SOME ISSUES ON IMPROVEMENT OF GROUND MOTION SYNTHESIS FOR SEISMIC ANALYSIS OF LARGE SPAN STRUCTURE

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Abstract

Synthesis of strong ground motion is widely adopted in seismic analysis of important engineering structures, to make up for the lack of recordings. Some issues are discussed in this paper to improve the existing synthesis approach of broadband ground motion from the requirement of large-span spatial structures, such as (1) the discordant in the superposition of the randomly generated high frequency motion and numerically calculated low frequency motion, since the former just generates a horizontal component while the latter provides three translational components; (2) the advantage of FK approach by comparison with the random synthesis, mainly on the phase spectrum if generated randomly or calculated for the velocity structure of the regional crust; (3) the necessity to take into account the relationship of the slip distribution and temporal parameters in finite fault source modeling; (4) to avoid the awkward situation if the source parameter estimated only from a set of scaling laws; (5) the two step procedure to take local site condition into account in the synthesis of broadband ground motion for a large scenario earthquake; (6) to generate large pulse in the synthesized motion for long-period structures; (7) the coherency of the synthesized motion field in accordance with that from the recordings at dense arrays.

Keywords: ground motion; synthesis; source model; large pulse; coherency

1. Introduction

Synthesis of strong ground motion is recently adopted in seismic analysis of significant engineering structure [1, 2]. The requirement of large span structures to the motion is to include three translational components at multi- ground points with broadband at least from 0.1 Hz to 20 Hz. Some issues are discussed in this paper to improve the existing synthesis approach of broadband ground motion.

2. A discordant in the existing synthesis of broadband strong ground motion

Numerical procedure, such as finite difference, finite element, is the most popular approach of synthesis of ground motion developed mainly for inhomogeneity of the regional crust [3]. It is feasible to take into account the effect of 3D velocity structure of the crust and local topography on ground motion. As well known, the procedure is not feasible for wave with wavelength less than the size of the discrete grid. For 3D simulation, the maximum mesh size must be several times of the minimum interested wavelength, even 20~25 times from a numerical proof-test [4]. In general, the interesting frequency range of ground motion in engineering seismic analysis is 0.1 Hz to 20 Hz. To satisfy this requirement the size of the discrete grid in numerical synthesis should be less than 5 m, given the shear wave velocity value 2000 m/s at ground layer of crust. Source size of a large earthquake could be tens to more than a hundred kilometers, the computational region in a numerical synthesis may be several hundred kilometers, and then numbers of the grid must be over thousand billions. Therefore, most sizes adopted in numerical syntheses are several hundred meters from the restriction by the computer resources, and the corresponding frequency band is 1 Hz or less. Up to frequency 8 Hz components synthesized for a M_W6.5 earthquake, total 3 billion grids with the size of 25 m are reported from a simulation [5]. These kinds of calculations for large earthquakes are time consuming, which usually take more than dozen hours even days, on server of high-performance computer or supercomputer.

Stochastic synthesis is powerful to generate high frequency ground motion, in general >1 Hz [6, 7]. It is widely adopted in practice, but the accuracy at long periods is not good enough [8]. One solution is to merge the motions generated by stochastic synthesis procedure at high frequencies with the numerical Green function results at low frequencies in time domain, called as hybrid broadband ground motion synthesis. The authors would like to emphasize the fact that there is discordance in the superposition. Numerical procedure is from discretization of dynamic function of elastic or visco-elastic medium, and provides three translational components of ground motion, FN (fault normal), FP (fault parallel) and UD (Vertical). While, the stochastic procedure is simple and just generates a horizontal component without a definite direction with the fault rupture plane, e. g. the horizontal RotD50 component [9]. Therefore, error from the superposition whatever with FN or FP may be dozens of percent. Furthermore, durations and time lags of motion time histories from the same subsource by the two procedures are different, since the paths from the subsource to the ground point by the two are not the same, so that they must make more errors in the superposition. This discordance turns into a bottleneck in improvement of broadband strong ground motion synthesis.

