INVESTIGATION OF GROUND MOTIONS AND STRUCTURAL RESPONSES IN NEAR FIELD DUE TO INCIDENT WAVES

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SUMMARY

This paper describes by using numerical analyses the effect of the characteristics of incident waves and the influence of soil properties on the surface ground motions. The shear and compressive incident waves consist of single Ricker's wave or a composition of five Ricker's waves. Responses of a frame structure to the ground motions are also considered. The results confirm that near the source vertical surface ground motions can be much larger than the horizontal one. In the analysis of structural responses a simultaneous ground motions should be taken into account.

INTRODUCTION

Some recent earthquakes show that near the source the ground motions can be different from the motion at far distance. Far from the source the amplitude of ground acceleration in the vertical direction generally becomes smaller than that in the horizontal direction. In the case of Kobe earthquake the peak vertical ground acceleration PGA_v at the distance of about 100km to the fault plane can still be as large as the horizontal PGA_h [Fukushima et al, 1998]. Since poorly compacted soil and even water are able to transmit compressive waves, which are not much affected by non-linear soil behaviour and liquefaction, vertical soil movements are not highly damped. Even though parts of the Kobe Port Island subsided due to the liquefaction up to about half a meter, the PGA_v increased with the decreasing depth as obtained by the strong-motion array (figure 1) [Oka et al.,1997].

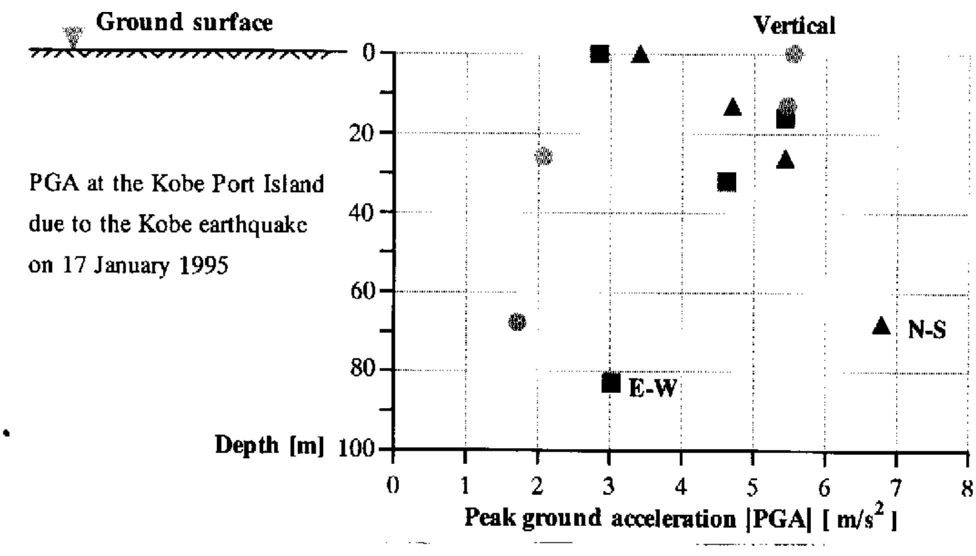

Figure 1: Change of the peak ground accelerations with the depth, E-W: East-West, N-S: North-South

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Near source vertical ground motions can also be charaterized by higher frequency content since surface layers generally have higher natural frequencies vertically than horizontally. The soil therefore prefers to transmit compressive waves with high frequencies and shear waves with low frequencies. Works on influences of near source ground motions on structural responses are still limited [Elnashai and Papazoglou, 1997, Christopoulos et al., 1999 and Chouw, 1999]. In this work the effect of soil condition on the wave propagation from the source to the ground surface as well as on the responses of a frame structure is considered.

