Synthesis of Near-fault Strong Ground Motion by Using Hybrid Method of Statistical and Theoretical Green's Function

Shuanglan WU[1], Bhuddarak CHARATPANGOON[2] and Junji KIYONO[3]

[1]Doctoral student, Dept. of Urban Management., Kyoto University
（C1-2-146, Kyoto-Daigaku Katsura, Nishikyo-ku, Kyoto, 615-8540, Japan）
E-mail:wu.shuanglan.73v@st.kyoto-u.ac.jp
[2]Member of JSCE, Assistant Professor, Dept. of Urban Management., Kyoto University
（C1-2-146, Kyoto-Daigaku Katsura, Nishikyo-ku, Kyoto, 615-8540, Japan）
E-mail: bhuddarak@gmail.com
[3]Member of JSCE, Professor, Graduate School of Global Environmental Studies, Kyoto University
（C1-2-146, Kyoto-Daigaku Katsura, Nishikyo-ku, Kyoto, 615-8540, Japan）
E-mail: kiyono.junji.5x@kyoto-u.ac.jp

An effect of ground displacement as well as velocity and acceleration becomes a significant factor when structures cross a fault because the fault produces both step-like static deformation and dynamic pulse-like ground motions. The static offsets can be as large as several centimeters to 10 meters and strong ground motion velocity pulses exceeding 100 cm/s have been observed. As there is no concrete synthesis method of design ground displacement, numerical simulation of ground motions, especially ground displacement, for such near-fault situations is of great necessity. This paper proposes a hybrid method combining the statistical Green's function and theoretical Green's function. It considers both dynamic and static terms, and it combines well-know, widely used statistical Green's function method and theoretically induced Green's function method. In order to further describe this hybrid method, we simulate two simple examples; strike-slip and dip-slip fault models. Results well showed dynamic displacement with the fling-step of near-fault movement.

Key Words : *strong ground motion, numerical simulation, static terms, dynamic terms, fling-step*

1. INTRODUCTION

There are various lifeline facilities and structures with spatial extent and/or long natural period, such as long span bridges, embankment, pipelines, high-rise or base-isolated buildings, which located in the vicinity of the surface fault, or cross active tectonic faults around the world. However, the observed performance of these essential structures following recent earthquakes suggested that conventional design methods do not satisfy the desired performance levels. When there is no other alternatives than to design the structures crossing an active fault, obtaining the spatially varying strong ground motion(especially including permanent tectonic displacements across the fault) is very necessary.

Numerous researches have been done on this topic. Alper Ucak .et.al calculated the synthetic broadband ground motions at the location of the Bolu Bidcuct by using a hybrid simulation approach, the low-frequency part using the discrete wave-number representation method, while the high-frequency parts using stochastic modeling method[1)]. Kataro Kojima and Izuru Takewaki proposes a double impulse input as a substitute of the fling-step near-fault ground motion[2)].Up to date, very few studies have addressed this problem, and a rational seismic design philosophy for such structures crossing active faults has not been established yet. Thus, in this paper, it referred a hybrid method to simulate near-fault ground motion, which combines the statistical Green's function (*Irikura*[3)4)]) with theoretical Green's function method *(Hisa*,[5)6)7)]).

In this study, we calculate dynamic displacement of the ground by using statistical Green's function that is widely used and being popular for the strong ground motion simulation. This method can generate dynamic ground displacement even in a vicinity of the fault; however, it is difficult to simulate fault movement such as a 'static' fling-step with permanent displacement of the fault. Acceleration time history by this method is frequently used for the input ground motion of structural seismic design and the application is flexible. On the other hand, the theoretical Green's function can also generate, of course, both dynamic and static ground motion but its application is limited to the idealized layered media. However the displacement especially near the fault almost directly reflects source characteristics, therefore, this simple idealized 'static' solution of theoretical Green's function method has a strong advantage. We here applied this hybrid method to two simple fault mechanisms, the strike-slip and dip-slip faults, and verified the effectiveness.

2. METHODOLOGY

As for the simulated time histories, it is highly required that it must accurately incorporate the near-fault source radiation pattern, account for far- and near-field seismic radiation, and have the ability to characterize motions for a broad range of fault types (e.g. strike-slip, normal and reverse faulting), as well as variable slip and full kinematic description of the rupture process. We must be able to accurately simulate the directivity effect as well as the sudden elastic rebound sometimes referred to as fling. Thus, it needs to calculate motions very close to the fault. We here consider the fling-step effect as important characteristics of near-fault displacement.

