SEISMIC RESPONSES OF IRREGULAR GROUND
–FOUR DECADES OF DEVELOPMENT FROM THEORY TO OBSERVATION–

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ABSTRACT :

The seismic response of the ground is controlled by the source characteristics, path effects, and local site conditions. Among them local site conditions may have the largest impact on both the characteristics and the levels of seismic motions. In this review the summary our four decades of development on irregular ground responses will be provided. In 1970s digital computers had emerged to be a powerful tool to calculate theoretical responses of irregular grounds. Ever since numerical techniques have been developed and applied to simulate actual basin responses with irregular configurations. Prof. Takuji Kobori and his colleague was one of the pioneering groups working on the seismic responses of irregular grounds. In the same era relatively long period, later arrivals have started to be observed. In 1985 the Michoacan, Mexico earthquake occurred and extraordinarily long-lasting motions inside the Mexico City Basin had caused quite extensive damages to high-rise buildings. In 1995 the Hyogo-ken Nanbu (Kobe) earthquake occurred and mysterious damage concentration, the so-called “damage belt”, was formed. After these tragedies many studies had been performed to find that irregular ground responses were the key. The history of four decades on irregular ground effect studies suggests that both theoretical and observational studies are equally important so that we must promote them further to archive our goal, that is, quantitative prediction of strong ground motions.

KEYWORDS: Irregular ground, basin effects, sediment-filled valley, site effects, State-of-the-Art

1. INTRODUCITON

For a rational seismic design it is indispensable to know in advance the characteristics of the input ground motions at a site for potentially dangerous earthquakes. The characteristics of the ground motions are determined as the convolution of the source characteristics, path effects, and local site conditions. Among them local site conditions may have the largest impact on both the characteristics and the levels of seismic motions, especially inside a sediment-filled basin. In this review we would like to summarize our four decades of development on irregular ground responses for strong motion prediction.

As a first order approximation we frequently assume that the soil layers are flat and extending infinitely in the horizontal directions, which leads us to model the ground as a one-dimensional (1-D) structure. In reality, however, soil and sedimentary rock layers are confined by the surrounding intact rock to form sediment-filled basins. At the edge of the basin, strong diffraction is taking place due to a large velocity contrast. In case of vertically or near vertically incident body waves, such diffraction at the edge creates “basin-induced diffracted waves”, which are transformed into surface waves very quickly. The basin-induced surface waves will propagate in the horizontal direction inside the basin back and forth. Under normal circumstances these basin-induced waves will arrive later than the direct body waves on the surface of the basin simply because the horizontal extent of normal basins are quite large compared to its vertical extent and so surface waves have a longer distance to travel. A site close to the edge of the basin is an exception to this condition and if the shape of the basin edge is sharp (i.e., the slope is steep), the edge-induced waves are arriving at the same time with body waves so that a strong constructive interference takes place. These are the phenomena that we have now understand quite clearly as a result of both theoretical and observational investigations in these four decades.

First we will review theoretical developments for irregular ground analyses started in early 70s and flourished till late 80s. Then we will see several important observational studies in the same era for basin responses. At first we could not solve the mystery of the observed phenomena, because a) numerical tools were not sufficient to represent actual ground with actual dimensions at that time, b) observational data were not sufficient to delineate the cause of the mystery at that time. But probably the primary problem at that time was c) communication between theoretician and observers were not well established. We will see several examples in which observations are successfully reproduced by simulations.

During these reviews it is my great honor to show how strong influence from Prof. Kobori and his colleagues had been contributed to promote progress in this important field of earthquake engineering. I hope this material will be useful to see the footprints of these pioneers in order to find future direction of research.

2. THEORTICAL STUDIES IN THE EARLY DECADES

2.1. 70s

Nowadays the effects of subsurface irregularities on the seismic response of ground have been recognized widely as an important factor, and extensive theoretical, observational, and experimental works have been performed on the subject. However, clear delineation of such effects on the observed records had not been demonstrated yet in 70s and even 80s, and so theoretical works occupied a main portion of the irregular ground studies in these decades.

A pioneering work of such theoretical studies was done by Aki and Larner (1970), who proposed a practical method using discrete wavenumber representation of wave field under the so-called Rayleigh assumption (i.e., no up-going inhomogeneous waves in the half-space). In their method, often called “Aki-Larner method”, frequency domain responses on the equally-spaced points along the medium interfaces (and the free surface if it is not horizontal) will be obtained. The wave domain and boundary conditions are complete except for the Rayleigh assumption in the half-space and the discretization of boundary conditions along the interfaces (and the surface) only in the horizontal direction. Thus the slope of any interfaces (or the surface) should not be so steep in order to represent wave filed correctly by the horizontal discretization scheme at that irregularity. Basically Aki-Larner method is quite efficient to obtain surface responses of an irregular ground and therefore Bouchon (1973) applied it to obtain time-domain response of a topographic irregularity and then later Bard and Bouchon (1980a, 1980b) used it to calculate time-domain responses of a sediment-filled basin. We should note here that in Aki-Larner method we need to use the so-called “complex frequency” to avoid aliasing of periodic structures, which is a requisite in any discrete wavenumber method (e.g., Bouchon and Aki, 1977; Bouchon, 1985), so that frequency-domain responses are not correct unless we remove the damping effects of the complex frequency (Kawase, 1988).