SURFACE GROUND MOTIONS DUE TO INCIDENT WAVES

In the investigation of the influence of incident waves on the ground motions at the soil surface the system in figure 2 is used. The soil consists of soft soil layers which are adjacent to hard soil with a shear wave velocity c_s of 1000m/s. The interface between soft and hard soil is indicated by the bold grey line (figure 2(a)). The soft soil has a maximum thickness of 50m. Surface layer of 20m has a shear wave velocity of 300m/s. The middle and lowest layers have the shear wave velocities of 350m/s and 450m/s, respectively. Both of these layers have the same thickness of 15m. The soft soil layers and a strip of adjacent hard soil up to the depth of 86m are modelled by finite elements. The remaining infinite part of the hard soil is modelled by boundary elements. The source of the ground motions is the vertically propagating shear or compressive waves as well as simultaneously propagating shear and compressive waves. These incident waves have the form of Ricker's wavelets. Their mathematical expression of a single Ricker's wavelet is [Ricker, 1977]

$$u_p(t) = u_0(2u^* - 1.0)e^{-u^*} \qquad (1)$$

where

$$u_0 = 1\ cm$$

$$u^* = \left(\frac{\pi(t - t_S)}{t_p}\right)^2$$

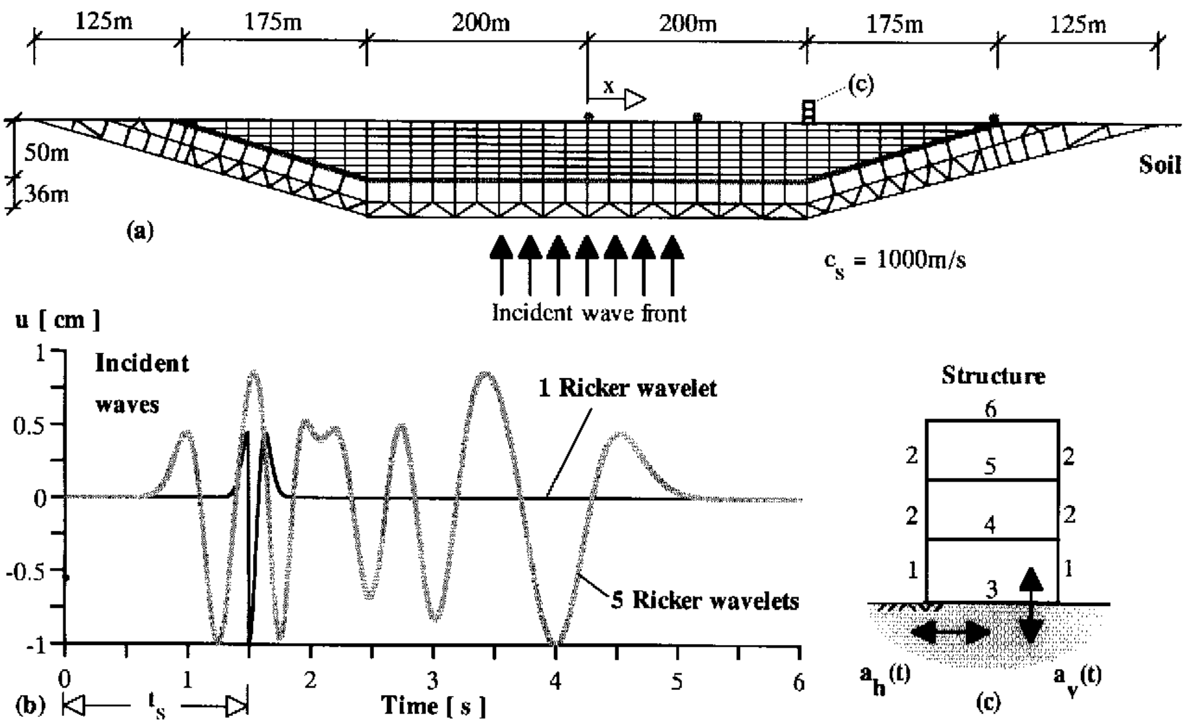

Figure 2(a)-(c): Source, soil and structure system. (a) Soil model, (b) incident waves and (c) structure