(1) Statistical ł Green's function

As the previous papers 4) and 5) shown, when the observation point is close to the fault plane, the dynamic traction Green's functions exhibit sharp peaks within the area close to the observation point. Thus, in this paper, the statistical Green's function method[3)4)] is adopted for calculating the dynamic terms. The basic principle of the statistical Green's function method is as following: A large earthquake is composed of a series of small earthquakes; records of small earthquakes (in case of empirical Green's function) or statistically calculated small earthquakes (statistical Green's function) are selected properly as ground response caused by small areal sources, namely statistical or empirical Green's functions which are then overlaid by specified cracking ways to obtain the time-history curve of large earthquake. Both displacement spectra and acceleration spectra are introduced to determine the quantity of neutron source $\boldsymbol{N^2}$ and stress drop ratio $\boldsymbol{C}$, which are compared with parameters obtained from the similarity of large earthquake and small earthquake for purpose of obtaining proper parameters of hypocenter, Eqs. (1) ~ (3) listed the main procedure.

$$U(t)=\sum_{m=1}^{NL}\sum_{n=1}^{NW}\frac{r_0}{r_{mn}}\left[u(t-t_{mn})+\sum_{k=1}^{(ND-1)n'}\frac{1}{n'}\cdot u(t-t_{mn}-k\cdot\frac{\tau}{(ND-1)n'})\right]=\sum_{m=1}^{NL}\sum_{n=1}^{NW}\frac{r_0}{r_{mn}}u'(t-t_{mn}) \quad (1)$$

$$t_{mn}=\frac{(r_{mn}-r_0)}{V_s}+\frac{\xi_{mn}}{V_R} \quad (2)$$

$$u'(t)=u(t)+\sum_{k=1}^{(ND-1)n'}\frac{1}{n'}\cdot u(t-k\cdot\frac{\tau}{(ND-1)n'}) \quad (3)$$

where, U(t) is the synthetic main-shock ground

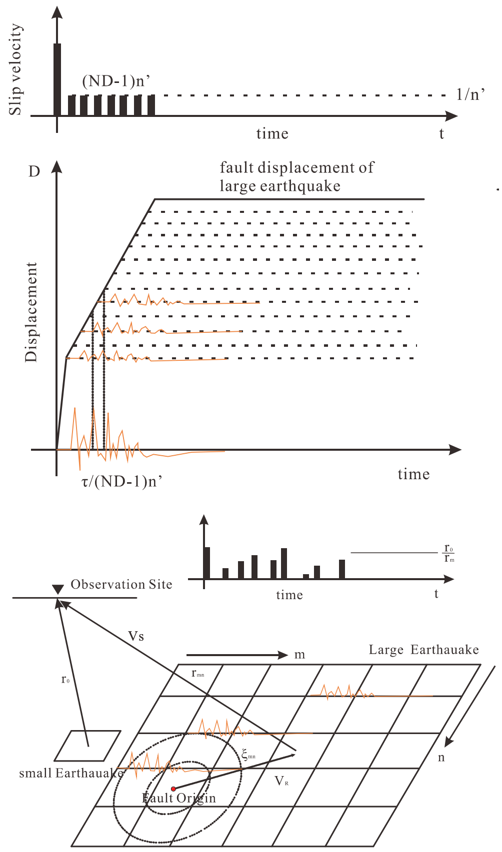


Fig.1 Schematic illustrations of the empirical Green's Function method (Kagawa.8)

motion displacement, u(t) is observation small ground motion, N is the scale ratio of main-shock to aftershock; C is the stress drop ratio; * stands for the convolution. F(t) is the modifying function, which taking into consideration of the difference of rise time between the large event and small ones. T is the rising time of large event, also is the time of the function of ;is a suitable modification factor, in order to degreed the influences by manual period time and adjusting the interval time. Also, the area of main shock and the small event are L×W and l×w respectively. And here assuming that L/l=W/w=N; and the delay time of point source (m ,n) on the rupture surface; and stand for the s-wave velocity near the earthquake source and slip velocity respectively. The is the distance from the small shock to the site or the receiver, and is the distance from the point source of (m,n) in the slip surface to the site or the receiver, and indicates the distance between the original rupture point source to arbitrary point (m,n) on the rupture surface.

