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ONE-, TWO-, AND THREE-DIMENSIONAL SITE EFFECTS IN SEDIMENT-FILLED BASINS

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ABSTRACT

Various site effects due to sediment-filled basins are reviewed. After checking an actual velocity structure of a large-scale sedimentary basin, the validity and limitations of one-, two-, and three-dimensional (1D, 2D, and 3D) theories for site effects are surveyed. The simplest 1D theory seems valid for stations far from basin edges for analyzing the site effects due to shallow and soft sedimentary layers at short periods (less than about depth = 50 m, Vs = 500 m/sec, and 1 ~ 2 seconds). For stations close to the basin edges, various 2D/3D effects (the refracted and SS waves, focusing, the local surface waves) would get mixed with the 1D effects. At longer periods (more than 1 ~ 2 seconds), the 2D/3D basin edge effects could become prominent even for stations far from the edges, especially for a shallow earthquake source outside the basin.

KEYWORDS

1D, 2D, 3D site effects; sediment-filled basin; the amplification factor; the impedance contrast; the basin edge effects; the refracted/reflected waves; the local surface waves; the focusing and defocusing effects; the 2D/3D resonance mode; the Kanto sedimentary basin; the Los Angeles basin; the Mexico City basin

INTRODUCTION

Since the 1906 San Francisco and 1923 Kanto earthquakes, it has been well recognized that sub-surface geological conditions and earthquake damage strongly correlate (e.g., Matsuzaka, 1926). Those facts led seismologists to studying site effects in the 1930s. Since then, together with increasing number of large-scale structures (e.g., high-rise buildings and long-span bridges), study of the site effects have been expanded from 1D effects due to sub-surface layers at short periods (less than 1 ~ 2 seconds) to 2D/3D effects in large-scale sedimentary basins at broad periods (up to 10 ~ 20 seconds).

The purpose of this paper is to review various site effects due to sediment-filled basins. First, the actual velocity structures in deep boreholes in a large-scale sedimentary basin are shown to illustrate the difficulties in studying the complete 3D site effects. Then, various site effects are reviewed in terms of the validity and limitations of the 1D, 2D and 3D theories. The non-linear and topographical effects are excluded in this paper.

VELOCITY PROFILE OF A LARGE-SCALE BASIN

First, we will look at actual geological and velocity structures of the Kanto sedimentary basin in Japan, where the Tokyo metropolitan area is located. As shown in Fig.1(a), geologically, the Kanto basin is a large sedimentary basin surrounded by pre-tertiary and volcanic bedrock. Fig.1(b) depicts the velocity profile of the basin, as measured directly along a deep borehole at Fuchu, whose location is also shown in Fig.1(a). The profile is indicative of the difficulties associated with analyzing the three-dimensional site effects, because of the drastic change of velocity profile within a relatively short distance. Here, the geological/velocity profiles vary from the thin, shallow, complicated and soft holocene layers, characterized by a depth of less than, approximately, 50 m and shear-wave velocity of 500 m/s, to the thick, deep, relatively simple, and hard tertiary layers characterized by depths of up to 2 to 3 km and velocity of, approximately, up to 2500 m/s. Generally, it is known that short-period ground motion (less than 1 to 2 seconds) is primarily amplified within the shallow layers, whereas long-period motion (of up to 10 ~ 20 seconds) is mainly amplified within the deep layers. Such complex dual (shallow and deep) geological structures are commonly seen in large basins, such as the Los Angeles and Mexico City basins.

Because such deep borehole data are scarce, it is extremely difficult to determine the detailed three-dimensional velocity profile of such large-scale basins. Therefore, we have to adopt appropriate approximating assumptions to model the site effects caused by sediment-filled basins.