3. Advantage of FK approach comparing to stochastic synthesis

The synthesis approach based on the frequency-wavenumber Green's function (in brief FK), a more rigorous procedure, could be a solution for the discordance [10]. The Green's function in FK is derived from elasto-dynamic wave theory, which expresses the displacement response caused by source moment tension in the horizontal layered crustal media [11]. Several of frequency-wavenumber domain methods, including discrete wavenumber integration, have been adopted in motion synthesis [12, 13]. The FK Green's function calculation by Zhu and Rivera optimized the Thompson-Haskell transfer coefficient matrix [14], guaranteed the numerical stability in the computation of high-precision accelerograms and has been widely used in recent years. The procedure involves integration over the rupture plane of the convolution of the slip and its time function on the whole plane with the Green's function for the appropriate depth and distance. Resulting three-component ground motions, the same as FN, FP and UD, contain all wave types and are solutions to the wave equation.

In what kind of way to adopt FK in synthesis, depends on if the frequency band of ground motion from FK meet the requirement of engineering seismic analysis. Confusingly, treatments of papers on international journals are quite different. For example, Mai and Beroza [15], Fortuno et al [16] believed that the direct calculation results of FK could not express the high frequency components of ground motion sufficiently, so adopted it only for low-frequency motion (<1Hz), instead of numerical procedure; while Cramien and Archuleta [13], Liu et al [17] adopted FK for high-frequency motion (>1Hz), the highest frequency of motion component by the latter was up to 20 Hz that met the engineering requirement well. Hartzell et al [18], Sun et al [19] adopted FK directly in broadband motion synthesis, while Frankel [20] adopted FK for high-frequency motion instead of by stochastic procedure, and superposed the motion with the numerical result. The authors of this paper believe that the FK performance in high frequency range depends on the improvement of the source modeling from our case study [21], and it needs further in-depth study.

The most obvious advantage of FK, comparing with the stochastic synthesis, is that the effect of the regional crustal velocity structure on ground motion is taken into account. The influence of the velocity structure on ground motion, especially that of shallow layers, is very significant. In the stochastic synthesis, ground motion time history at a site from a subsource is obtained from inverse FFT transform of a complex spectrum that the amplitude spectrum is a convolution of source spectrum, two attenuation terms and an amplification factor of the near-surface velocity structure; the phase spectrum is usually adopted as a set of random numbers uniformly distributed in the range (0, 2π) [22, 23]. The reason of this treatment is that ground motion in high frequency range shows a strong randomness given the point source and the distance from the source to site, if the regional crustal velocity structures are quite different. Fundamentally, the phase difference comes from the difference of phase velocity, and the latter is controlled by dispersion caused from ground surface and interface(s) in the crust. The influence of random phase spectrum on ground motion is complicated [24], in practice, the mean is chosen from dozens of motions generated by random phase spectra for engineering seismic analysis. It must cause additional errors, the difference between the amplitudes of response spectra of motions at a site by stochastic procedure with different random phase spectra could be up to two times, from our case studies [25] for a given point source, and even larger for a finite fault case. More important for the analysis of large-span structure is the fact that the mean motion could not properly express the spatial coherency between ground motions.

4. Relationship between the slip distribution and temporal parameters in source modeling

Beresnev pointed out that the temporal rate of slip, not the spatial heterogeneity on faults, is the predominant factor forming the high-frequency radiation, and the addition of asperities causes little systematic increase in the spectral level of high-frequency radiation [26]. It means that the frequency band of synthesized motion, especially at high frequency, is controlled by source modeling in some way. The authors of this paper get a similar conclusion from our case study on kinematic source modeling for the synthesis of broadband ground motion by FK approach [21], such as the temporal evolution of slip is the dominant influencing factor at short periods, whereas the spatial variation of slip is the main influencing factor at long periods. Therefore temporal parameters are discussed here, though we have developed a procedure for slip distribution [27].

The source time function (STF in brief), the rise time involved, and rupture velocity are the main factors to describe the temporal evolution of slip on the entire rupture plane. A credible STF model serves as a proxy for the true slip-rate history. To date, several analytical functions for STF have been presented, the Hartzell STF is advantageous for FK procedure from the understanding of the authors of this paper, since the corresponding rupture dynamics has an f^2 spectral decay rate and does not contain spectral holes. The rise time is defined as the time for slip to reach its final value from zero at a point on the rupture plane during an earthquake. Fundamentally, the larger slip the longer rise time normally required to guard against unreasonably large value of the maximum slip rate. Thus, slip and rise time should be correlated, the rise time was set as proportional to the local slip by some researchers, and it was assumed as proportional to the square root of the slip, which has an inherent correlation between them larger than 0.9. However, the strong relationship may cause a dependence of the synthetic motion on the subsource size.

