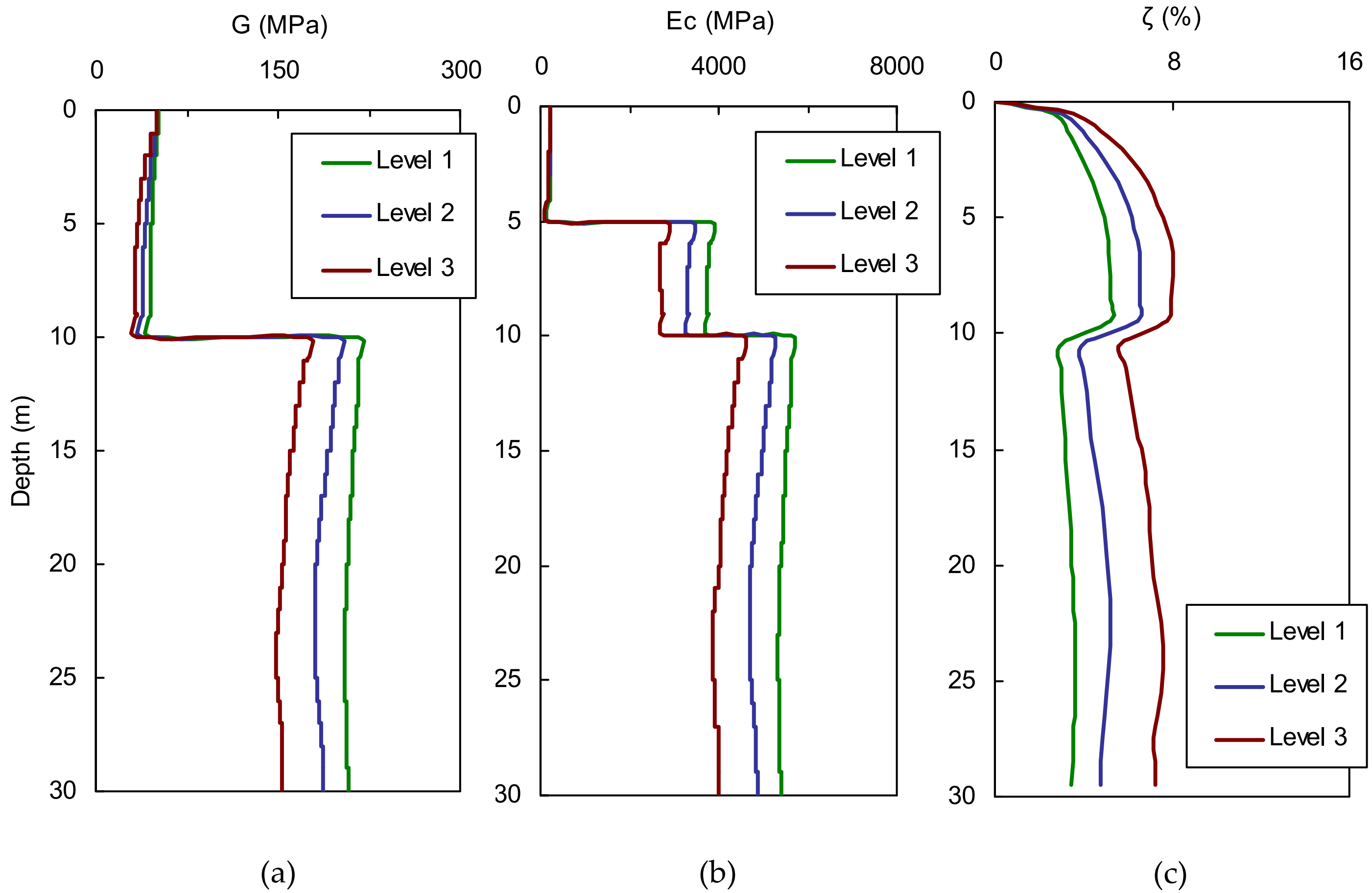
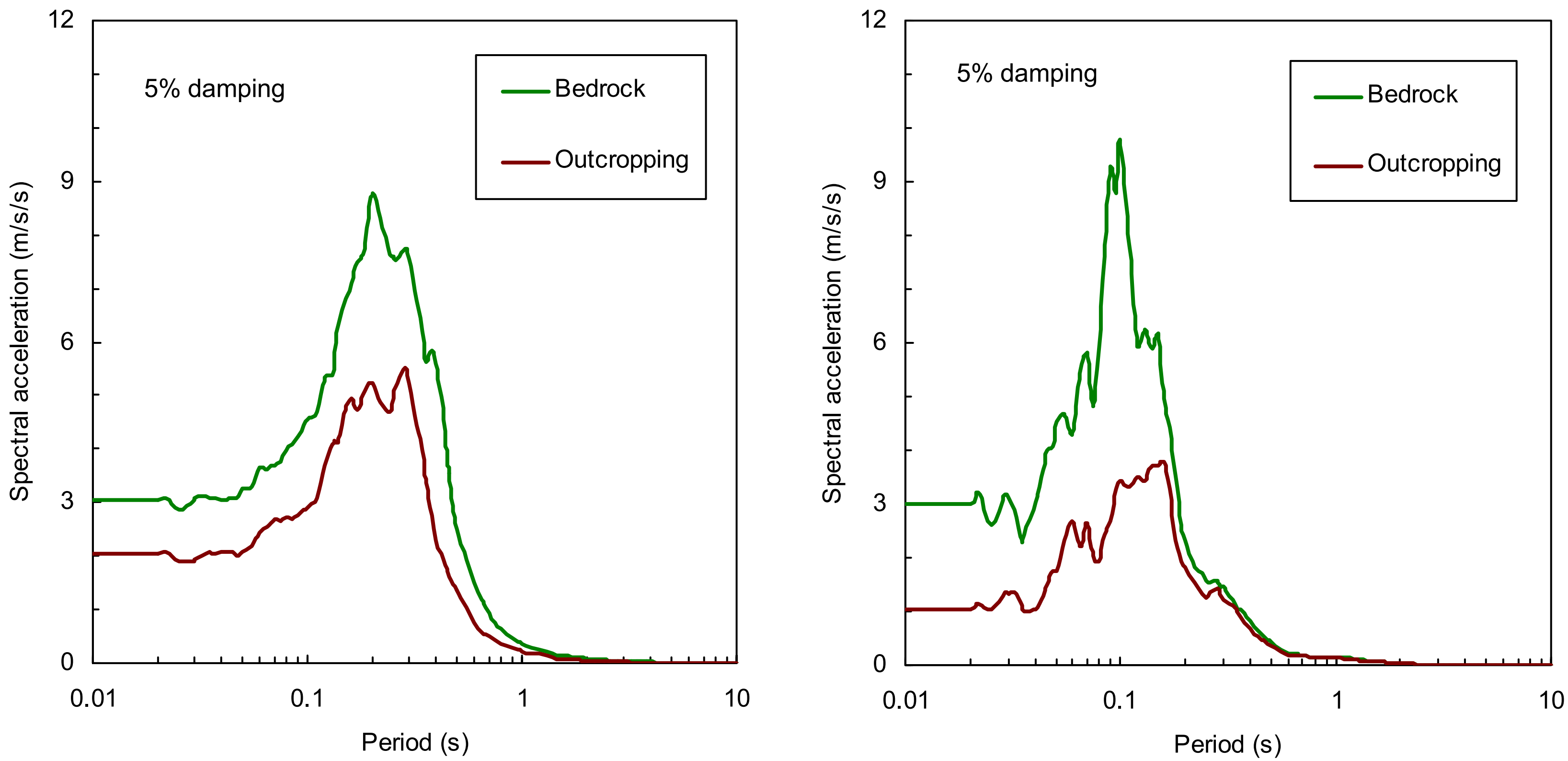
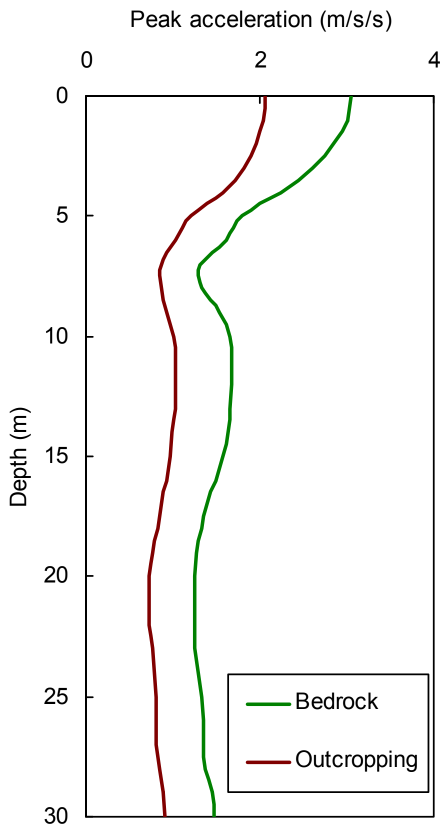