Table 1: Data of the incident waves

Single Ricker's wave	Five Ricker's waves	
t_p = 0.25s / 0.33s / 0.5s t_s = 1.50s	t_{p1} = 1.33s	t_{s1} = 4.00s
	t_{p2} = 1.00s	t_{s2} = 3.00s
	t_{p3} = 0.80s	t_{s3} = 2.50s
	t_{p4} = 0.67s	t_{s4} = 1.25s
	t_{p5} = 0.50s	t_{s5} = 1.75s

Table 2: Data of the frame structure

	Number of the structural member					
	1	**2**	**3**	**4**	**5**	**6**
Length [m]	4.575	3.05	9.15	9.15	9.15	9.15
Mass [kg/m]	67	33	6950	2447	2358	1209
EA [kN]	$1.72*10^6$	$8.37*10^5$	$1.0*10^8$	$3.19*10^6$	$3.19*10^6$	$2.36*10^6$
EI [kNm2]	$2.10*10^4$	$9.80*10^3$	$1.0*10^7$	$2.00*10^5$	$2.00*10^5$	$1.00*10^5$

Kelvin-chain parameters: E_1=1.0 and E_n=$1.0*10^{29}$

The dominant frequency f_p of the incident waves is $1/t_p$. For the current analyses the dominant frequencies 2Hz, 3Hz and 4Hz are considered. Since a single Ricker's wavelet has only one dominant frequency, in order to consider incident waves with broader dominant frequency content incident waves composed of five Ricker's wavelets with different characteristics are also considered. The data of the incident waves is given in table 1. t_s is the arriving time of the maximum amplitude of a single Ricker's wavelet as can be seen in figure 2(b).

The considered three-storey frame-structure is located on the soil surface at a distance x from the vertical line of symmetry of the soil layers (figure 2(a)). The dynamic behaviour of the frame structure is described by a continuous mass model. The numbers of the structural members are given in figure 2(c). Table 2 shows the data of the structure. The mass of the girders includes the corresponding mass of the dead load. The effect of the gravity load, represented by the compressive forces in the columns, is considered in the analysis of the structural response. The column forces of the 1st, 2nd and 3rd storey due to the dead load are 255.35kN, 150.7kN and 50.23kN, respectively. The material damping of the structure is described by a Kelvin chain, which is defined by the parameters E_1 and E_n. For the chosen E_1- and E_n-value all structural members have damping of about 1%. The first horizontal and vertical modes of the structure have the frequencies of 1.24Hz and 6.25Hz, respectively.

Figure 3 shows the surface responses a_h and a_v at the distance x=0m, 100m, 200m and 375m in the horizontal and vertical directions, respectively. These locations are indicated by grey dots in figure 2(a). The incident waves have the dominant frequency f_p = 3Hz. The largest horizontal response can be observed at x=100m, while the largest vertical one occurs at x=200m. This may be caused by wave focusing. At x=0m the uniformly vertically propagating shear waves produce no response in the vertical direction of the soil system due to symmetry.

The responses due to the incident compressive waves occur earlier than the responses due to the incident shear waves, since compressive waves have a higher propagating velocity (figure 4). In this case the compressive waves do not produce horizontal ground responses a_h at x=0m due to symmetry. Large surface responses also occur at the soft soil area while at the transition location x=375m the propagating waves cause only small responses. These results show that incident compressive waves can indeed produce much larger vertical ground motions than the horizontal one. The peak vertical ground acceleration PGA_v at x=100m, for example, is about seven times larger than the horizontal acceleration PGA_h.