The rupture velocity controls the triggering of each subsource and is critical in summing up the time histories from subsources at a ground point. In our case studies, the rise time and rupture velocity are jointly estimated for the slip distribution under the constraint on the seismic energy radiated during the entire rupture process [26]. The local rupture velocity and rise time are correlated with the slip with coefficients of 0.3 and 0.6 with small random perturbations, respectively. By keeping the increase of rise time with subsource size, we could remove the dependence of the result motion on the subsource size.

5. To avoid the awkward situation in source modeling only from scaling laws

Finite fault model (FFM in brief) of source is currently adopted in strong ground motion synthesis to describe the potential inhomogeneous distribution of slip on the rupture plane, and to take into account the near-rupture effect, such as directivity effect and hanging wall effect [28]. For the source modeling, two sets of parameters usually are estimated from scaling laws for a given magnitude or moment. Global parameters define the rupture size and the average slip, and local ones are for slip distribution. The latter highlights the predominant action of asperity to hold the physical nature of the inhomogeneous distribution, and takes into account the complexity and the randomness from the incomplete deep-going knowledge on the source at present [27]. However, there must be an awkward situation if all the source parameters estimated only from the scaling laws, since neither the source nor the slip distributions of earthquake sources with the same magnitude are always the same. So we must do our best to estimate the parameters from additional available information.

In general, the geometrical characteristics of FFM could be estimated from geological and geophysical investigations of the region, remote sensing image recognition, seismo-tectonic investigation, study of seismicity especially on aftershock distribution, and so on. Sometimes the average slip could be checked by the remained displacements in regional paleoseismological investigation. In some cases, the rupture length can be estimated from geological mapping, rupture width can be estimated from regional thickness of the seismogenic layer which is generally shown as the regional seismicity distribution in depth [29]. However the resulted values, especially for the local parameters, are often the maximum values, not corresponding to the given magnitude. A truncated normal distribution is suggested to manage these maximum values and the randomness in the parameter estimation [30], as follows.

$$f\left(x_i,\mu,\sigma,x_{\max}\right)=\begin{cases}\dfrac{\phi\left[\left(x-\mu\right)/\sigma\right]}{\sigma\cdot\Phi\left[\left(x_{\max}-\mu\right)/\sigma\right]} & x\le x_{\max}\\ 0 & x>x_{\max}\end{cases} \tag{1}$$

where x is the parameter to be estimated, $\phi(g)$ is probabilistic density function of the standard normal distribution, $\Phi(g)$ is probabilistic distribution function of the standard normal distribution, μ, σ and $x_{\max}$ are the mean, standard deviation and the maximum value of x.

6. Two-step procedure to take into account local site condition

As well known, local site condition influences ground motion significantly. The condition, such as very soft soil layer, violent undulating topography and large sediment basin, and its effects on motion are very complicated. A powerful procedure to take the condition into account in ground motion synthesis is numerical approach, however there must be shortcomings as the same mentioned above in all numerical procedures that the more detail of the calculating model for local site condition, the larger amount of discrete grids are needed. In general, the grid size to describe local topography or shallow soil layer may be several meters, the model including large earthquake source - wave propagation path and site condition should be at least ten times of those without local condition consideration, so the calculation must not be accomplished with common computing resources. The amount of calculation may be much smaller, if we just calculate for the local site condition with inputs on the boundaries of the small model, and the inputs are from FK approach. The idea matches with the current understanding of the crustal structure, the data on lateral inhomogeneity in layers of the crust decreases with depth obviously.

This kind of two-step procedure was studied for the synthesis of low-frequency ground motion [31]. The whole region under consideration was modeled into two parts, a deep homogenous model with the source in it and a shallow inhomogeneous model from the ground surface to the bottom of the upper crust. The latter was divided further into finite element grids. Firstly, displacement time history at each node on the bottom of the overburden layer grid caused by each subsource was calculated by analytic Green's function in full space. Displacement time histories from all subsources at a node were superimposed with the corresponding time lags to provide the input at that node in the next step. Secondly, displacement time histories at the nodes on ground surface were calculated by a space-time decoupling explicit finite element procedure with a second-order local artificial transmitting boundary with displacement field input from the first step. Results of some cases were acceptable, and showed that the numerical calculation was feasible for sites with complex sedimentary layers in low frequency range. The two-step procedure has been applied in several hazard assessment projects of engineering sites or cities near to active faults.

