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SEISMIC WAVE AMPLIFICATION IN KOBE DURING HYOGO-KEN NANBU EARTHQUAKE

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ABSTRACT

The Hyogo-ken Nanbu Earthquake, which occurred on 17 January 1995 due to the inland fault rapture near Kobe caused devastating structural damages to Kobe and its vicinity, registering 6 and partially 7 (severest) on the Japan Meteorological Agency (JMA) seismic scale. The heaviest damages were centered on a banded stretching zone along the Kobe coast, which was called the disaster belt. In this paper, focusing on the geological features at Kobe, the authors conducted the computer simulation separately by taking deep and shallow models in view of the abrupt-dipping rock formation at depth and the gradually increasing surface soft deposits toward the coast.

KEYWORDS

Site amplification, Deep diluvium, Shallow alluvium, Seismic wave propagation, BEM-FEM coupling, Hyogo-ken Nanbu Earthquake, Disaster belt, Time Domain analysis

INTRODUCTION

The Hyogo-ken Nanbu Earthquake, a devastating earthquake of a magnitude of 7.2 on the Richter scale, attacked Kobe and other parts of Kinki area of Japan on January 17, 1995, bringing death and destruction, paralyzing transportation networks, destroying sections of expressways and triggering fires. It was caused by a horizontal shift along the fault that runs from Awajishima Island through the cities of Akashi and Kobe toward the Rokko Mountains. The epicenter of the massive quake was about 20 km deep in northern Awajishima.

The central Kobe area, stretching along the foot of the steep Rokko Mountains in the west-east direction, stands on the alluvia which are accumulated on diluvia, both of which were brought by running river water, but the diluvia brought by extraordinary floods are much stiffer than the alluvia. The diluvia are underlain by granite rocks. The rock formation indicates an abrupt dipping at the foot of the Rokko Mountains and extends horizontally toward the sea shore at several hundred to one thousand meters deep. The surface alluvium, on the other hand, increases gradually as the geography moves from the mountains to the sea. The depth along the seashore is around 20 m or more according to the geological map. Figure 1 depicts the topography at one representative north-south section.

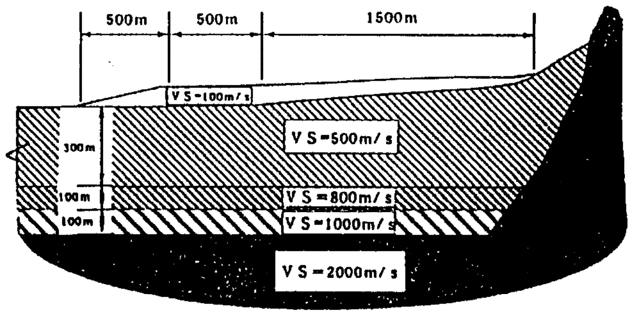


Fig. 1. Topography of Kobe area (N-S cross section)

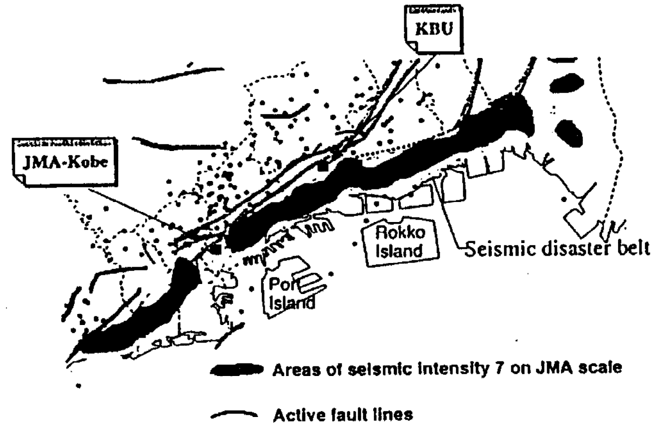


Fig. 2. Seismic disaster belt zone

The Hyogo-ken Nanbu Earthquake has brought destructive damages to structures in Kobe and in its vicinity. The Japan Meteorological Agency has registered the seismic damages as the intensity 6 in Kobe area and partially the severest rank 7, on the JMA scale. Very unique and puzzling is that the heaviest damaged area called the disaster belt stretched on a narrow zone along the Kobe coast as shown in Fig. 2. This phenomenon is contradictory to the conventional understanding of the soil amplification of seismic waves, that is proportional to the alluvium depth. The causes of the seismic belt of intensity 7 should be answered from the seismic wave propagation viewpoint.