Figure 9. Influence of the intensity of input motion on distributions of degraded moduli and damping with depth: (a) shear modulus; (b) constrained modulus; (c) damping ratio

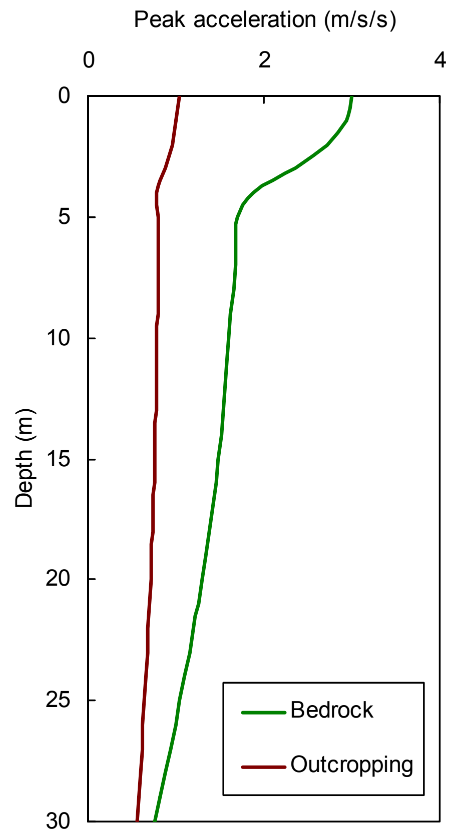


(a) (b)

Figure 10. Influence of input motion position on the response spectra of ground surface motions: (a) horizontal component; (b) vertical component



(a)



(b)

Figure 11. Influence of input motion position on distributions of peak accelerations with depth: (a) horizontal component; (b) vertical component