A further improvement of the procedure may be to adopt the input of the second step calculation of finite element model from the displacement field at the bottom of the shallow model by FK approach from the deep horizontal layered half space model. The issue to be dealt with for this two-step procedure, involves the difference between the large model with internal source for the deep part and the much smaller model for the shallow part. The key point is the difference between the inputs of the shallow model and the displacements at the same positions calculated by the deep model.

7. Large pulse in the synthesized motion

One capability of the ground motion synthesis should be validated is if large pulse can be generated in the motion with proper physical meaning, since this feature of ground motion is very significant for long-period structures, such as high-rise buildings and large-span bridges.

Pulse-like ground motion is a type of long-period ground motion, and is studied from records in many earthquakes, such as the 1966 Parkfield, the 1971 San Fernando, the 1994 Northridge, 1995 Kobe and the 1999 Chi-Chi earthquakes. The awareness of destructive powers of the pulses has been increased in seismic design. Some suggestions to modify design spectrum with an amplification factor of narrowband bell function at the pulse periods [32, 33]. From the author's point of view, this kind of modification is angular without enough physical meaning. It must be ideal if the pulse could be generated naturally in the synthesis.

In our case studies, the source of the 1994 Mw 6.7 Northridge earthquake was modeled, as rich pulse-like motions had been recorded in it [21]. The synthesized velocity time histories at rock site stations were band-pass filtered from 0.1 to 20 Hz, and then compared with the corresponding records. As examples, the comparison of the time histories at three stations is shown in the following figure. The smooth curves in Fig. 1 are the pulses extracted from the time histories.

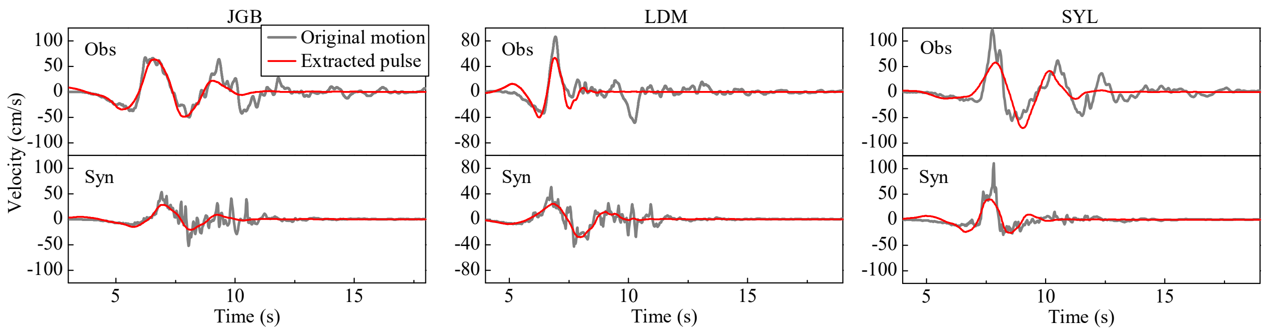

Fig. 1 - The synthesized and observed velocity time histories at three stations in the Northridge earthquake.

One can see from the figure is that the FK synthesis can generate large velocity pulse indeed. The result time histories show similar characteristics to those of the records broadly.

8. Coherency of the motion field

Spatial variation of ground motion denotes the differences in amplitude and phase of motions at points with distance of several hundred meters. During an earthquake, the motions at supports of large-span structures with this distance to each other may be different, and may cause more severe response than that from consistent motion inputs. Inconsistent motion inputs in the seismic analysis of large-span bridges, are emphasized by many researchers, and are taken into account in some seismic design codes, e. g. the Euro code 8 [34]. Therefore, the inconsistent input is very significant for analyzing this kind of structures to validate if the synthesis approaches express the spatial structure of the real ground motion field, i.e. the spatial correlation between motions at adjacent points, in other words, the coherency in frequency domain. The spatial structure of motion field can be validated by means of the coherency coefficients between motion pairs with various distances.

The achievements on spatial variability of ground motion field up to now are mainly from the observed data from dense arrays. The models of the spatial correlation or coherency of the motion are also built from the data with random field theory. The data recorded at dense seismograph arrays have provided valuable information and more detailed descriptions for the spatial variation of the motions. The statistical result shows that motions at adjacent points can be considered as perfect correlative, and can be analyzed by deterministic wave theory, in the band lower than a specific frequency; motions at adjacent points are imperfect correlative with some randomness, in the band higher than the frequency. An area can be estimated by the motion field with the interesting frequency component, the higher frequency the smaller radius of the area [35].