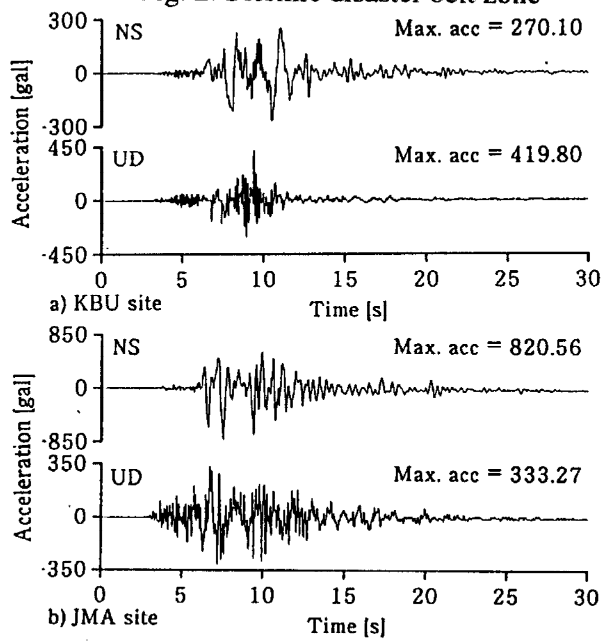


Fig. 3. The Hyogo-Ken Nanbu Earthquake accelerograms at KBU and JMA-Kobe

Features of the earthquake records

The earthquake motions have been recorded at several locations. Among them, the Kobe Marine Meteorological Observatory (JMA-Kobe) and Kobe University basement (KBU) are taken as the representatives. The KBU record was registered in terms of velocity so that the associated acceleration was computed. Those seismic records indicate very impulsive motions as characterized by two big peaks at the beginning of the time history and followed by the soil vibrations at the site. See Fig. 3 for the time histories. The Fourier transforms of the NS components are depicted in Fig. 4. The record at KBU, supposedly showing the motion on the base rock, indicates that it has predominant longer period motions than 1.0 s, while the JMA-Kobe record shifted their periodic contents to the shorter period range through amplification at the site. Other unprecedented features are that it attained remarkably high velocities and significantly large displacement amplitudes when compared with other recent earthquakes in Japan.

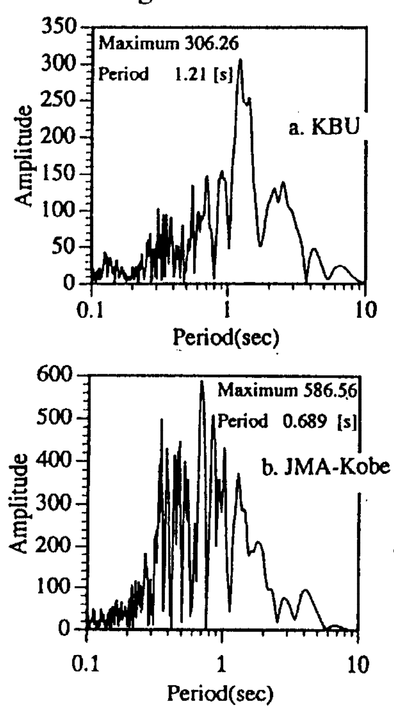


Fig. 4. Fourier amplitudes of earthquake motions

COMPUTER SIMULATION

The topography effects on seismic waves are separately considered by taking different models for the stiff deep soils called Osaka/Kobe group layers and for the surface soft soils. The localized amplification and phase difference along the horizontal distance should adequately be interpreted at least by the two-dimensional analysis. Therefore, the computer simulation is conducted by utilizing the time domain FEM-BEM hybrid method in order to reproduce the soil behavior from the foot of the Rokko Mountains to the seashore stretching in the north-south direction. The irregular alluvia are modeled by the finite elements while the extending half-space is modeled by the boundary elements. The internal damping of 3 % was imposed in a form of Rayleigh-type to the finite elements region. The boundary elements are assumed to have constant values within elements both for displacement and traction and to vary stepwise with each increment of time (Takemiya and Adam, 1995a)

Deep soil model

First, focusing on the topography of the abrupt dipping of the rock formation at the foot of the Rokko Mountains, the wave propagation is investigated in the deep Osaka/Kobe Group layers. Figure 5 shows the FEM-BEM model for the computer simulation. In order to find the seismic wave propagation mechanism in the focused soil layers, the Ricker waves of different characteristic periods are assumed for the SV wave incidence in the far field. For numerical computation purposes the boundary is closed on the coast side at enough distance far from the area of interest to exclude any side boundary effect on the computation results.