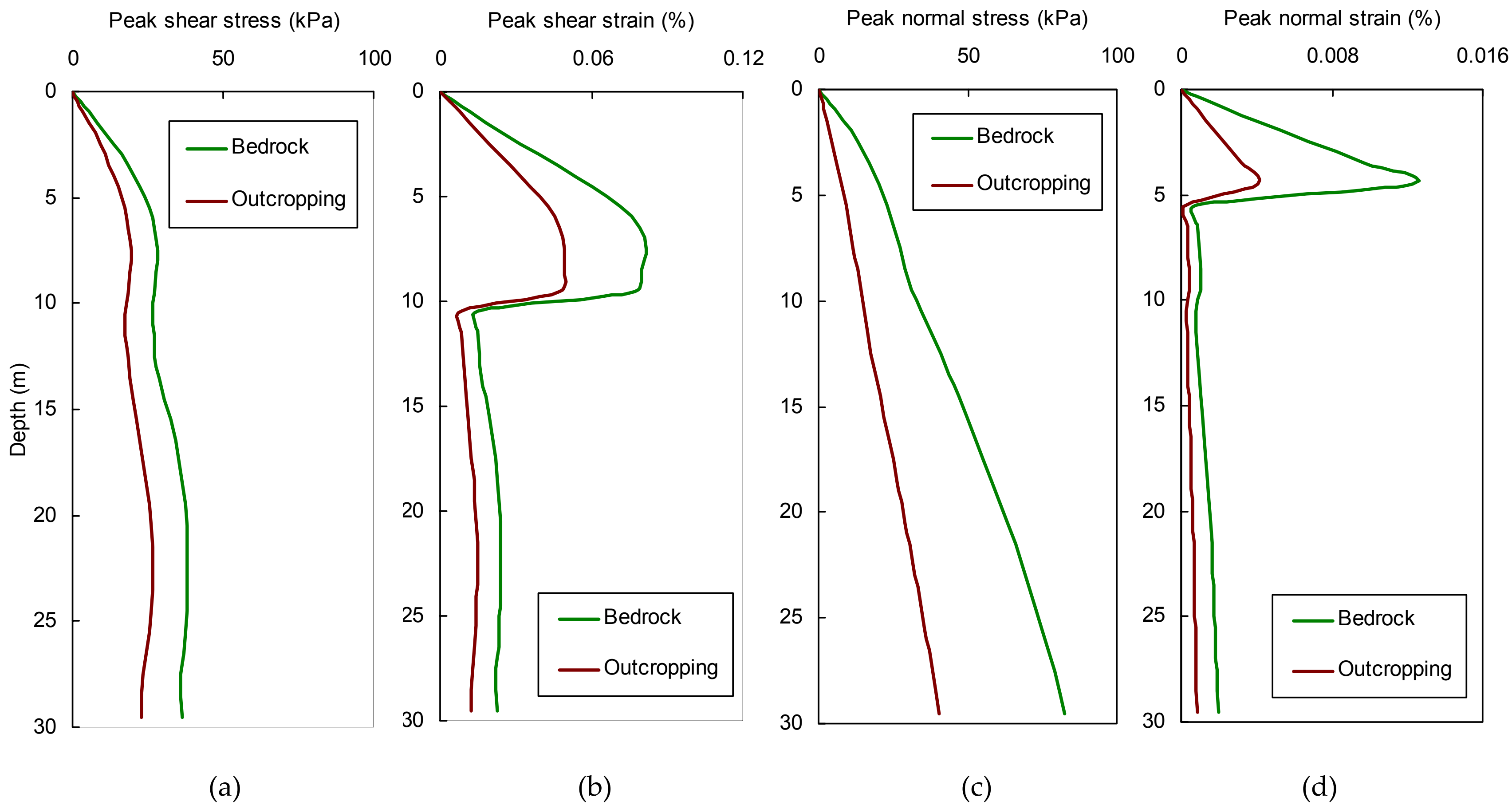


Figure 12. Influence of input motion position on distributions of stresses and strains with depth: (a) peak shear stress; (b) peak shear strain; (c) peak normal stress; (d) peak normal strain