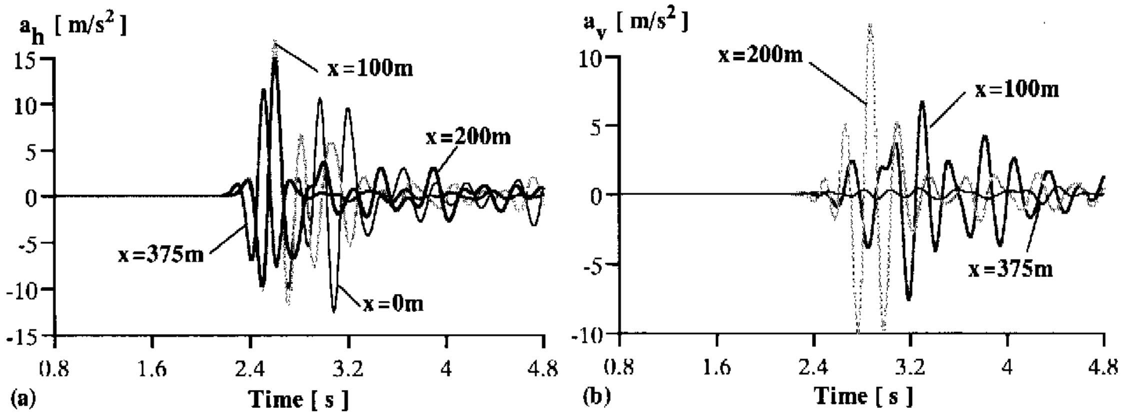

Figure 3(a) and (b): Change of the ground motions with the distance x due to incident shear waves. (a) Horizontal and (b) vertical surface accelerations

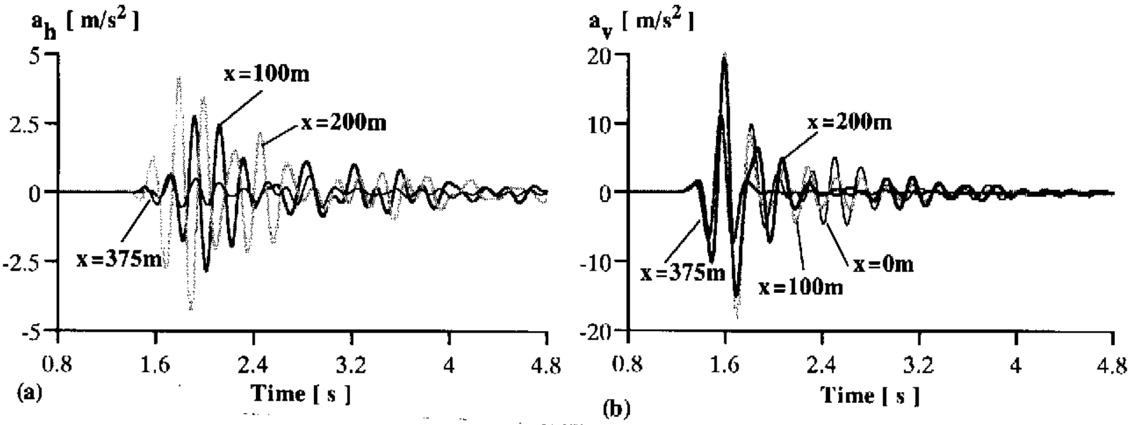

Figure 4(a) and (b): Change of the ground motions with the distance x due to incident compressive waves. (a) Horizontal and (b) vertical surface accelerations

Figure 5 shows the PGA-ratio in case of incident waves with the dominant frequency f_p = 2Hz, 3Hz and 4Hz. The ground motions are caused by a simultaneous incident shear and compressive waves. The results show that not only the ratio of the stiffness of soil deposit to that of adjacent hard soil but also the characteristic of the source will determine the ground response. The different PGA-ratios at the surface of the soft soil is affected by location and dominant frequency, while at the transition location x=375m the ratio for all considered cases is almost the same. The increase of the ratio in the cases f_p = 3 and 4Hz can be caused by the relationship between the dominant frequency of the source and the natural frequencies of the soil layers. These results confirm that at the near source region the ground motions can be much larger in the vertical direction than in the horizontal direction.