Trifunac (1971) presented the exact solution for a semi-circular (cylindrical) alluvial valley subject to incident SH waves by using a Hankel function expansion, although the solution is an infinite series summation. This kind of method can provide complete frequency-domain solutions as a summation of mode functions and so it is expanded to different boundary conditions (e.g., Trifunac, 1973; Wong and Trifunac, 1974). Later Kobori and Shinozaki (1978, 1980) solved an SH-wave incidence problem of soil-structure interaction considering the effects of an alluvial basin by introducing two semi-circular boundaries, one for a building foundation and the other for an alluvial basin around it as shown in Figure 1. In Figure 2 responses of a massless foundation embedded into an irregular ground are shown. When the building is rested close to the basin edge and an incoming SH wave is horizontal from the opposite side of the basin (θ=0 degree case), the amplitude of the building will be largest.

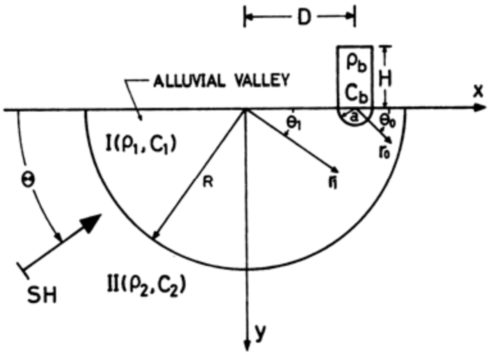

Figure 1 Basin and structure models used in Kobori and Shinozaki (1978).

Volumetric numerical techniques such as finite difference or finite element can represent unrestricted boundary configurations as shown in the pioneering work of Boore (1970), Lysmer and Drake (1971), and Drake (1972). However, the biggest problem of the method was its computational burden on both calculation speed and memory space. In another word they are in nature not computationally efficient and so we should wait for the advent of high-performance digital computers for such domain-type methods to be applied to irregular ground problems. Another serious shortcoming is the bounded region of analysis. In order to avoid the influence of reflected waves at the artificial boundary, it becomes necessary to model a large region of the ground around an irregular part. This makes their efficiency even worse, especially for the analysis of a large irregularity over a wide range of frequency and duration time. To overcome such a difficulty various attempts to develop transmitting boundaries or infinite elements where outgoing waves in the surrounding media are approximately prescribed. A popular FEM code called FLUSH (Lysmer et al., 1975) used one of such elements (later it is called "Thin Layer Element") to represent outgoing waves propagating into surrounding horizontal layers on the rigid bedrock.

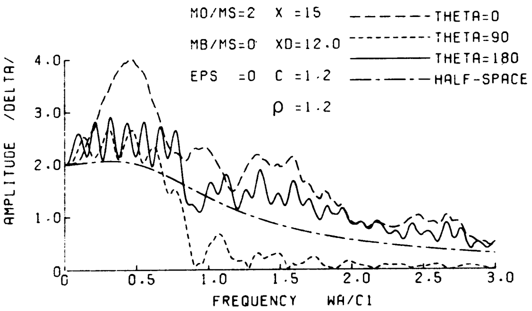

Figure 2 Dimensionless frequency responses of a massless footing inside the basin (after Kobori and Shinozaki, 1978).

To describe outgoing waves through an infinite body correctly, the boundary-type methods such as a boundary integral equation method (BIEM) are more suitable because they satisfies the radiation condition implicitly. The first application of BIEM to irregular ground analyses was done by Wong and Jennings (1975), who used the formulation proposed by Banaugh and Goldsmith (1963) to obtain the response of a canyon with an arbitrary shape. Since then, a number of authors have investigated the effects of irregularities by using different types of integral equations and their numerical treatments (e.g., Kobori and Shinozaki, 1977; Sanchez-Sesma, 1978; Sanchez-Sesma and Esquivel, 1979). The biggest disadvantage of BIEM and BEM is the time-consuming effort to evaluate the Green's function for a half-space, since it cannot be expressed in a simple form except for the two-dimensional (2-D) antiplane (SH) case. The easiest way to overcome this difficulty is to use the Green's function of an unbounded medium and to express the free-surface condition by using additional boundary elements along the surface. The problem with this alternative lies in the reliability of its results without prestudy, because the required size of the surface to simulate a half-space depends upon the frequency, the shape of irregularity, and the type of incident wave. This problem requires careful scrutiny.

2.2. 80s and early 90s

The developed methods in 70s had been expanded through 80s along with the development of digital computational power. As already mentioned, Bard and Bouchon (1980a, 1980b) showed for the first time the time-domain responses of sediment-filled basins for SH, SV, and P wave incidences along the horizontal surface. It was clear that the horizontally propagating waves, which later called "basin-induced surface waves", are generated at the irregular interfaces even for the vertically incident body waves. These waves are propagating along the surface of a basin, which clearly makes the duration of motion longer inside the basin. As mentioned in the next section, this theoretical discovery should be very important to understand the mechanisms of the observed time histories of strong motions, however, we had needed more time to commonly understand its importance in the engineering community. Also further development on Aki-Larner method and its application to various problems had been performed in 80s (e.g., Bard and Bouchon, 1985; Koketsu, 1987)