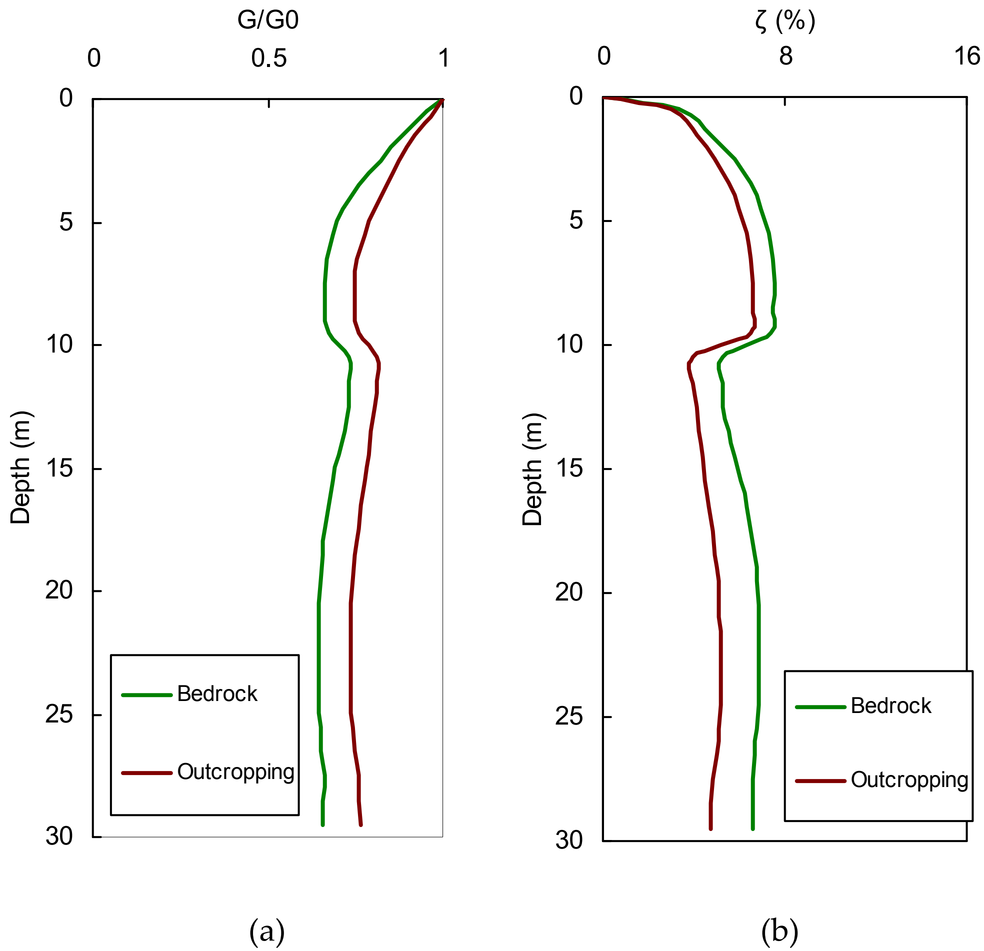


Figure 13. Influence of input motion position on distributions of (a) shear modulus reduction and (b) damping ratio

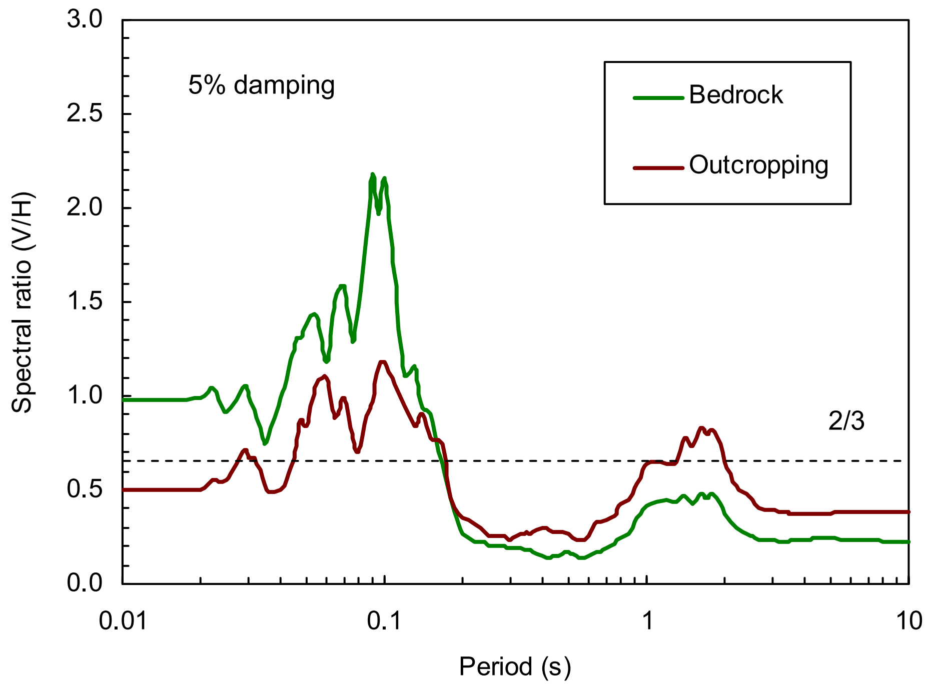


Figure 14. Influence of input motion position on the response spectral ratio between vertical and horizontal surface motions (V/H)