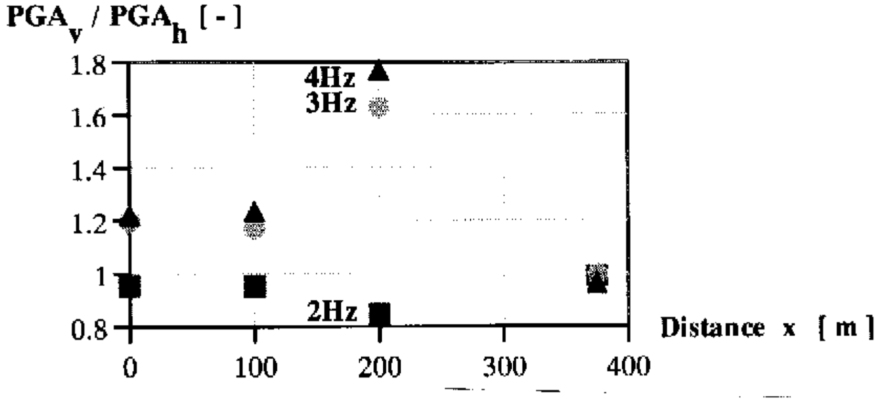

Figure 5: Influence of the dominant frequency f_p on the incident waves on the PGA-ratio

RESPONSE OF A STRUCTURE TO THE GROUND EXCITATIONS

Figure 6 shows the ground motions, the response spectra and the response of the frame-structure to these ground motions due to simultaneous incident shear and compressive waves with a dominant frequency f_p of 3Hz. Although the source of the ground motions is the same, the response of the soil is very different –not only in its amplitude but also in frequency content. The wave propagation from the source to the soil surface is affected by the formation of the layer deposit causing a large soil response at the middle of the deposit and at the distance x=200m.