For the domain-type method, efforts for new developments had been performed also, as seen in Fuyuki and Matsumoto (1980), Boore et al. (1981) and Ohtsuki and Harumi (1983), among others. Later in the decade there are attempts to combine two different methods to overcome difficulties to represent outgoing waves. For example Fukuwa et al. (1985) and later Khair et al. (1989, 1991) proposed FEM combined with BIEM for

2-D basin problems with P, SV, and SH wave incidences. Mita and Luco (1987) also developed a FEM-BIEM hybrid method for soil-structure interaction analysis. Sato et al. (1989) proposed axisymmetric FEM with Thin-Layer Element Method (the same as the transmitting boundary of FLUSH, except for a damper attached at the bottom) to simulate wave propagation within different crustal structures. Later Sato (1990) presented a successful example in simulating long period basin response of the Osaka basin during 1961 Kita-Mino earthquake, Japan as a totally theoretical simulation from the source to the site.

As for the boundary-type formulation it was 80s when the development of the methods flourished. We cannot list all the papers investigated for an irregular structure by using some kind of boundary-type methods, so that we named here only a few representative ones among others; Dravinski (1982), Wong (1982), Sanchez-Sesma et al., (1985), and Dravinski and Mossessian (1987). The author also applied the direct boundary element method (BEM) to the subsurface irregularity problems (Kawase et al., 1982, 1985). The advantage of the direct BEM over the indirect BIEM is its excellent applicability and reliability without much precautions, since it expresses the boundary values directly through the element integration of the Green's function. The Green's function for a half-space in frequency domain can be expressed in the form of an infinite integral with respect to the horizontal wavenumber. Most previous researchers listed above who analyzed inplane problems used this type of formulation. Bouchon and Aki (1977), however, showed that these infinite integrals can be transformed into infinite sums over discrete wavenumbers under the assumption of periodicity. Therefore, the author introduces the discrete wavenumber boundary element method (DWBEM) in which the direct BEM is combined with the discrete wavenumber Green's function (Kawase, 1988). The advantage of this method is its efficiency in computation and flexibility for boundary configurations. As one of the applications of the discrete wavenumber method, Bouchon (1985) and Campillo and Bouchon (1985) have proposed a method which can be considered as a kind of BIEM and looks very efficient. However, their method cannot treat steep boundaries without losing efficiency as shown by Bouchon (1985) for a semi-circular canyon. In the DWBEM exact term-by-term evaluation is used for the element integrations which may contain singularities in the integrand.

The DWBEM was later used for single- and two-layered basin structures in order to explain extraordinarily long duration of strong motions observed in Mexico City during the 1985 Michoacan, Mexico earthquake (Kawase and Aki, 1989). In Figure 3 we show a trapezoidal homogeneous basin model and in Figure 4 the surface responses of for an incident SH waves to see clearly basin-induced surface waves propagating back and forth inside the basin. Kawase and Aki (1989) showed that the interaction between an incident S-wave and the edge of the basin that generates basin-induced surface waves is stronger when the predominant period of an incident wave is higher than the fundamental predominant period of the basin.

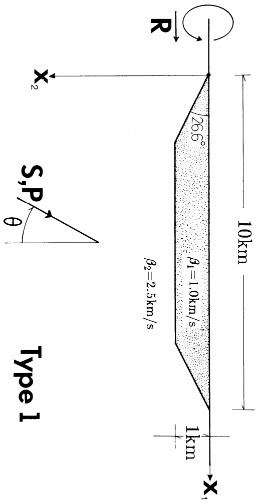

Figure 3 A trapezoidal basin model used in Kawase and Aki (1989).

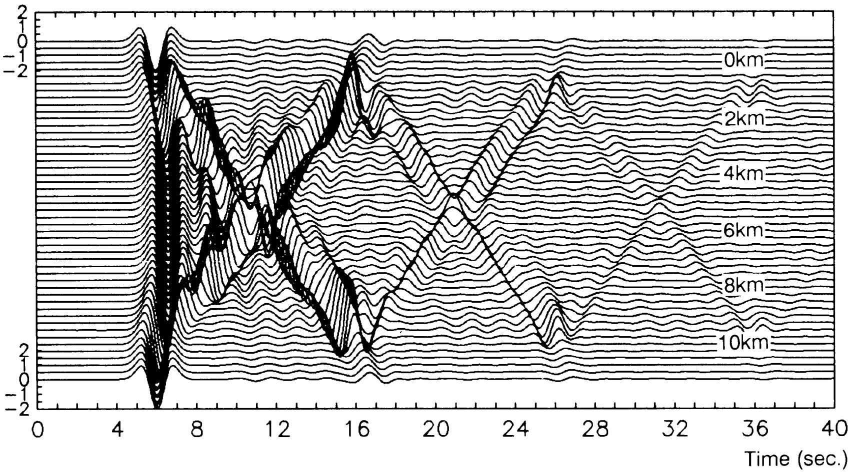

Figure 4 Time-domain responses of a trapezoidal basin due to a vertically incident SH wave with a Ricker wavelet with the characteristic period of 2 second (after Kawase and Aki, 1989).