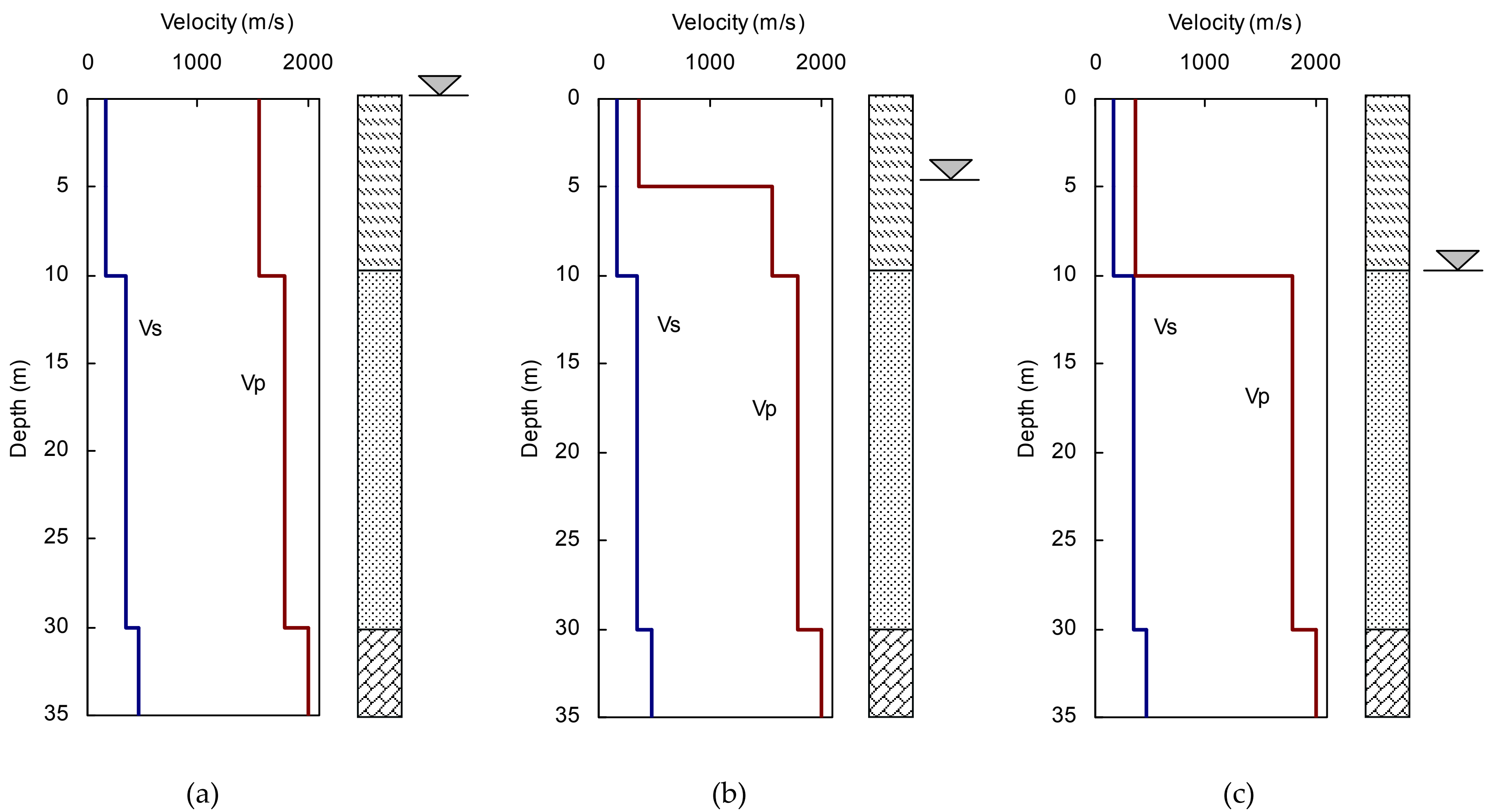


Figure 15. Three cases of water levels under investigation: (a) WL=0 m; (b) WL=5 m; (c) WL=10 m

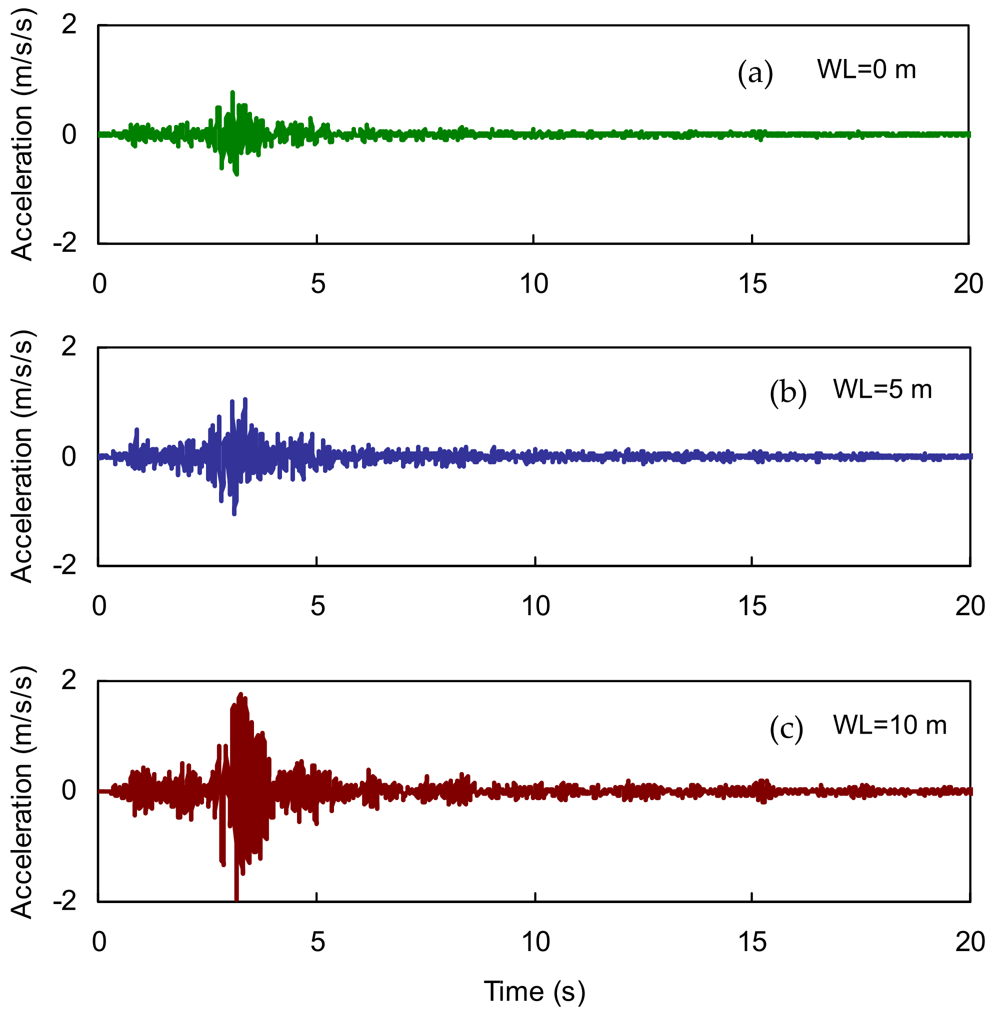


Figure 16. Vertical ground surface accelerations under various water levels: (a) WL=0 m; (b) WL=5 m; (c) WL=10 m