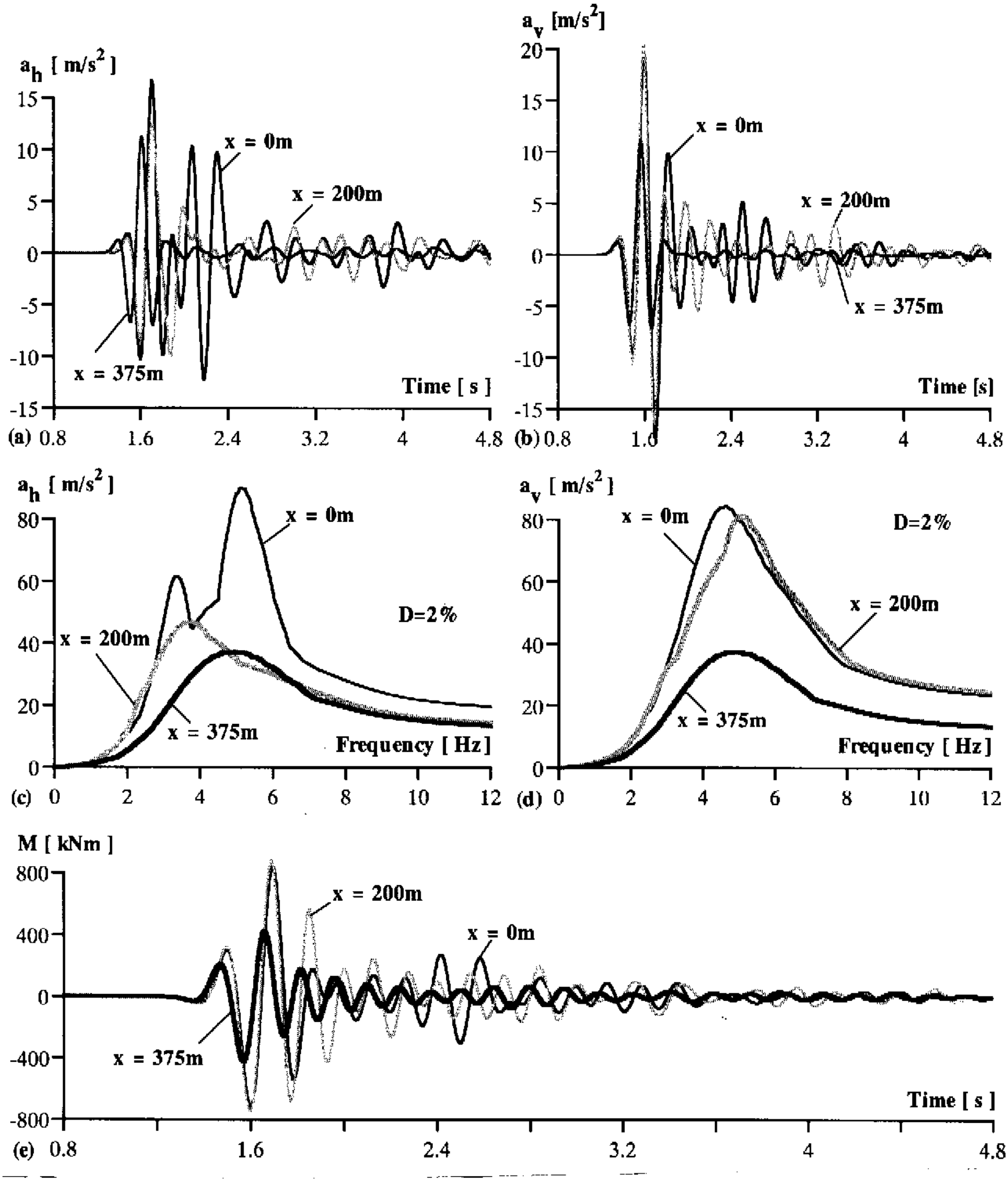

Figure 6(a)-(e): Alteration with the distance x in the case of single Ricker's wavelet as incident wave.
(a)-(b) Alteration of the ground excitations, (c)-(d) Alteration of their frequency content, and
(e) Alteration of the bending moment at the middle of the middle girder

The higher frequency content of the vertical ground motions can be clearly seen from the response spectra of the ground motion at the distance x=200m (figure 6(d)). All ground motions have one dominant frequency except the horizontal ground motions at the middle of the soil deposit. More investigations are needed to clarify the effect of the relationship between the soil deposit and source characteristics on the ground motion behaviour. Figure 6(e) shows the bending moment at the middle of the middle girder due to the simultaneous vertical and horizontal ground motions. The bending moment is mainly caused by the vertical ground excitations, since the excited horizontal fundamental mode of the structure produce no bending moment at that location.

The effect of the ground excitation direction on the development of axial forces in the uppermost right column is displayed in figure 7. The results show that a consideration of the horizontal ground motions alone will clearly underestimate the structural response. While the axial force due to the horizontal ground motion is defined by the excited horizontal fundamental mode, the force due to the vertical ground motion is determined by the direct excitation of all columns. This direct excitation causes much larger axial forces. Although the PGA_h and PGA_v do not occur at the same time, a coincidence of other peaks -for example at 1.88s- causes an additional increase of the axial force. The time coincidence between PGA_h and PGA_v will usually not be expected, since the vertical ground motion generally occurs earlier due to the faster propagating velocity of the compressive waves.