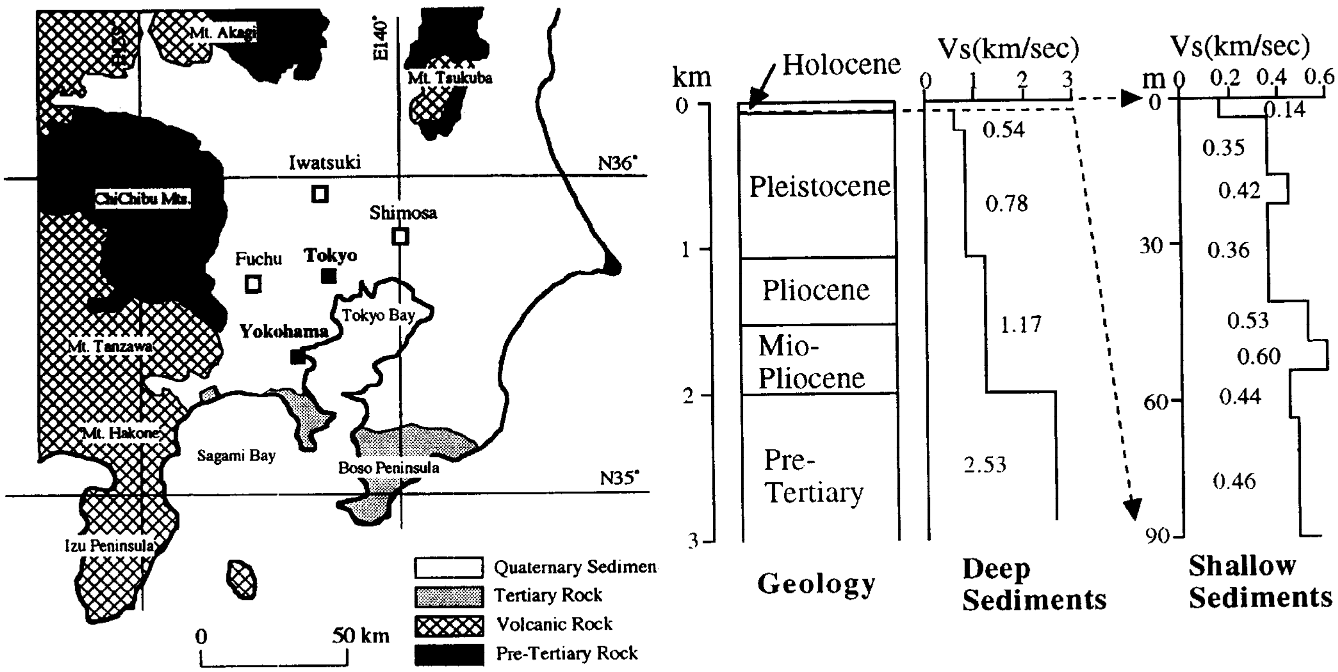


Fig.1. (a) Right: Geological map of the Kanto sedimentary basin together with three deep borehole sites at Fuchu, Iwatsuki, and Shimosa; (b) Left: Geological and velocity profiles for shallow and deep sedimentary layers at the Fuchu site (from Kinoshita, 1986).

ONE-DIMENSIONAL (1D) SITE EFFECTS

1D Site Effects

The simplest way to study the site effects in a sediment-filled basin is by assuming a 1D model of the structure right under the observation station. It should be noted that there is a difference between geotechnical engineers and seismologists about the choice of wavefield for the 1D study of site effects. Geotechnical engineers usually assume a 1D wavefield in shallow structures (< about 50 m), while seismologists normally model using 3D wavefields in deep structures. Therefore, this paper classifies the 1D models for studying site effects into the following three (see Fig.2):

- 1-1 D: both the structure and the wavefield are 1D (vertical axis only)
- 1-2 D: the structure is 1D and the wavefield is 2D (one vertical and one horizontal axes)
- 1-3 D: the structure is 1D and the wavefield is 3D (one vertical and two horizontal axes)

Below, we summarize the various 1D site effects as predicted by the above models.