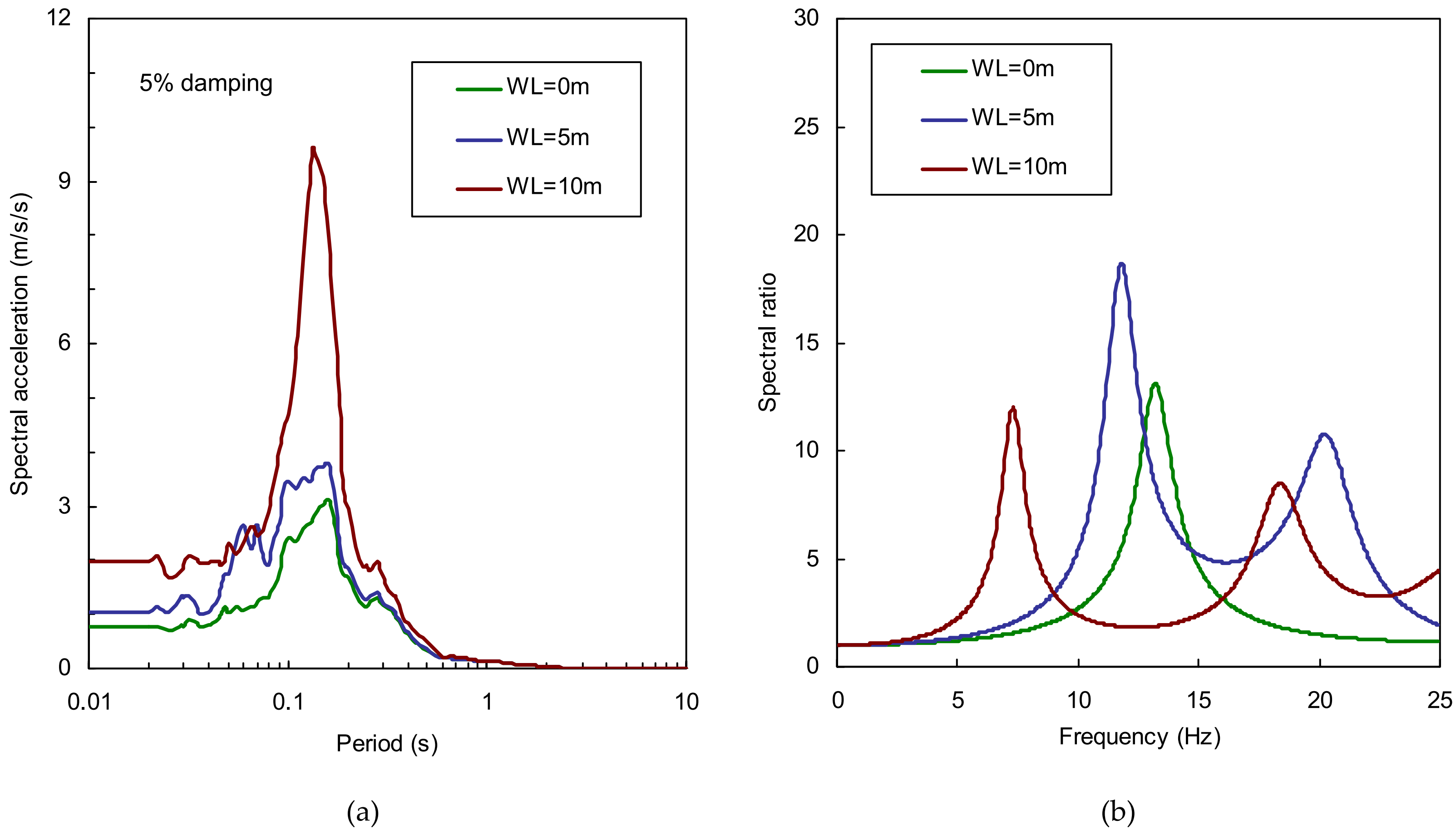


Figure 17. Influence of water level on vertical ground motion: (a) surface response spectra; (b) transfer function (surface-to-base)