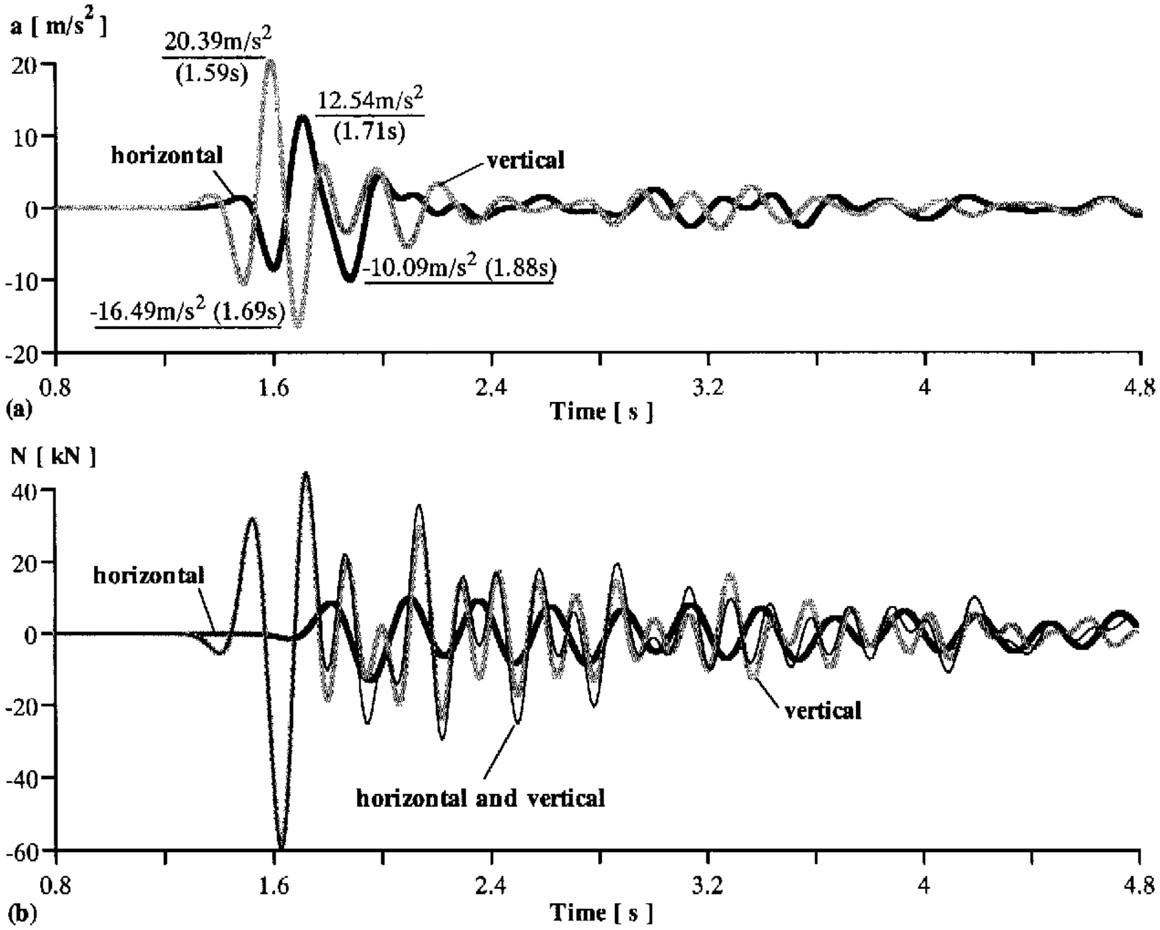

Figure 7(a) and (b): Influence of the ground motion direction on the development of the axial force. (a) Vertical and horizontal ground excitations at x=200m, (b) Axial force in the uppermost right column

Figure 8 shows the ground surface motions at the distance x=0m, 200m and 375m due to simultaneous incident shear and compressive waves. They composed of five Ricker's wavelets. In the considered cases the PGA_h is larger than PGA_v. The ground motions have –as expected- a broader dominant frequency content than in the case of a single Ricker's wavelet as it can be seen in figure 8(c) and (d). The change in the frequency content of the ground excitations may not have strong influence on the responses of the considered structure, because the significant first natural frequencies of the structure and the dominant frequencies of the vertical and horizontal ground motions are far away from each other. Figure 8(e) shows the horizontal displacement u_h at the top of the structure due to a simultaneous horizontal and vertical ground excitations. For the considered structural responses the vertical ground excitations have no significant influence, and according to the horizontal ground excitations the responses of the structure at the distance x=0m and 200m are larger than that at the transition location x=375m.