1-1 D Site Effects

These are the simplest case of site effects that are caused by flat alluvial/sedimentary layers (1D structure) due to the vertically propagating plane body waves (1D wavefield). The assumption of the vertical wavefield for the shallow sediments is justified by virtue of Snell's law. The theory of multiple reflection/transmission of 1D waves was initiated by Sezawa, Kanai and colleagues in the 30's in order to investigate the amplification effects and dominant periods due to a few soft layers overlying a half-space (e.g., Sezawa, 1930). The theory was generalized in the 60's in order to include multiple layers using the propagator matrix method (e.g., Haskell, 1960). Subsequently, observational studies using shallow boreholes (< 50 m) confirmed the validity of the simpler theory for short periods (< 1 second; e.g., Kanai et al., 1959; Herrera and Rosenbluth, 1965). The most useful tool that emerged from this theory is the amplification factor, which is the ratio of the free surface motion to the incident wave with unit amplitude. The basic conclusions from the 1-1D model of site effects could be summarized as follows: 1) Compared with the input motion, the surface motion has large amplitudes due to the impedance contrast between the bedrock and the sediment layers; 2) the surface motion has long duration due to the multiple reflections/transmissions of the propagating waves within layers; 3) the surface motion shows clearer predominant periods, when the impedance contrast is larger.

Since the 1970s, various observational and theoretical studies have reported limitations of the 1-1 D modeling. For example, later parts of the ground motions recorded for the 1940 Imperial Valley, the 1966 Parkfield, the 1968 Tokachi-oki, the 1971 San Fernando earthquakes were found to be due to the surface waves (e.g., Trifunac and Brune, 1970, Shima, 1970, Trifunac and Udwadia, 1974, Hanks, 1975). Trifunac and Udwadia (1974) found that the ground motion in the Los Angeles basin was dominated by the source and path effects rather than the site effects. They concluded that the 1-1D modeling might be useful only for geological constructs with large impedance contrasts, such as the shallow alluvial valleys in Tokyo and Mexico City. The data from deep boreholes depicted in Fig.1 showed that the 1-1 D theory is valid only for near-vertical incidence, but fails for oblique incidence, because of the total reflections at the bottom of the basin and the excitation of the surface waves (Kinoshita, 1986).

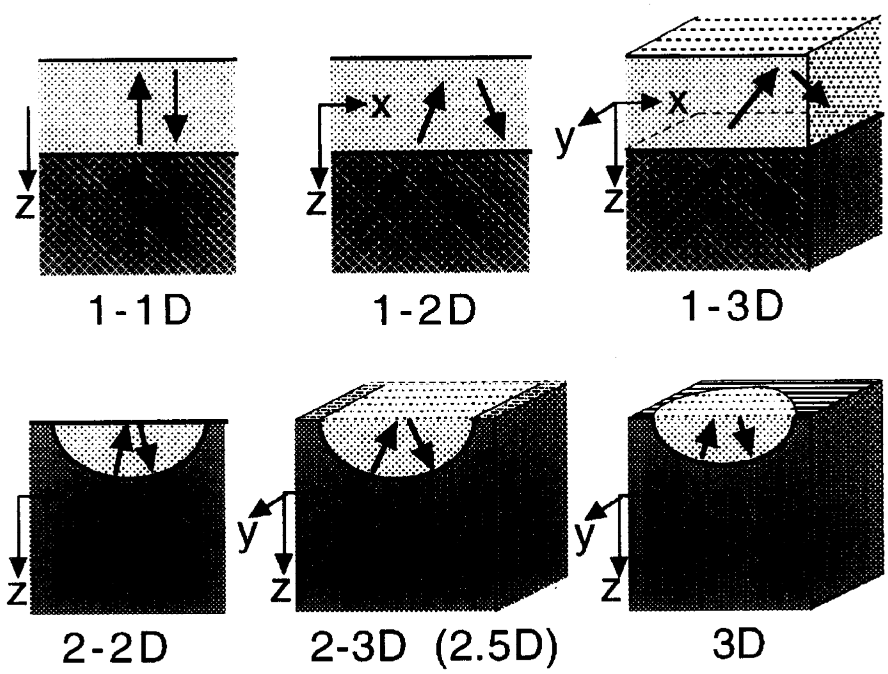


Fig.2. The notations regarding the dimensionality for the structure and wavefield used in this study; the first and second numbers represent the structure and the wavefield, respectively.