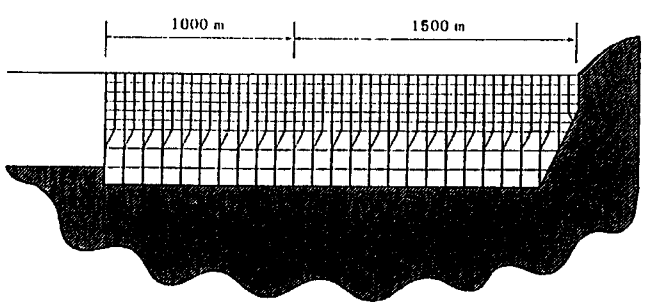


Fig. 5. Deep soil model for FEM-BEM simulation

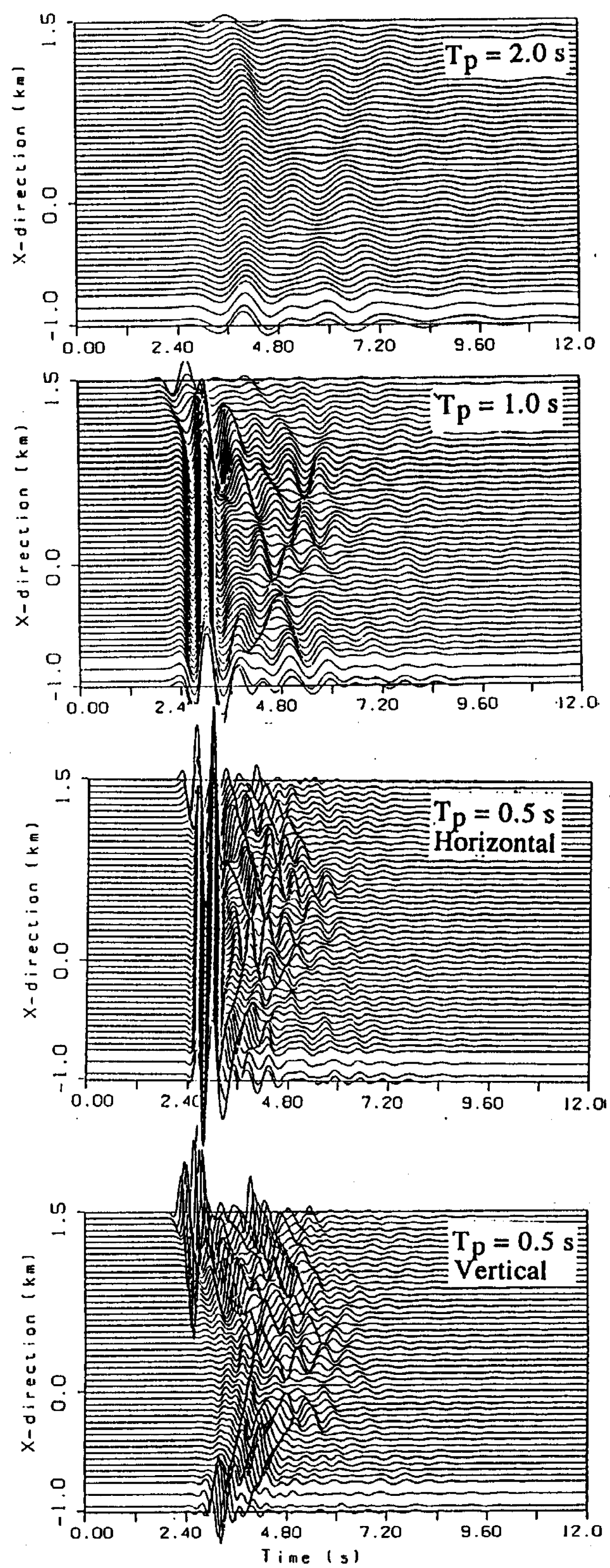


Fig. 6. Response time histories due to SV Ricker wave incidence

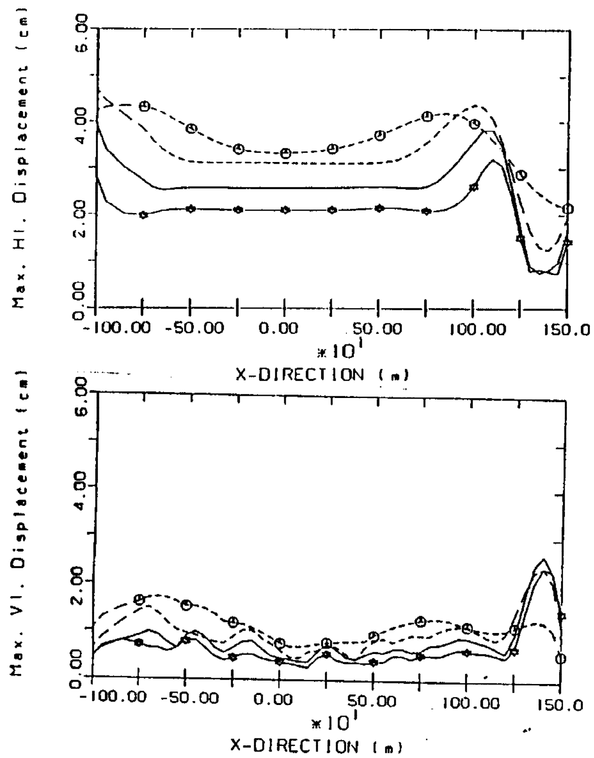


Fig. 7. The maximum displacement response

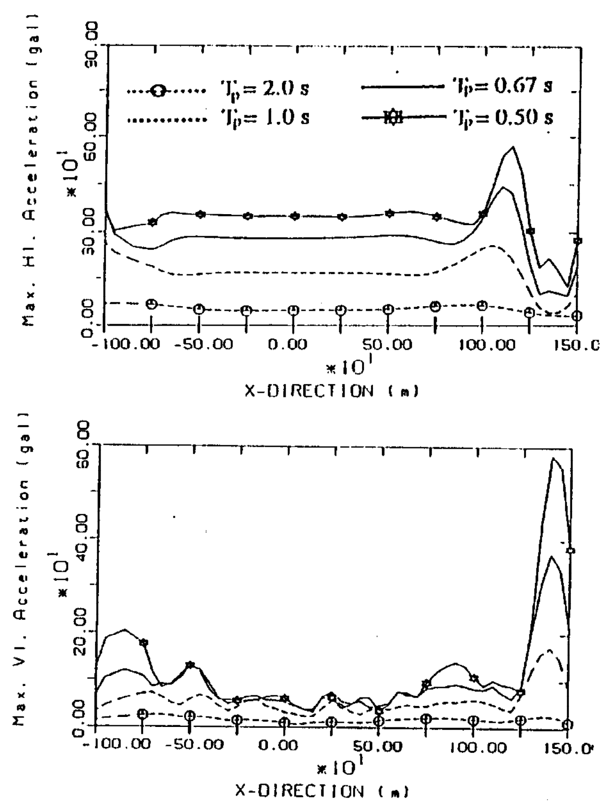


Figure 8. The maximum acceleration response

Figure 6 shows the surface acceleration response in time histories. It is noted that the long period wave of T_p = 2.0 s results in very small wave scattering. The motion for T_p = 1.0 s indicates the substantial horizontal wave propagation. The motion for the short period wave of T_p = 0.5 s generates significant both vertical and horizontal motions.

Figure 7 gives the resulting maximum amplitude for displacement responses. It is noted that the amplification for the horizontal response components is confined in a certain limited distance around 500-1000 m from the rock dipping location whereas the vertical components nearer to the dipping location

Figure 8 shows the maximum acceleration profile. The trend of localized amplification is the same as the displacements but the maximum amplitudes are reversed in order. The shorter the incident wave period, the higher the amplitude of the acceleration. This is due to the fact that the acceleration is inversely proportional to the period squared. For instance, for the maximum input of 14.81 results in the maximum horizontal response of 70 gal in case of T_p = 2.0 s, while the input of 237 gal leads to the response of 590 gal in the case of T_p =0.5 s. For the horizontal responses, the amplification ratio attains the biggest value for the wave incidence of T_p = 2.0 s indicating around 4 and it becomes less as the period becomes shorter and the smallest value at T_p =0.5 s wave incidence. The vertical response which resulted from the wave scattering is shifted toward the dipping location of the topography within most narrow area. The short period wave incidence of T_p = 0.5 s attains the highest amplitude whereas the long period wave incidence T_p = 2.0 second the smaller values. Interesting to note is that the vertical motions in this amplified zone are larger than the horizontal motions. In the far distance beyond this amplified zone the response amplification ratio remains almost constant value that can be predicted by the one-dimensional wave propagation as shown in Figs 6 and 7.