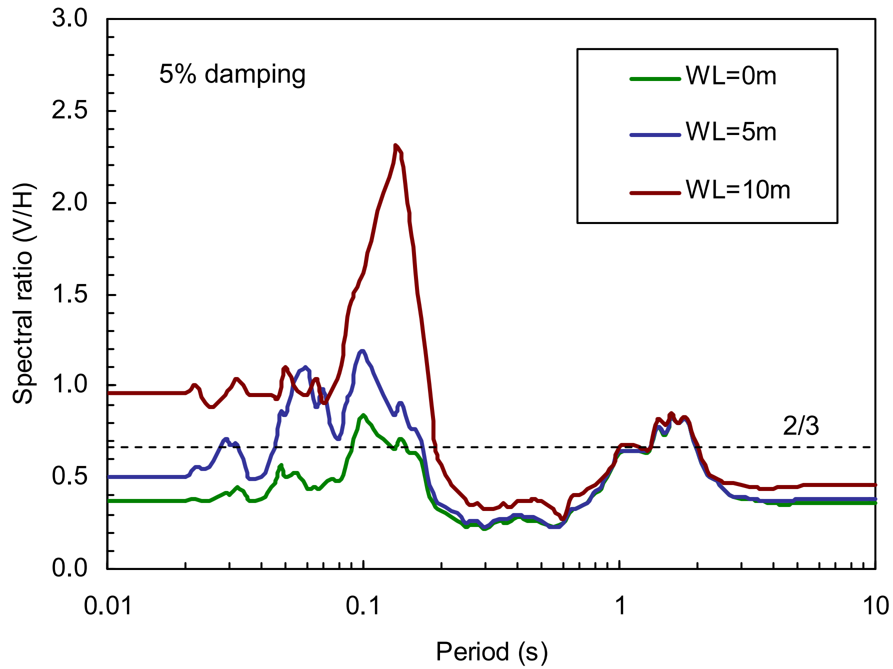


Figure 18. Influence of water level on the response spectral ratio between vertical and horizontal surface motions (V/H)

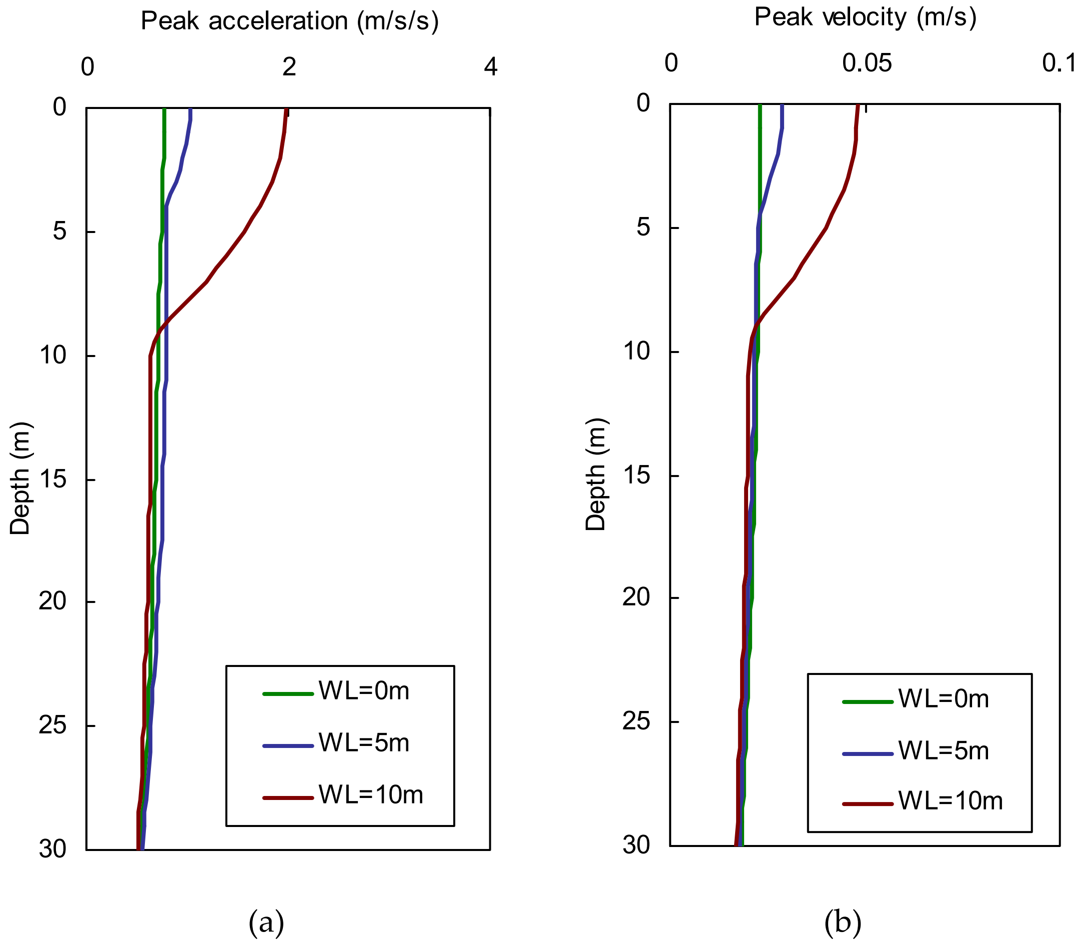


Figure 19. Influence of water level on distributions of (a) peak vertical acceleration and (b) peak vertical velocity