1-2 and 1-3 D Site Effects

These are the 1D site effects for the obliquely incident body waves, surface waves, and seismic waves from line or point sources (2D or 3D wavefields). In addition to the 1-1 D effects discussed above, various reflected/transmitted waves (e.g., the PS and SS phases) and the generation of the surface waves make the observed waves complex and with longer duration (e.g., Trifunac and Brune, 1970, Shima, 1970, Trifunac and Udwadia, 1974, Hanks, 1975). Theoretical synthetic methods for computing Green's functions and the normal mode solution have successfully reproduced the ground motions recorded in the Imperial Valley, Acapulco, Parkfield, and Tokyo (e.g., Heaton and Helmberger, 1978; Hartzell et al., 1978; Kudo, 1978). However, the 1D models of the geological structure that they employ may be insufficient in taking into account all the path and site effects of the actual 3D heterogeneous structures.

Numerous strong motion records for the 1994 Northridge earthquake and aftershocks provided excellent opportunities to test various modelings. Generally, 1-3D methods successfully simulated the records obtained in the San Fernando valley, which lies above the earthquake fault, for broad frequencies (e.g., Zeng and Anderson, 1996). However, 2D/3D methods were needed for the records in the Los Angeles basin located to the south of the fault (e.g., Pitarka and Irikura, 1996; Gao *et al.*, 1996). This can be explained by the fact that the basin-edge effects, in the case of the Los Angeles basin, become prominent for obliquely incident waves as will be shown.

TWO-DIMENSIONAL (2D) SITE EFFECTS

The next simplest modeling is to take a 2D cross section from a source to a receiver. Regarding the wavefield, we can choose 2D (2-2 D) or 3D (2-3 D, also called 2.5 D) as shown in Fig.2. In order to investigate 2D site effects, numerous numerical and observational studies have been carried out since the 70s (see extensive reviews, e.g., Aki, 1988). Perhaps, the most interesting phenomena found from those studies are the focusing and defocusing effects (e.g., Boore *et al.*, 1971; Jackson, 1971; Hong and Helmberger, 1978), the generation of the refracted waves and the local surface waves at basin edges (e.g., Aki and Larner, 1970; Lysmer and Drake, 1972; also see Fig.3), and the 2D resonance modes (e.g., Trifunac, 1971; Bard and Bouchon, 1985).

2D Basin Edge Effects

Sharp impedance contrasts which cross basin edges possibly constitute the strongest violations of the assumptions used in 1D models of site effects. As shown in Fig.3 (a), the incident waves are refracted along the basin edge and propagate inside the basin. Some of them reflect at the free surface and at the bottom of the basin (e.g., the SS phases; Scriver and Helmberger, 1994), and eventually grow into the surface waves at a distance from the edge. When the waves refracted/reflected from the basin edge and from the bottom constructively interfere, they give rise to extremely large amplitudes at locations close to the edge (focusing effects). This probably helps explain why highly damaged areas during an earthquake are often concentrated on stripes along basin edges (e.g., Jackson, 1971). The "disaster belt" observed in Kobe for the 1995 Hyogo-ken Nanbu earthquake could have been caused by such an effect (e.g., Pitarka *et al.*, 1996). Also, large ground motions observed in Santa Monica during the 1994 Northridge earthquake could be similarly explained (Gao *et al.*, 1996).