It must be mentioned that the disaster belt of JMA intensity 7 is located in this flat zone, which means that the deep soil amplification may not be concerned with it. However, the observed fact in the KBU record that the vertical maximum acceleration exceeded the horizontal maximum value may be reasoned by the above deep soil topography effect.

Surface soil model

Figure 9 gives a simplified wedge-shaped model for analysis when the focus is placed on the alluvium deposits on which Kobe city directly stands. The dimensions and sharp contrast of soil stiffness are assumed here based on the available geological data, as indicated in the figure.

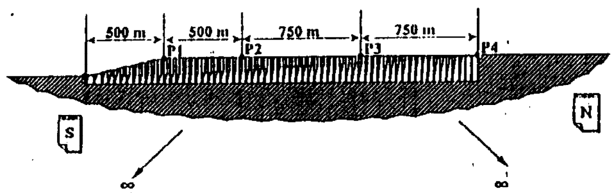


Fig. 9. Surface alluvium model for FEM-BEM simulation

As before, the Ricker waves of various characteristic periods are used as incident SV wave at the far field. In contrast to the behavior of deep soil layers, this shallow soil deposit generates the horizontal wave propagation for the wave incidence of period less than 1.0 s. Figure 10 shows the wave interferences of the horizontally propagating waves with the vertically traveling major waves. At the longer wave incidence as $T_p = 2.0$ s, only the incident but double valued wave form appears with no surface wave generation. The motion at $T_p = 0.5$ s indicates the most significant horizontal wave propagation both in horizontal and vertical components. The maximum responses are depicted in Fig. 11. This reveals that the big response amplification occurs at short period motion both in acceleration and displacement in the wider distance that includes the disaster belt zone of seismic intensity 7. The vertical acceleration are appreciably generated due to the wedge-shaped topography even for the vertical SV wave incidence. Detailed discussion can be found in the author previous work, (Takemiya and Adam, 1995b).

The more complicated simulation was conducted for earthquake-like motions and the recorded motions of the Hyogo-ken Nanbu Earthquake. The short period motion is an approximation by a set of Ricker waves to the JMA - Kobe in the range of period contents shorter than 1.0 s. The long period motion, on the other hand, is another set of Ricker waves to approximate the KBU record in the longer period range, (Takemiya and Adam, 1995c).

The maximum response profiles are drawn in Fig. 12(a) for the acceleration and in Fig. 12(b) for the