3. OBSERVATIONAL STUDIES IN THE EARLY DECADES

3.1. 70s

As mentioned in the introduction, complete observational evidence of two- (2-D) and three-dimensional (3-D) irregular ground responses could not be provided until recently. Observational evidence of the basin-induced surface waves was reported for the first time by Toriumi (1975) who found distinctive later arrivals in the ground motions observed in the Osaka basin. At that time, no clear interpretation on the physical entity of the wave was given but later it was confirmed to be the basin-induced surface waves (Toriumi, 1984; Kagawa et al., 1992; Hatayama et al., 1995).

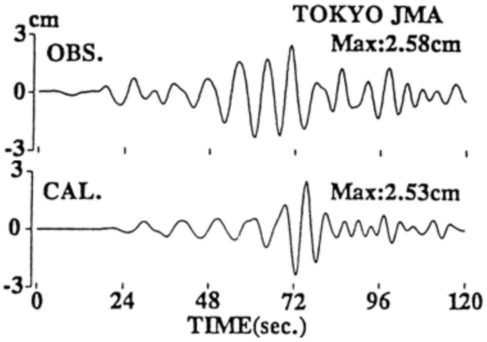

Figure 5 Comparison of the observed displacement seismogram at the center of Tokyo and the 2-D FDM synthetics (after Yamanaka et al., 1989).

In California, U.S.A, the existence of the basin-transduced surface wave (surface waves impinged to and transmitted into the basin) was reported by Hanks (1975) who showed a series of displacement seismograms recorded during the San Fernando, California earthquake of 1971. For the rock sites near the source, the duration of displacement records is short and the waveform is simple while those inside the Los Angeles basin are quite long and dispersed. Hanks (1975) noted that despite the relatively short distance from the fault the observed waveforms inside the basin have the characteristics of surface waves. Especially, continuous arrivals of relatively short period (~3 seconds) waves are a clear indication of basin-transduced surface waves.

3.2. 80s and early 90s

In the Kanto, Japan basin, Seo (1980) reported long period basin responses at several sites inside the Kanto basin and interpreted them as surface waves propagating inside the deep Kanto basin. Researchers had been working on the refraction survey project for a long time to delineate P and S wave velocity structure of the Kanto basin. Later Yamanaka et al. (1989) used observed seismograms in and around the Kanto basin during the 1980 Izu-Hanto-Toho-Oki earthquake to compare their 2-D FDM synthetics. They succeeded to explain basic features of the observed long-period motions as shown in Figure 5, however, the amplitude and duration of the records inside the basin were still deficient.

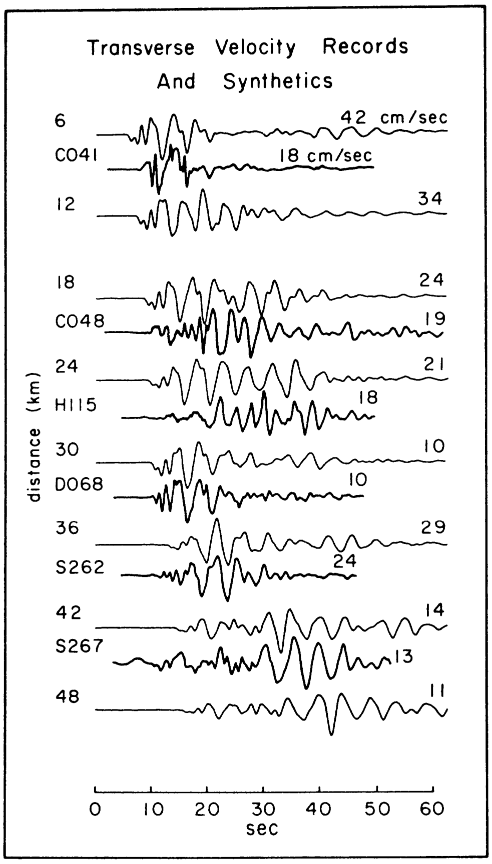

Figure 6 Comparison of band-pass filtered, observed velocity seismograms (bold lines) to the 2-D FDM synthetics (after Vidale and Helmberger, 1989).

In California Vidale and Helmberger (1989) succeeded in simulating observed velocity seismograms in the San Fernando and Los Angeles basins during the 1971 San Fernando earthquake reported first by Hanks (1975). Figure 6 shows the comparison of filtered transverse components of the observed velocity records with those of the synthetics based on a 2-D Finite Difference Method. The matching of the synthetics with the data is generally very good. But we should note that source properties are controlled so as to match the synthetics with the observed at D068 and therefore the synthetics are not fully theoretical but similar to the convoluted ones with a reference record.

Kawase and Sato (1992) used strong motion data and geological data distributed for a blind prediction experiment conducted by the Japanese Working Group on Effects of Surface Geology. First they analyzed observed ground motions at two stations on the soft soil inside the Ashigara basin. By using nonstationary spectra at the basin station we can see a very isolated later phase at about 40 seconds in the N30°W component whose predominant period ranges from 1.0 to 1.5 second. Based on the polarization and an apparent group velocity between two stations, it is interpreted to be the basin-induced Love wave. We cannot see any similar later phases either in the N60°E component or in the horizontal components of the record on the surrounding rock. Kawase and Sato (1992) constructed a 2-D model and obtained its response by using their own finite element code similar to those by Lysmer et al. (1975). The convolved Fourier spectra showed that the 2-D model give additional amplification in the N30°W component at around 1.5 Hz, which is a little higher than the observed spectral peak at around 1 Hz; the amount of additional amplification is enough to fill the gap between the 1-D model and the observed Fourier spectra. We should note that there is no need to introduce a 2-D model in the frequency range higher than 2 Hz and for the N60°E component. The discrepancy of the 2-D amplification frequency between the model and the reality is attributable to inappropriate modeling of soil layers between the edge of the basin and the site. The important lesson here is that a soil column just below the site controls its 1-D response, while the whole path from the generation point to the site controls the 2-D/3-D response. Thus, we need structural information for 2-D/3-D models much more widely than for 1-D models.