The local surface waves generated at the basin edge (also called the basin edge induced surface waves) were found theoretically by Aki and Larner (1970) and Lysmer and Drake (1972), and observationally by Toriumi (1974) in the Osaka basin, Seo (1978) in the Kanto basin, and by Lie and Heaton (1984) in the Los Angeles basin. Theoretical studies for the local surface waves were thoroughly carried out by Bard and Bouchon (1980a, 1980b, 1985). They pointed out that 1) the surface waves constitute the main motion in basins after the body waves; 2) the larger the incident angle is, the larger the amplitude of the surface is; 3) when the impedance contrast is large, the surface waves reflect at the basin edges and travel repeatedly between edges; and 4) for deeper basins, these alternating surface waves interfere in phase and grow into the 2D resonance modes. In addition, we point out that 5), like body waves, the local surface waves exhibit clear predominant periods for large impedance contrasts (e.g., Hisada *et al.*, 1991); 6) the surface waves are more efficiently attenuated than the body waves, because they travel mainly in sedimentary layers with large damping (e.g., Horike, 1988; Aki, 1988); and 7) they are dominant at longer periods, because of the high attenuation of the short-period components and the dominance of the lower normal modes (e.g., Hisada *et al.*, 1991). Therefore, although the 2D resonance mode was observed in a small-scale basin (e.g., King and Tucker, 1984), the surface waves repeatedly traveling between edges and the 2D/3D resonance mode are probably not common in large basins for short periods. This could validate the 1D methods at short periods for stations far from basin edges.

In the late 80s, the extensive damage of oil storage tanks in Niigata City for the 1983 Japan Sea earthquake, of high-rise buildings in Mexico City for the 1985 Michoacan earthquake, and of wooden houses in the San Francisco Bay area for the 1989 Loma Prieta earthquake have been responsible for drawing world-wide attention to those 2D (and 3D) effects. Subsequently, numerous 2D methods have been applied to investigate the long-period ground motions recorded in actual basins: the Los Angeles basin (e.g., Vidale and Helmberger, 1988), the Kyoto basin (e.g., Horike, 1988), the Kanto basin (e.g., Yamanaka *et al.*, 1989; Yamamoto *et al.*, 1989), the Mexico City basin (e.g., Kawase and Aki, 1989), and so on.

In order to include the 3D source and path effects into 2D modelings, several techniques have been proposed. Vidale and Helmberger (1988) and Yamamoto *et al.* (1989) approximately included 3D dislocation sources into 2D FDM (Finite Difference methods) and BEM (Boundary Element methods), respectively. Reagan and Harkrider (1989) combined the normal mode solution with 2D FDM codes; the methods are usefull for computing the ground motion of basins from distant sources. Although these approximate methods are easily applied to the existing 2D codes, they cannot be used for near sources. Thus, they may be replaced by rigorous 2-3 D (2.5 D) methods in the future (e.g., Luco *et al.*, 1990).

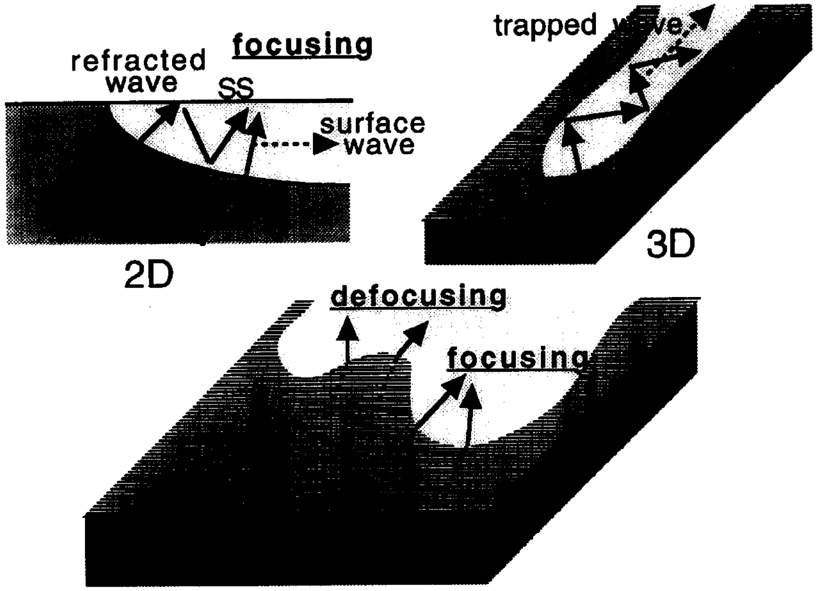


Fig.3. Examples for the two- and three-dimensional basin edge effects.