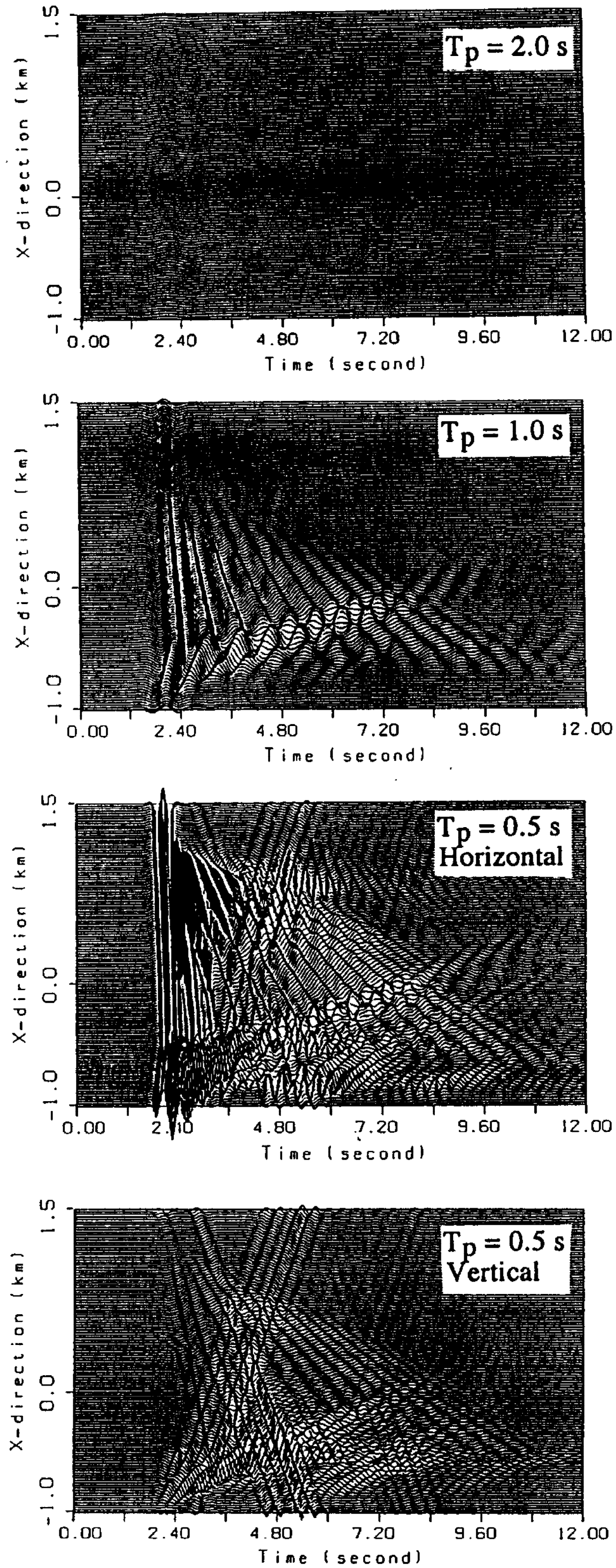


Fig. 10. Response time histories due to SV Ricker wave incidence (Surface alluvium effect)

displacement. The KBU records, being affected by the dipping topography of the rock base, is supposedly amplified at the long period motion. The displacement response is reproduced to match well the receded value. However, the acceleration amplification fails to match the expected value at the location of disaster belt ranging from 500-1000 m from the seashore toward inland, although some amplification appears in the area closer to the Rokko Mountains but it does not lead to the acceleration amplification. The deconvoluted JMA-Kobe motions leads to a similar displacement to the observation and gives rise to the expected acceleration amplification at the disaster belt zone. The short period type motion results in closer to the acceleration response by JMA-Kobe whereas the long period motion to the associated displacement response.

The velocity response is related to the input energy to structures. The unusually high velocity recorded may be caused by long period motions from the comparison in the figure.

Figure 13 shows the time history of acceleration, velocity and displacement due to the deconvoluted JMA-Kobe records as input motion. Interesting to note is that the response indicates large displacement of long period motions while the intensive acceleration of short period motions takes place. This soil behavior leads the worst situation to the aboveground structures when they become in resonance in the acceleration period. The phase difference along the horizontal distance is clear since the horizontal wave propagation can be noticed. The wave interference has occurred between such waves and the those propagating in the vertical direction along the alluvium depth. This phenomenon, referred to as " bump effect" leads to a big acceleration amplification and impose unfavorable force action to structures on the surface.