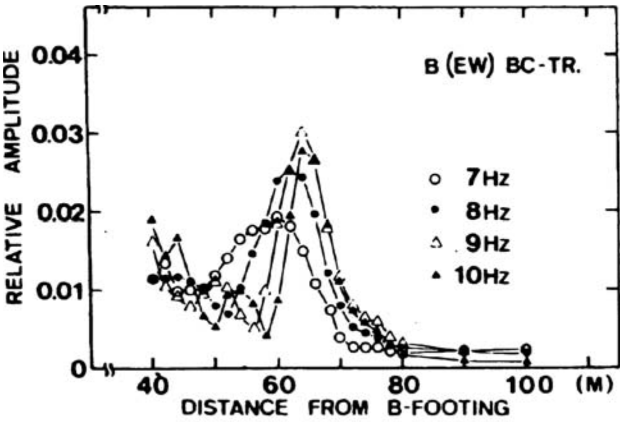

Figure 7 Relative amplitude distributions for transverse component along the measurement line from the source footing B. At around 85m there is a basin edge. (after Shinozaki and Kobori, 1991b).

A series of quite interesting experimental studies for irregular ground had been reported from Shinozaki and Kobori (1988, 1991a, 1991b) who used a hydraulic vibrator to generate seismic waves to a small basin and observed surface motions along a line from the source footing. As shown in Figure 7, near the edge of a basin constructive interference between the incident and the reflected surface waves are taking place so that high amplitudes near the edge (but not very close to the edge) at a certain frequency can be observed, as predicted in Kobori and Shinozaki (1978, 1980).

4. DEVASTATING EARTHQUAKES AND THEIR MYSTERY

4.1. 1985 Michoacan Mexico Earthquake

The site effects had been paid much less attention than they should be, except in Japan, for the first half of these four decades. The situation was drastically changed by the catastrophic disaster in Mexico City during the Michoacan, Mexico earthquake of 1985, in which strong amplification due to extremely soft clay layers caused many high-rise buildings to collapse despite the long (~350 km) distance from the source. The real cause of the observed long duration during the earthquake is not well resolved yet even though a lot of research has been conducted since then (e.g., Bard et al. 1988; Kawase and Aki 1989; Singh and Ordaz 1993; Furumura and Kennett, 1998, among others) primarily because the velocity structures in and around the Mexico City and in between the source region and Mexico City are not well controlled. However, there is no room for doubt that the primary cause of the large amplitude of strong motions in the soft soil (lakebed) zone relative to those in the hill zone is a simple one-dimensional (1-D) site effect of very soft clay layers. As for the mystery of the long duration, thanks to the attenuation line observation from the shoreline of the Pacific Ocean to Mexico City, we are now finding that the primary cause of the long duration may be not only the deep basin structure around Mexico City but also the large scale structure of the Mexican Volcanic Belt (e.g., Barker et al., 1996; Furumura and Singh, 2002, Iida and Kawase, 2004).

4.2. 1994 Northridge earthquake and 1995 Hyogo-ken Nanbu (Koeb) earthquake

Near the edge of a basin, generation and propagation of basin-induced diffracted and surface waves and incidence of body waves from the bottom of the basin are taking place simultaneously. If they meet together in phase at some point then constructive interference happens and amplitude of ground motion there becomes much larger than a simple 1-D response. This amplification effect near the edge of the basin is named "the (Basin) Edge Effect" by Kawase (1996). The damage concentration found in Kobe during the Hyogo-ken Nanbu (Kobe) earthquake, often called the damage belt because of its large length (~20km) compared to its small width (~1km), was created as a consequence of both source extension along the strike of the damage belt and the edge effect along the northwestern edge of the Osaka basin. Kawase (1996) used a 2-D rectangular basin to reproduce the observed strong motions in Sannomiya, downtown Kobe, and the high PGV values in the damage belt near the JR Sannomiya station as shown in Figure 8. He also showed snapshots for 1 Hz Ricker wavelet input in the vertical cross section to delineate mechanisms of constructive interference happening near the edge of the basin. More quantitative simulation for Kobe can be found in Matsushima and Kawase (1998) where a complex rupture process and a 3-D basin model were introduced in their calculation using the FDM code of Graves (1996).

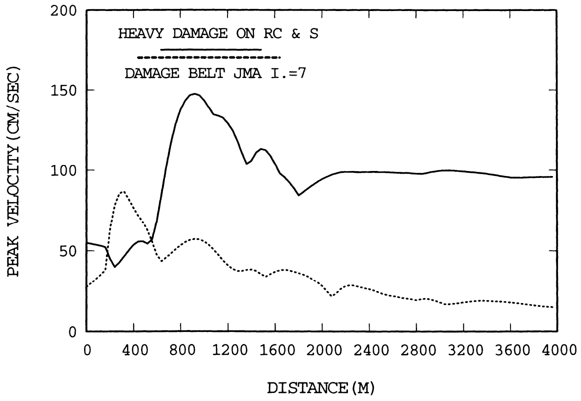

Figure 8 Peak ground velocity distributions along the surface of the 2-D basin structure near the edge with the location of the damage belt (after Kawase, 1996).