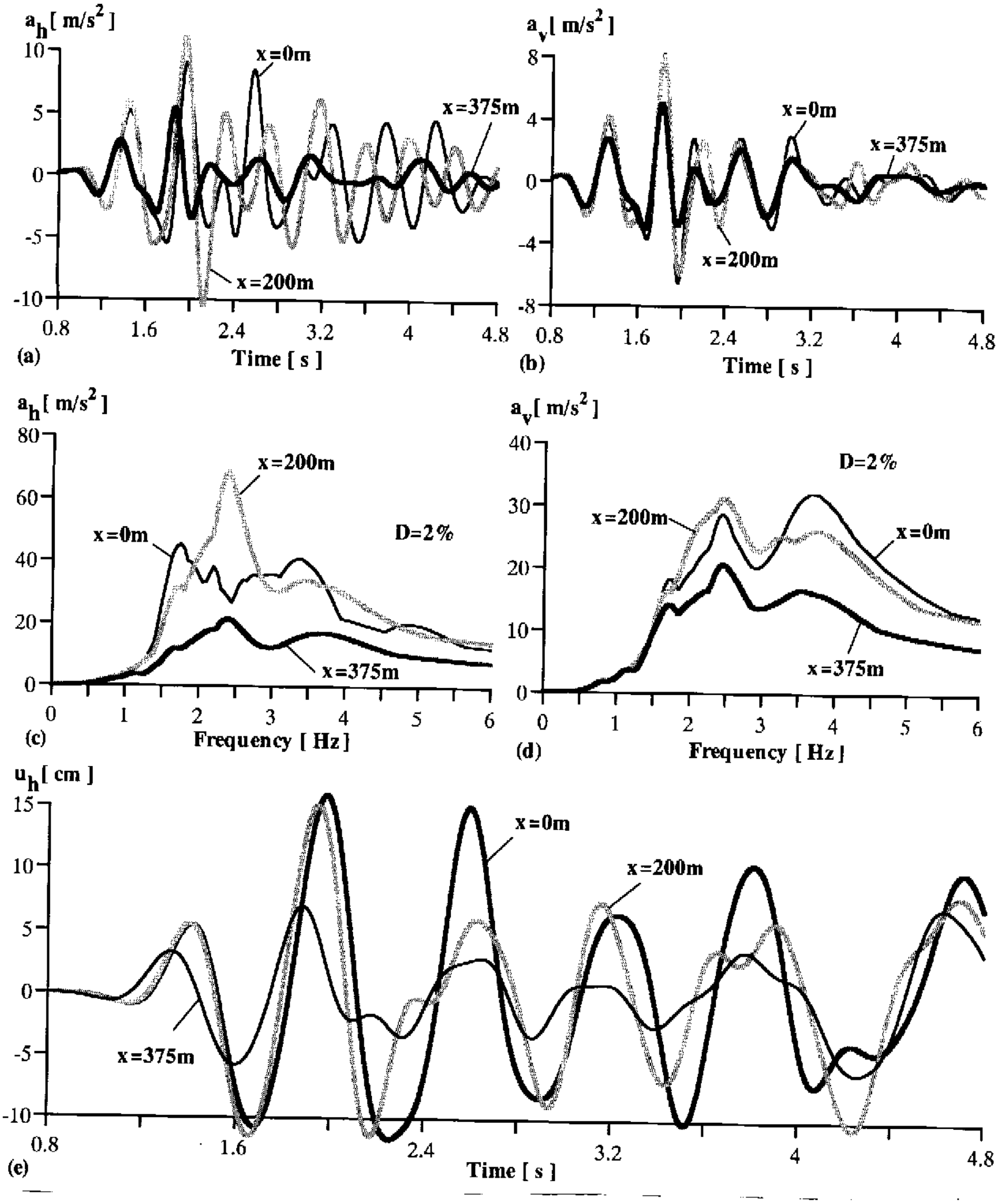

Figure 8(a)-(e): Alteration with the distance x in the case of five Ricker's wavelets as incident waves. (a)-(b) Alteration of the ground excitations, (c)-(d) Alteration of their frequency content, and (e) Alteration of the horizontal displacement at the top of the structure

CONCLUSION

The investigation confirms that the amplitude and frequency content of ground motions are strongly influenced by the distance of the considered location from the source, the soil condition as well as the characteristics of the incident waves. Not only ground motions in the horizontal direction but also in the vertical direction alter with the distance. As a consequence of this the characteristic of response of structures is also altered with the distance from the source, since structural responses are determined by the excited natural structural vibration modes in the vertical and horizontal direction. In order to obtain a realistic structural response a simultaneous horizontal and vertical ground excitation should be taken into account.

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