Coherency function is considered as the best descriptor of the similarity and cross-variation between two ground motions. The bigger coherency coefficient, the stronger relativity is between the motions at the two points. When the value of the coefficient is 1.0, the motions are the same completely [36].

The result of our case studies shows that the correlation between motions with distance 200 meters on rock site is strong, the mean values of coherency coefficients are from 0.7 to 0.8, and the maximum is up to 1.0 [37]. There is a trend that the coherency decreases with the distance, the coefficient between motions with distance 400 meters or less is almost more than 0.8 and it gets small for distance of thousand meters. The correlation between high-frequency motions (>5Hz) is weak, the coherency coefficients corresponding to various distances are all less than 0.5, and the mean values are mostly less than 0.25. The result is consistent with the conclusion from the statistics of the observed data on some dense arrays like SMART-1 during the past earthquakes, the spatial correlation of ground motions at two surface points depends on the distance and frequency components of the motions, decreases as distance and/or frequency increases [35].

The authors of this paper believe that the spatial variability of the synthesized ground motions at points with distance of several hundred meters comes physically from the fact that the motions are caused from the same source and similar paths and site conditions. If coherency, as a purely statistical measure, is not related to physical parameters of source and path, it cannot be reliably extrapolated to any site. A synthesis of ground motion field taken into account the effects from source, path and site must be convenient for revealing the nature. The motion field synthesized by FK procedure must be even better, since it is governed by not only path and site condition, but also the source, even the rupture process of the convolution of the slip time function on the plane with the corresponding Green's function.

9. Conclusion

In order to improve the synthesis approach of broadband ground motion from the requirement of seismic analysis of large-span spatial structures, the following issues are discussed in this paper. There is a discordance in the existing hybrid synthesis approach that superpose the motions generated by stochastic synthesis procedure at high frequencies with the numerical Green's function results at low frequencies in time domain, since the latter provides three translational components of ground motion, FN, FP and UD, while the former just generates a horizontal component without a definite direction with the fault rupture plane. The FK synthesis approach could be a solution for the discordance, since it is a more rigorous and is derived from electrodynamics wave theory, by convolutional integration of the all slips and their time functions on the whole rupture plane with the Green's function for the appropriate depth and distance, and provides three-component ground motions, the same as FN, FP and UD, containing all wave types. The most obvious advantage of FK, comparing with the stochastic synthesis, is that the effect of the regional crustal velocity structure on ground motion is taken into account from horizontal layered model. The phase spectrum of the motion could be estimated from the difference of phase velocity controlled by dispersion caused from the crustal velocity structure, with clear physical meaning. In FK synthesis, the temporal evolution of slip is the dominant influencing factor at short periods, while the spatial variation of slip is the main influencing factor at long periods, therefore the relationship between the slip distribution and temporal parameters should be taken into account in source modeling to guarantee the enough frequency band, especially at high frequency. The rise time and rupture velocity should be estimated jointly for the slip distribution under the constraint on the seismic energy radiated during the entire rupture process, and the dependence of the result motion on the subsource size could be removed by keeping the increase of rise time with subsource size. To avoid the awkward situation if all the source parameter estimated only from the scaling laws, the data of regional geological and geophysical investigations, remote sensing image recognition, seismo-tectonic investigation, seismicity study should be adopted as much as possible in the source modeling, and the resulted values, especially for the local parameters, are often the maximum values, a truncated normal distribution could be applied to manage these maximum values and the randomness in the parameter estimation. A two-step procedure to include local site effect in the synthesis, could consumedly reduce the amount of calculation by considering the local site condition with inputs on the boundaries of the second step calculation of finite element model from the displacement field at the bottom of the shallow model by FK approach from the deep horizontal layered half space model. The difference between the large model with internal source for the deep part and the much smaller model for the shallow part, and the difference between the inputs of the shallow model and the displacements at the same positions calculated in the deep model, are to be dealt with for the improvement of this two-step procedure. The FK synthesis could generate large velocity pulse in the ground motion with proper physical meaning, and motion field with spatial correlation between motions at adjacent points in consistent with the conclusion from the statistics of the observed data on some dense arrays.

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11. Copyrights

12. References

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