The basin edge effect is not a particular, extraordinary phenomenon found only in Kobe. Any kind of a basin edge would have the edge effect, although the degree of interference depends on the edge shape as well as the input waveform. An example for the northern edge of the great Los Angeles Basin near Santa Monica was reported by Graves and Pitarka (1998) who succeeded in explaining velocity waveforms of the observed ground motion record at Santa Monica City Hall during the Northridge, California earthquake of 1994.

5. AFTER THE FINAL WEAPON BECOMES POPULAR

In the middle of 90s engineering work stations have started to equip sufficient CPU speed and memory, together with enough storage space so that ordinary researchers can use the final weapon of irregular ground analyses, the truly three-dimensional domain-type method, mostly explicit time-domain FDMs. There are so many research examples nowadays using FDMs, Spectral Element methods, or FEMs to solve wave propagation problems with arbitrary-shaped irregular ground structures. Here we would like to introduce only one such example. Sato et al. (1998a, 1998b, 1999) used a FDM code developed by Graves (1996) to reproduce successfully observed waveforms during the 1923 Kanto earthquake. They carefully constructed the basin structure based on geological information, refraction survey data, reflection survey data, and boring data. They also used a small event as a calibration event to verify the appropriateness of their initial basin structure. Rich information collected by other researchers before they studied, together with their careful approach, made their success a deserved one. It is not easy to achieve that level of reproduction for most of the soft basins in the world and so there are a lot of basins with mega cities waiting for detailed investigation for quantitative strong motion prediction.

6. CONCLUSIONS

The summary our four decades of developments on irregular ground response analysis and their simulations is presented in this review. We first divide the subject into two categories, namely, theoretical studies and observational ones and history of development are summarized briefly. Then efforts devoted to solve mysteries raised by the devastating earthquakes, namely, 1985 the Michoacan, Mexico earthquake and the Hyogo-ken Nanbu (Kobe) earthquake are briefly covered. Finally recent developments using the so-called final weapon, that is, a three-dimensional volumetric method are mentioned.

As seen in the literature to succeed to explain observed waveforms we need both good theoretical tools and realistic basin structures. The more the target waveforms, the better the understanding of the nature, yet more difficult to match all the data with different conditions at the same time. Despite of our significant achievements in this field of earthquake engineering, it seems a little ironical to me but, Prof. Kobori had never been able to trust our capability to predict strong ground motions, even though he lead us to promote site effect and soil-structure interaction studies rigorously. Thus it is our responsibility to keep proving that the response of nature can be predictable, as long as we know the mechanisms behind the phenomena.

In order to find future directions of research one must need to look back to seeing the footprints of pioneers such as Prof. Takuji Kobori and his colleagues for irregular ground responses. I hope that this material will be useful for researchers and engineers, especially new comers in this field, to start with.

REFERENCES

Bard, P.-Y. and M. Bouchon (1980a). Seismic response of sediment-filled valleys. Part 1. The case of incident SH waves, *Bull. Seism. Soc. Am.*, **70**, 1263-1286.

Bard, P.-Y. and M. Bouchon (1980b). Seismic response of sediment-filled valleys. Part 2. The case of incident P and SV waves, *Bull. Seism. Soc. Am.*, **70**, 1921-1941.

Bard, P.-Y., M. Campillo, F. J. Chavez-Garcia, and F. J. Sanchez-Sesma (1988). The Mexico earthquake of September 19, 1985 – A theoretical investigation of large- and small-scale amplification effects in the Mexico City Valley, *Earthquake Spectra*, **4**, 609-633.

Barker, J. S., M. Campillo, F. J. Sánchez-Sesma, D. Jongmans, and S. K. Singh (1996). Analysis of wave propagation in the Valley of Mexico from a dense array of seismometers, *Bull. Seism. Soc. Am.*, **86**, 1667-1680.

Boore, D. M. (1970). Love waves in nonuniform wave guides: finite difference calculations, *J. Geophys. Res.*, **75**, 1512-1527.

Bouchon, M. (1973). Effect of topography on surface motion, *Bul. Seism. Soc. Am.*, **63**, 615-632.

Bouchon, M. (1985). A simple complete numerical solution to the problem of diffraction of SH waves by an irregular surface, *J. Acoust. Soc. Am.*, **77**, 1-5.

Bouchon, M. and K. Aki (1977). Discrete wave-number representation of seismic-source wave field, *Bull. Seism. Soc. Am.*, **67**, 259-277.

Campillo, M. and M. Bouchon (1985). Synthetic SH seismograms in a laterally varying medium by the discrete wavenumber method, *Geophys. J. R. Astr. Soc.*, **83**, 307-317.

Drake, L. A. (1972). Love and Rayleigh waves in non-horizontal layered media, *Bull. Seism. Soc. Am.*, **62**, 1241-1258.

Dravinski, M. (1982). Influence of interface depth upon strong ground motion, *Bull. Seism. Soc. Am.*, **72**, 596-614.