THREE-DIMENSIONAL (3D) SITE EFFECTS

Recent observations using seismic array data have indicated that the generation and propagation of the local surface waves are strongly affected by 3D basin structures (e.g., Frankel *et al.*, 1991). For example, the main motion observed in the Tokyo lowlands from the shallow sources, which are located on the south-west to north-west of the Kanto basin, is often due to the long-period Love waves (4 to 10 seconds) that emanate from the western edge of the basin rather than from the direction of the sources (Kinoshita *et al.*, 1992, also see Fig.1).

Since the 1980s, various methods have been applied to simple basin models in order to study basic 3D site effects in sediment-filled basins: the ray methods (e.g., Lee and Langston, 1983), FEM (Finite Element methods; e.g., Sato *et al.* , 1988), BEM (Boundary Element methods; e.g., Niwa and Hirose, 1987; Mossesian and Dravinski, 1990), the wave-expansion methods (e.g., Sanchez-Sesma, 1983), and the Aki-Larner method (e.g., Horike *et al.*, 1990; Ohori *et al.*, 1992). Generally, the phenomena similar to those analyzed by the 2D models but more complicated were reported: focusing, defocusing, and various basin edge effects including the 3D resonance modes and the trapped waves within narrow sediment-filled valleys (see Fig.3 (b) and (c)). Fig.4 shows an example using a simple deep basin model (Ohori *et al.*, 1992). The comparison among the 1D, 2D and 3D amplification factors at the center of the basin shows that the higher the dimensionality, the higher the dominant frequency, and the larger the maximum amplitude. This is because the bedrock outside the basin edges restricts the motion of the basin at lower frequencies, but causes the focusing effects at higher frequencies at the basin center.

In the 1990s, thanks to the dramatic development in parallel computing technologies, 3D ground motion simulations have been applied to actual sediment-filled basins: the Kanto basin (e.g., Toshinawa and Ohmachi, 1992; Kato *et al.*, 1993; Hisada *et al.*, 1993), the Los Angeles basin (e.g., Yomogida and Etgen, 1993; Qu *et al.*, 1994; Olsen *et al.*, 1995), and others (e.g., Frankel and Vidale, 1992; Graves, 1993). As an example, Fig.5 shows the long-period Love waves (around 8 seconds) as computed in the Kanto basin (Kato *et al.*, 1993. Although the Tokyo station is located on the nodal plane of the source radiation pattern, the large amplitudes of the first half of the records are well simulated. The large amplitudes are caused by the concentration of the surface waves due to the focusing effects in a small 3D sediment-filled basin near the source. On the other hand, in addition to the focusing effects, the surface waves generated along the western edge of the Kanto basin are needed to reproduce both the large amplitude and long duration of the records, which were actually observed in Tokyo as mentioned earlier(Kinoshita *et al.*, 1992; Hisada *et al.*, 1993).

Currently, Finite Difference methods (FDM) are most popular for studying numerically 3D site effects of actual basins because they are relatively easy to run on the most advanced parallel computers (e.g., Olsen *et al.*, 1995). However, the regularly structured mesh of FDM may not be intrinsically appropriate to model sedimentary basins, which exhibit rapid velocity changes within a short distance along the depth and the basin edges, as shown in Fig.1. In addition, FDM requires careful tests for the accumulation of numerical errors, especially for the Rayleigh waves traveling long distances (e.g., the numerical grid dispersions; see Frankel and Vidale, 1992). Instead, FEM, BEM or FEM-BEM combined methods may be more promising, although it is not easy to make them run efficiently on parallel computers.