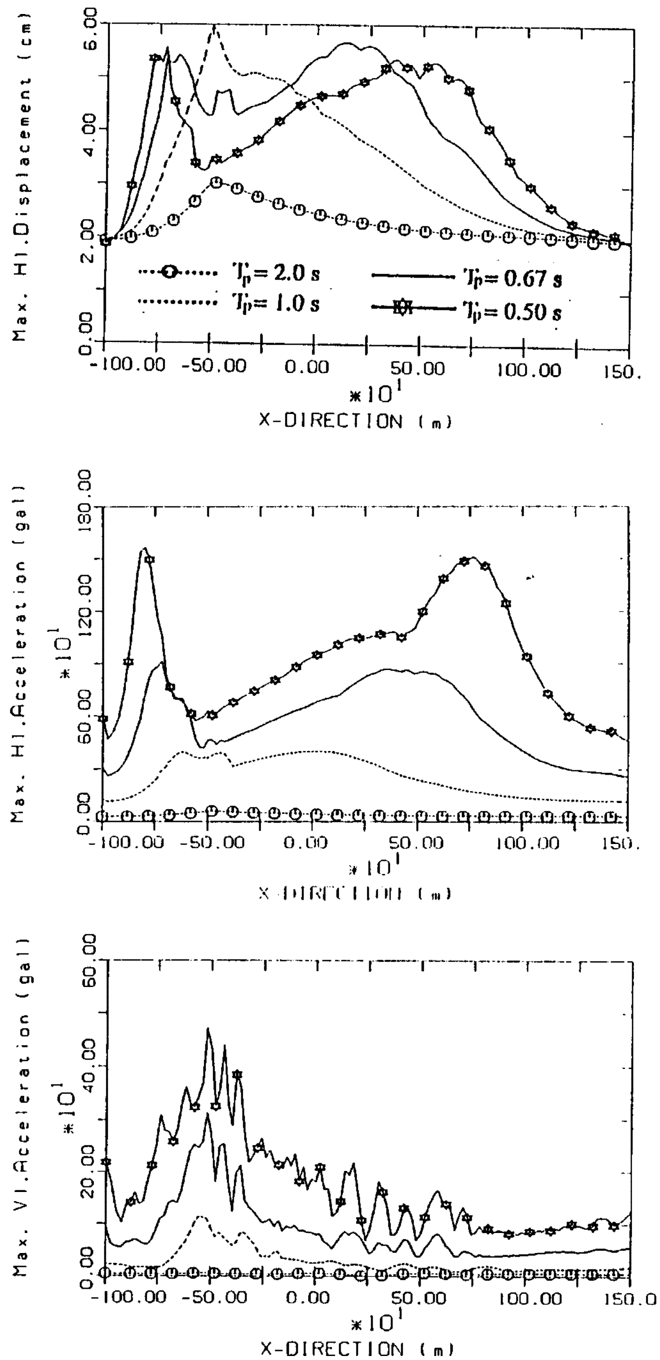


Fig. 11. The maximum response profiles due to SV Ricker