Dravinski, M. and T. K. Mossessian (1987). Scattering of plane harmonic P, SV and Rayleigh waves by dipping layers of arbitrary shape, *Bull. Seism. Soc. Am.*, **77**, 212-235.

Fukuwa, N., T. Sato, H. Kawase, and S. Nakai (1985). Effects of surface irregularities on strong ground motions, *Proc. of Structural Engineering Symposium*, **31B**, 1-10 (in Japanese with English abstract).

Furumura T. and B.L.N. Kennett (1998). On the nature of regional seismic phases-III. The influence of crustal heterogeneity on the wavefield for subduction earthquakes: the 1985 Michoacan and 1995 Copala, Guerrero, Mexico earthquakes, *Geophys. J. Int.*, **135**, 1060-1084.

Furumura, T. and S. K. Singh (2002). Regional wave propagation from Mexican subduction zone earthquakes: The attenuation functions for interplate and inslab events, *Bull. Seismo. Soc. Am.*, **92**, 2110-2125.

Fuyuki, M. and Y. Matsumoto (1980). Finite difference analysis of Rayleigh wave scattering at a trench, *Bull. Seism. Soc. Am.*, **70**, 2051-2069.

Graves, R. W. (1996). Simulating seismic wave propagation in 3D elastic media using staggered-grid finite differences, *Bull. Seismo. Soc. Am.*, **86**, 1091-1106.

Graves, R.W. and A. Pitarka (1998). Modeling the basin edge effect in the Santa Monica region during the 1994 Northridge earthquake, The Effects of Surface Geology on Seismic Motion, Irikura, Kudo, Okada, and Sasatani (eds.), Balkema, Rotterdam, 907-914.

Hatayama, K., K. Matsunami, T. Iwata, and K. Irikura (1995). Basin-induced Love waves in the eastern part of the Osaka basin, *J. Phys. Earth*, **43**, 131-155.

Iida, M. and H. Kawase (2004). A comprehensive interpretation of strong motions in the Mexican Volcanic Belt, *Bull. Seismo. Soc. Am.*, **94**, 598-618.

Kagawa, T., S. Sawada, and Y. Iwasaki (1992). On the relationship between azimuth dependency of earthquake ground motion and deep basin structure beneath the Osaka plain, *J. Phys. Earth*, **40**, 73-83.

Khair, K. R., S. K. Datta, and A. H. Shah (1989). Amplification of obliquely incident seismic waves by cylindrical alluvial valleys of arbitrary cross-sectional shape. Part I. Incident P and SV waves, *Bull. Seismo. Soc. Am.*, **79**, 610-630.

Khair, K. R., S. K. Datta, and A. H. Shah (1991). Amplification of obliquely incident seismic waves by cylindrical alluvial valley of arbitrary cross-sectional shape. Part II. Incident SH and Rayleigh waves, *Bull. Seismo. Soc. Am.*, **81**, 346-357.

Kawase, H., K. Yoshida, S. Nakai, and Y. Koyanagi (1982). Dynamic response of structure on a layered medium, -A dipping layer and a flat layer, *Proc. of the 6th Japan Earthq. Eng. Sym.*, Tokyo, Japan, 1641-1648.

Kawase, H., T. Sato, S. Sato, and G. Tanaka (1985). Analytical and observational study on seismic scattering property of a site with geological irregularity, *Proc. of the 8th Int. Conf. on Struct. Mech. in Reactor Technology*, Brussels, Belgium, 1-6.

Kawase, H. (1996). The cause of the damage belt in Kobe: "The basin-edge effect", Constructive interference of the direct S-wave with the basin-induced diffracted/Rayleigh waves, *Seismological Res. Lett.*, **67**, 25-34, 1996.

Kobori, T. and Y. Shinozaki (1977). Scattering of SH waves from surface irregularities, *Zisin, J. of the Seismological Society of Japan*, Series-II, **30**, 127-142 (in Japanese with English abstract).

Kobori, T. and Y. Shinozaki (1978). Dynamic soil-structure interaction under topographical site condition, *Proc. of the 5th Japan Earthq. Eng. Sym.*, Tokyo, Japan, 489-496.

Kobori, T. and Y. Shinozaki (1980). Dynamic soil-structure interaction under a topographical site condition, *Proc. 7th World Conf. on Earthq. Eng.*, **5**, 189-196.

Lysmer, J. and L. A. Drake (1971). The propagation of Love waves across nonhorizontally layered structures, *Bull. Seism. Soc. of Am.*, **61**, 1233 - 1251.

Lysmer, J., T. Udaka, C.-F. Tsai, H. B. Seed (1975). FLUSH: a computer program for approximate 3-D analysis of soil-structure interaction problems, UCB/EERC-75/30, Earthquake Engineering Research Center, University of California, Berkeley, pp.139.

Matsushima, S. and H. Kawase (1998). 3-D wave propagation analysis in Kobe referring to “The basin-edge effect”, The Effects of Surface Geology on Seismic Motion, Irikura, Kudo, Okada, and Sasatani (eds.), Balkema, Rotterdam, 1377-1384.

Mita, A. and J. E. Luco (1987). Dynamic response of embedded foundations: A hybrid approach, *Computer Method in Applied Mech. Eng.*, **63**, 233-259.