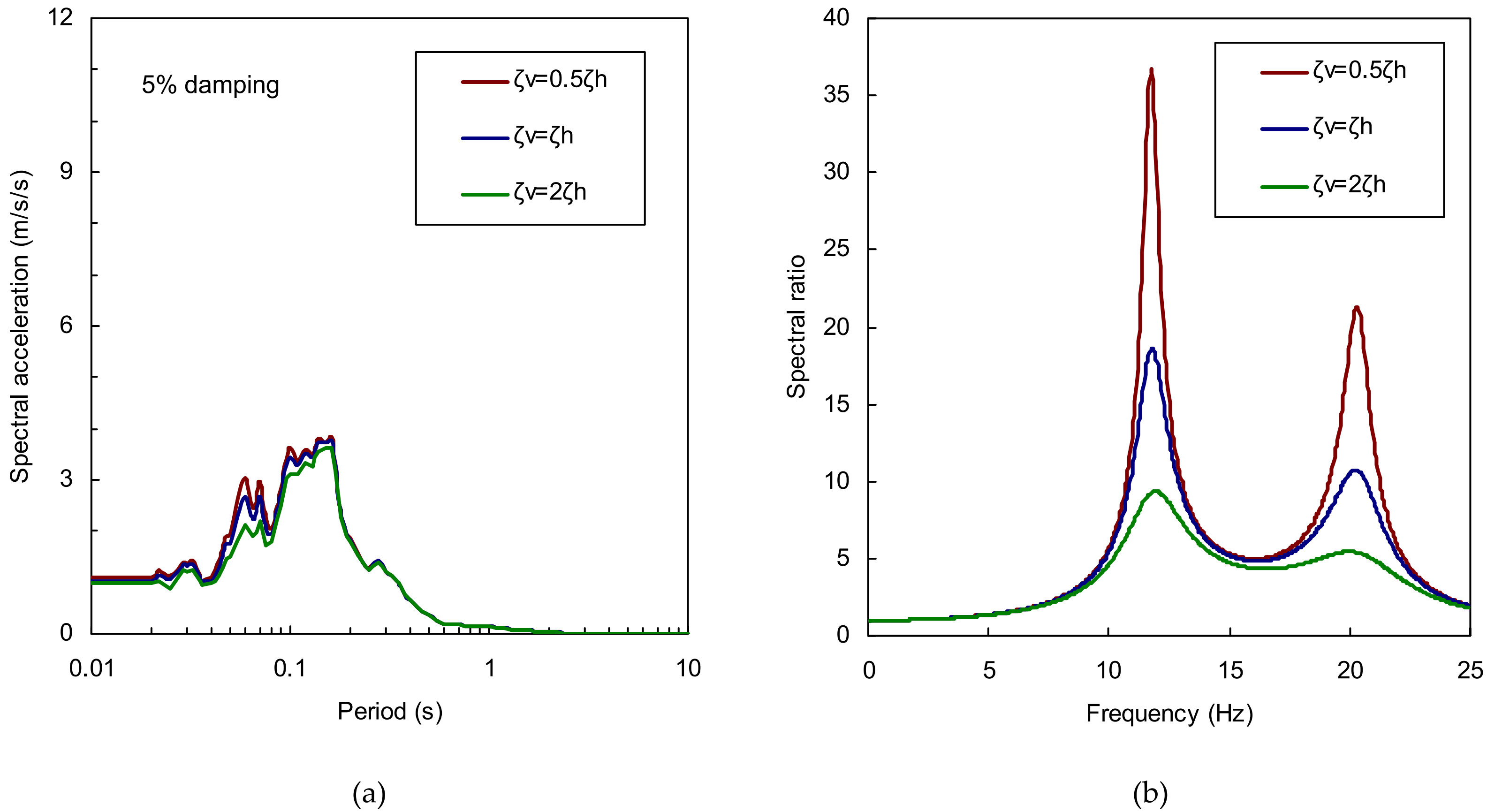


Figure 20. Influence of damping ratio on vertical ground motion: (a) surface response spectra; (b) transfer function (surface-to-base)

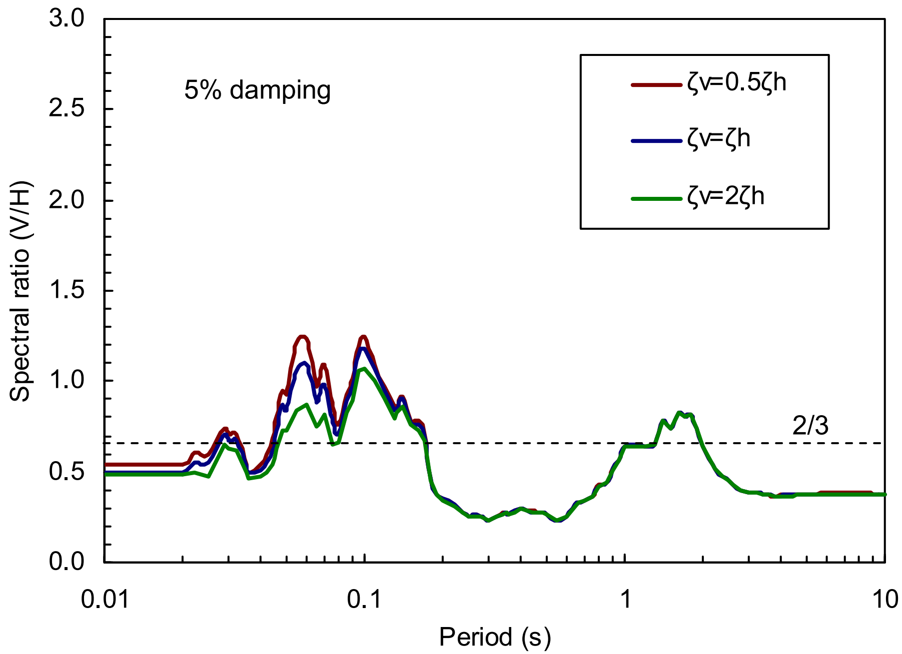


Figure 21. Influence of damping ratio on the response spectral ratio between vertical and horizontal surface motions (V/H)