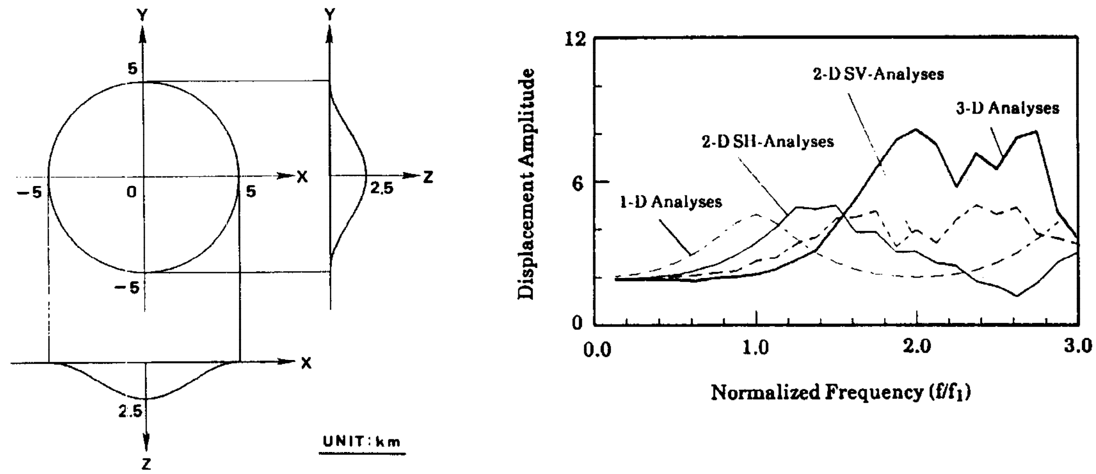
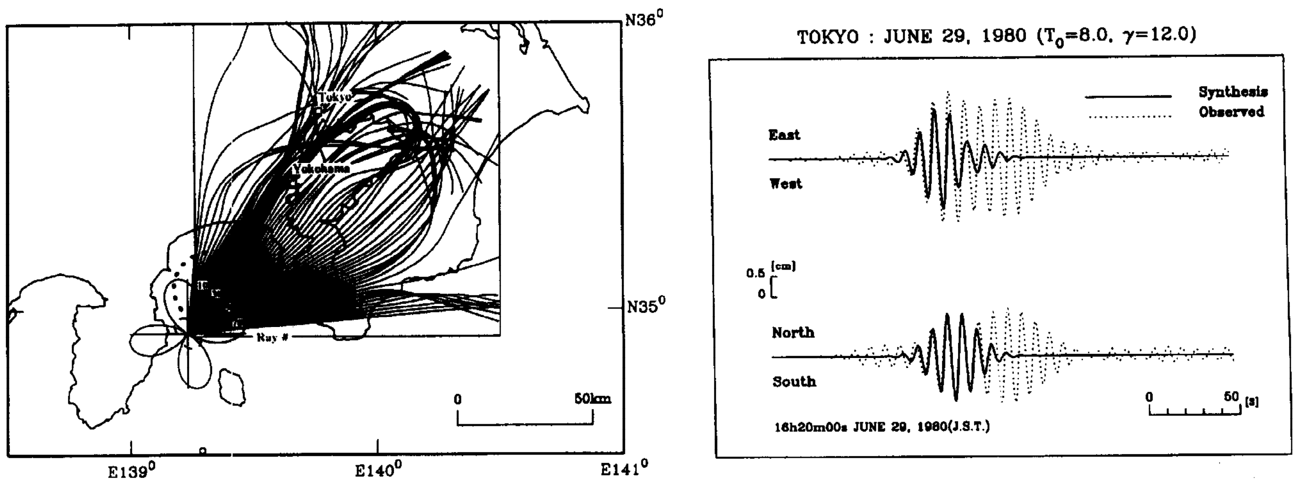
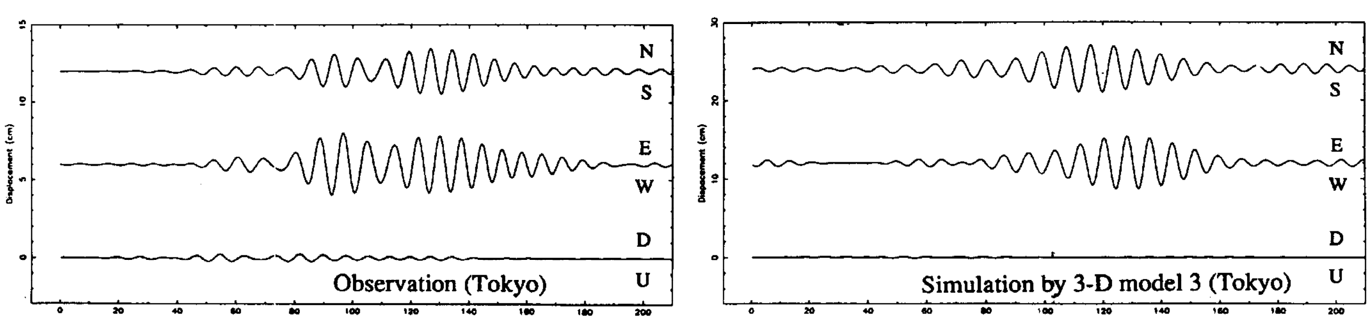