Ohtsuki, A. and K. Harumi (1983). Effect of topography and subsurface inhomogeneities on seismic SV waves, *Earthquake Eng. Struct. Dyn.*, **11**, 441-462.

Sanchez-Sesma, F. J. (1978). Ground motion amplification due to canyons of arbitrary shape, *Proc. of the 2nd Int. Conf. on Microzonation*, San Francisco, California, 729-738.

Sanchez-Sesma, F. J. and J. A. Esquivel (1979). Ground motion on alluvial valley under the incident plane SH waves, *Bull. Seism. Soc. Am.*, **69**, 1107-1120.

Samchez-Sesma, F. J., M. A. Bravo, and I. Herrera (1985). Surface motion of topographical irregularities for incident P, SV, and Rayleigh waves, *Bull. Seism. Soc. Am.*, **75**, 263-269.

Sato, T., M. Hasagawa, S. Nakai, T. Watanabe, and T. Tanaka (1989). Analysis of theoretical seismograms by the Thin Layer Finite Element Method and its allocation to the 1980 Izu-Hanto-Toho-Oki earthquake in Japan, *Proc. 9th World Conf. Earthq. Eng.*, **II**, 763-768.

Sato, T. (1990). Simulation of observed seismograms on sedimentary basin using theoretical seismograms in the period range from 2 sec to 20 sec –Synthesis of seismograms at Kobe and Osaka stations for the 1961 Kita-Mino earthquake-, *Proc. of 8th Japan Earthq. Eng. Sym.*, Tokyo, Japan, 193-198 (in Japanese).

Sato, T., D.V. Helmberger, P.G. Somerville, R.W. Graves, and C.K. Saikia (1998a). Estimates of regional and local strong motions during the Great 1923 Kanto, Japan, earthquake (MS 8.2), Part 1: Source estimation of a calibration event and modeling of wave propagation paths, *Bull. Seismo. Soc. Am.*, **88**, No. 1, 183-205.

Sato, T., D.V. Helmberger, P.G. Somerville, R.W. Graves, and C.K. Saikia (1998b). Estimates of regional and local strong motions during the Great 1923 Kanto, Japan, earthquake (MS 8.2), Part 2: Forward simulation of seismograms using variable-slip rupture models and estimation of near-fault long period ground motions, *Bull. Seismo. Soc. Am.*, **88**, 206-227.

Sato, T., R.W. Graves, and P.G. Somerville (1999). 3-D Finite-Difference simulations of long-period strong motions in the Tokyo Metropolitan Area during the 1990 Odawara earthquake (M_J 5.1) and the Great 1923 Kanto earthquake (M_S 8.2) in Japan, *Bull. Seism. Soc. Am.*, **89**, 579-607.

Seo, K. and H. Kobayashi (1980). On the rather long-period earthquake ground motions due to deep ground structures of Tokyo area, *Proc. 7th World Conf. Earthq. Eng*., 9-16.

Shinozaki, Y. and T. Kobori (1988). Ground motion of subsurface irregular soil excited by vibrator, *Proc. 9th World Conf. on Earthq. Eng.*, **II**, 671-676.

Shinozaki, Y and T. Kobori (1991a). Designing and performance tests of servohydraulic type vibrator: forced vibration tests with a servohydraulic-type vibrator, Part 1, *J. of Structural and Construction Eng.*, Transactions of AIJ, **423**, 105-112.

Shinozaki, Y and T. Kobori (1991b). Surface motion of subsurface irregular ground: forced vibration tests with a servohydraulic-type vibrator, Part 2, *J. of Structural and Construction Eng.*, Transactions of AIJ, **426**, 67-78.

Singh, S.K. and M. Ordaz (1993). On the origin of long coda observed in the lake-bed strong-motion records of Mexico City, *Bull. Seismo. Soc. Am.*, **83**, 1298-1306.

Toriumi, I. (1975). Earthquake characteristics in the Osaka plain, *Proc. of the 4th Japan Earthq. Eng. Sym.*, 129-136 (in Japanese).

Toriumi, I., S. Ohba, and N. Murai (1984). Earthquake motion characteristics of Osaka plain, *Proc. of 8th World Conf. on Earthq. Eng*., **2**, 761-768.

Trifunac, M. D. (1971). Surface motion of a semi-cylindrical alluvial valley for incident plane SH waves, *Bull. Seism. Soc. Am.*, **61**, 1755-1770.

Trifunac, M. D. (1973). Scattering of plane SH waves by a semi-cylindrical canyon, Earthquake Eng. Struct. Dyn. **1**,267-281.

Wong, H. L. (1982). Effect of surface topography on the diffraction of P, SV, and Rayleigh waves, *Bull. Seism. Soc. Am.*, **72**, 1167-1183.

Wong, H. L. and M. D. Trifunac (1974). Surface motion of a semi-elliptical alluvial valley for incident plane SH waves, *Bull. Seism. Soc. Am.*, **64**, 1389-1408.

Wong, H. L. and P. C. Jennings (1975). Effect of canyon topography on strong ground motion, *Bull. Seism. Soc. Am.* **65**, 1239-1257.

Yamanaka, H., K. Seo and T. Samano (1989). Effects of sedimentary layers on surface-wave propagation, *Bull. Seism. Soc. Am.*, **79**, 631-644.