wave incidence

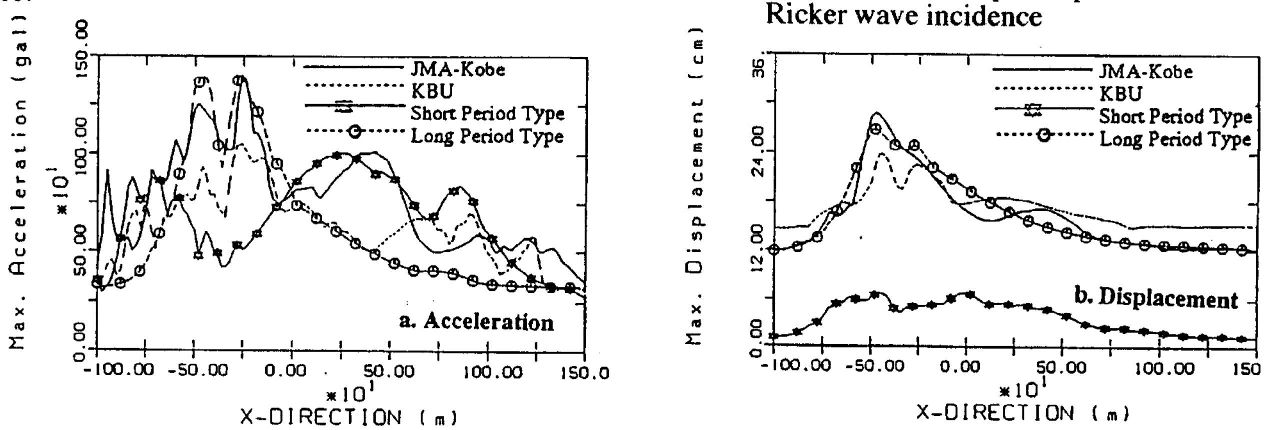
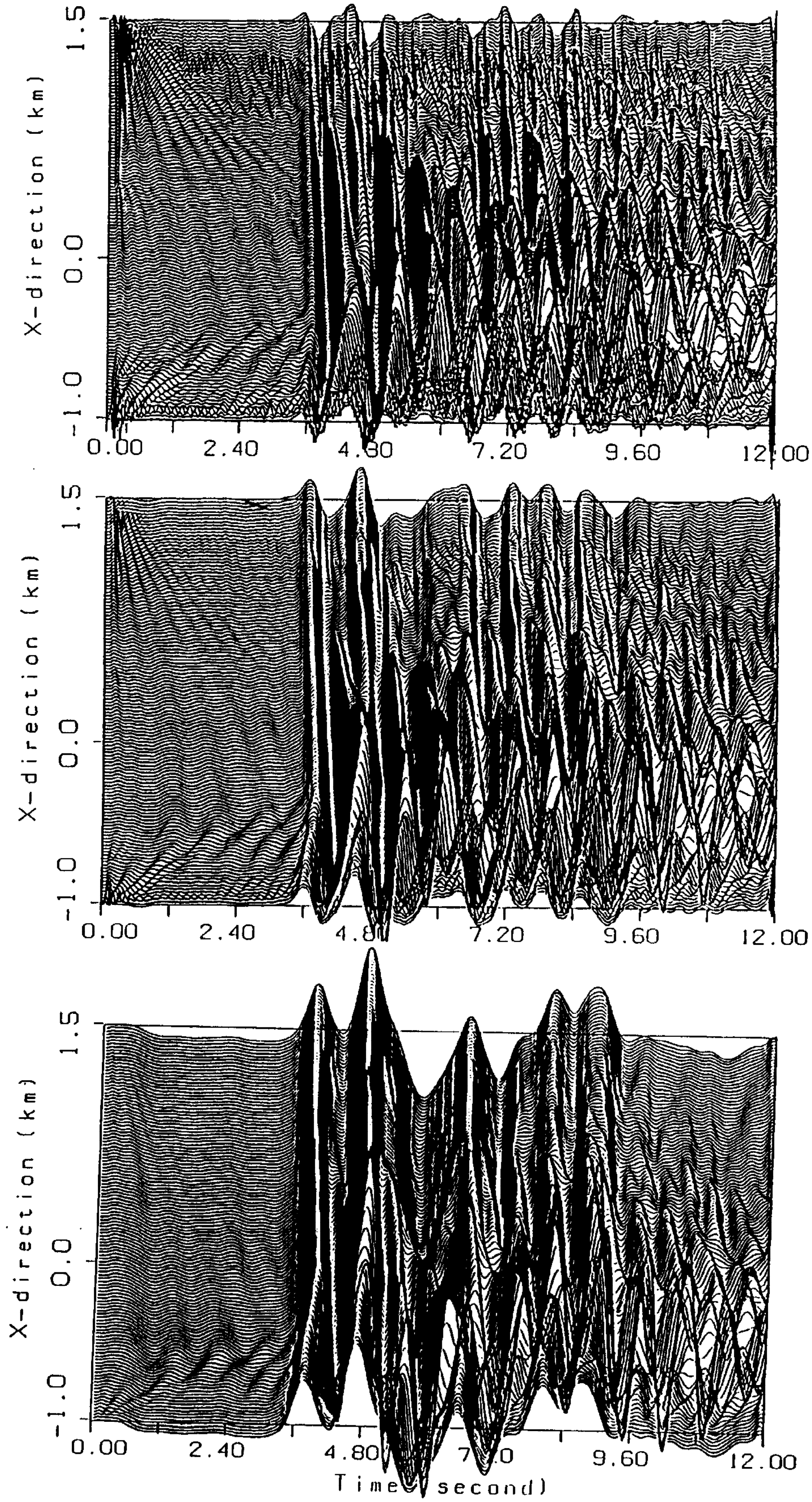