Fig.4. (a) Right: A 3D basin model, and (b) Left: the 1D, 2D, and 3D amplification factors (x 2) at the center of the basin due to the vertical incident plane wave (from Ohori *et al.*, 1992).



(a) The ray tracing (right) and comparison of the Love wave at Tokyo using the the GB method



(b) The observation (right) and simulation (left) using BEM

Fig.5. 3D simulations of the surface wave propagation in the Kanto basin using (a) Above: the surface wave Gaussian Beam method and (b) Bolow: the Bounday Element method (from Kato *et al*, 1993; Hisada *et al.*, 1993)

Because the conventional 2D/3D numerical methods mentioned above still cannot deal with short-period ground motions from distant sources, including shallow and soft sediment structures, we may need appropriate hybrid methods. For stations far from basin edges, where the basin edge effects are well attenuated, the methods that combine 2D/3D methods with the 1D methods may be useful in simulating the short-period motions including geotechnical non-linear effects. For example, the 2D FDM + 1-1D method successfully reproduced the 1995 Hyogo-ken Nanbu aftershock records in Kobe up to 3 Hz (Pitarka *et al.*, 1996).

Finally, despite recent rapid advances in computational methods, it should be noted that there is scarce information to construct accurate 3D basin models of velocity and attenuation profiles. Rough estimations for 3D P-wave structures using geological data and/or refraction/reflection surveys are available for only a few basins, such as the Kanto, Osaka, and Los Angeles basins.

CONCLUSIONS

We reviewed various site effects due to sediment-filled basins from the classic 1D theories to recent 3D numerical methods. The 1-1D theory seems valid for studying site effects due to shallow and soft sedimentary layers at short periods (< about Vs=500 m/sec, d=50 m, and 1 ~ 2 seconds), as long as the basin edge effects (the refracted and SS waves, focusing, the local surface waves) are negligible. When longer period motions due to a shallow source outside the basin are considered, the basin edge effects could become dominant even for stations far from the edges. Even if most advanced numerical technologies are employed, it is probably impossible to simulate realistic short-period ground motions (less than 1 ~ 2 second) in large-scale 3D basins, because accurate velocity and attenuation data are not currently available. Numerous strong ground motion records from recent earthquakes could provide good opportunities to check more quantitatively structure models and methodologies for the 1D, 2D, and 3D site effects.

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