Fig. 12. The maximum response profiles due to different input motions



a. Acceleration

b. Velocity

c. Displacement

Fig. 13. Horizontal responses time histories due to deconvoluted JMA-Kobe input motion

CONCLUSIONS

In this paper, in order to get better understanding of the site effect in the Hyogo-ken Nanbu Earthquake, 1995, two types of models are taken for the computer simulation: the deep soil model to describe the dipping of the rock formation of deep stiff soil layers called Osaka/Kobe group, and the shallow wedge - shaped surface soft alluvium on those layers. The results reveal the wave propagation mechanism in the irregular topography at Kobe, which can interpret rationally the puzzling observed information at the Hyogo-ken Nanbu Earthquake.

From the analysis of the deep soil model, we state that the abrupt dipping of the rock formation causes the wave scattering that leads to the seismic wave amplification near this location. Under the assumption of the SV wave incidence the horizontal response amplification occurs remarkably at the period of 1.0 to 2.0 s at some short distance away from the dipping location of the base rock. The vertical response amplification, on the other hand, occurs closer to the dipping location of the base rock at the short period motions around 0.5 s. Noteworthy is that the latter response component exceeds the former. This substantiate the features of the acceleration record at the Kobe University basement in which the vertical component with higher frequency contents is bigger than the horizontal component with less high frequency contents.

From the analysis of the surface soil model, we note that the gradually increasing alluvium amplifies the seismic waves most in the period of 0.4 to 0.7 s more than the motions in the long period longer than 1.0 s. The horizontally propagating wave interferences with the vertically propagating wave lead the amplification of seismic waves at the location that coincides with the so-called disaster belt zone. The computed maximum acceleration, velocity and displacement values based on the incident wave of the deconvoluted motion of the JMA record agree well with those corresponding observed values.

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