(2)Theoretical Green's function

Based on the proposed method by Hisada[5)~11)], an efficient method for computing near-fault ground motions in a layered half-space, an efficient method for carrying out the fault integration of the representation theorem. As the observation point is close to the fault plane, the dynamic traction Green's functions exhibit sharp peaks within the area close to the observation point. While this method character that subtracting and adding the static Green's functions can eliminate the singularities of the original Green's function. Thus, Hisatda's method proposed the following representation theorem;

$$U_k(Y;\omega)=\int_\Sigma\{T_{ik}(X,Y;\omega)-T^s_{ik}(X,Y)\}D_i(X;\omega)d\Sigma+\int_\Sigma T^s_{ik}(X,Y)D_i(X;\omega)d\Sigma \quad (4)$$

where T_{ik} is the traction Green's function of the layered half-space at circular frequency, ω, and T^s_{ik} is the static traction Green's function of the layered half-space (ω =0).

Addition and subtraction of singular integrands is common when dealing with integral evaluations or integral equations (e.g., Apsel and Luco[12]; Colton and Kress[13]).It is clearly seen that the second integral in equation (4) involves the static Green's function. And more importantly, since the values of the static functions remain invariant for all frequencies, these functions need to be evaluated only once. The second integral describes the attenuation of the slip function due to the static traction of the Green's functions.

In this study, we only adopt the second term of Eq.(4) and calculate the static displacement of the fault according to the following equation (5).

$$U_k(Y;\omega)=\int_\Sigma T^S_{ik}(X,Y)D_I(X;\omega)d\Sigma \quad (5)$$

(3) Combination of statistical and theoretical Green's function

As the statistical Green's function method does not consider the static displacement because the statistically calculated small earthquake does not have a permanent displacement even if the observation point is located very near the fault. In order to obtain near fault time history, we make a simple proposal that combines the dynamic term, which are from the statistical Green's function method, and the static term, which are from the theoretical Green's function. And it is much faster when compared with some other simulation methods.

Table 1 Material properties of the layered half-space

Number of layer	1
Density (g/cm^3)	2500
Vr (km/s)	infinite
V_p (km/s)	5.0
V_s (km/s)	3.0
Q_p	200
Q_s	100
Thickness (km)	0

3. Synthesis of Near-fault Displacement Time Histories

In this section, in order to make a further description of this combined method mention above, the combined method was applied to the synthesis of ground motions for two simple and idealized fault models such as the strike-slip and dip-slip fault in homogeneous half-space.

(1) Example 1: Strike-slip model with surface faulting in a homogeneous half-space

First of all, basic characteristics of the near-fault ground motion using a simple strike-slip model with surface faulting (see Fig.2) is calculated taking into account both the static- and dynamic- terms of the near-filed ground motions.

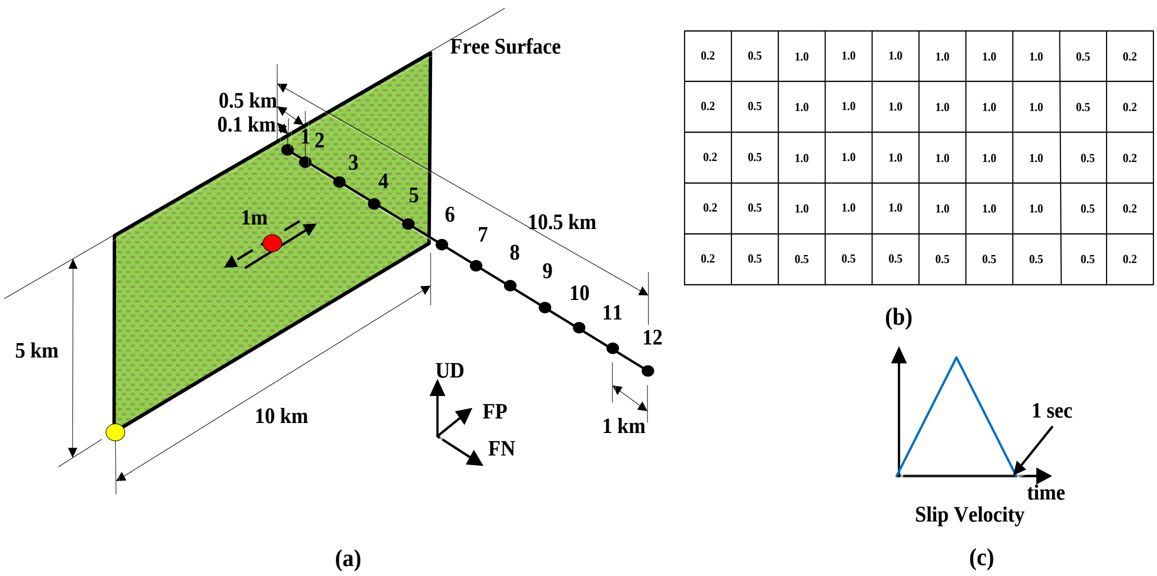
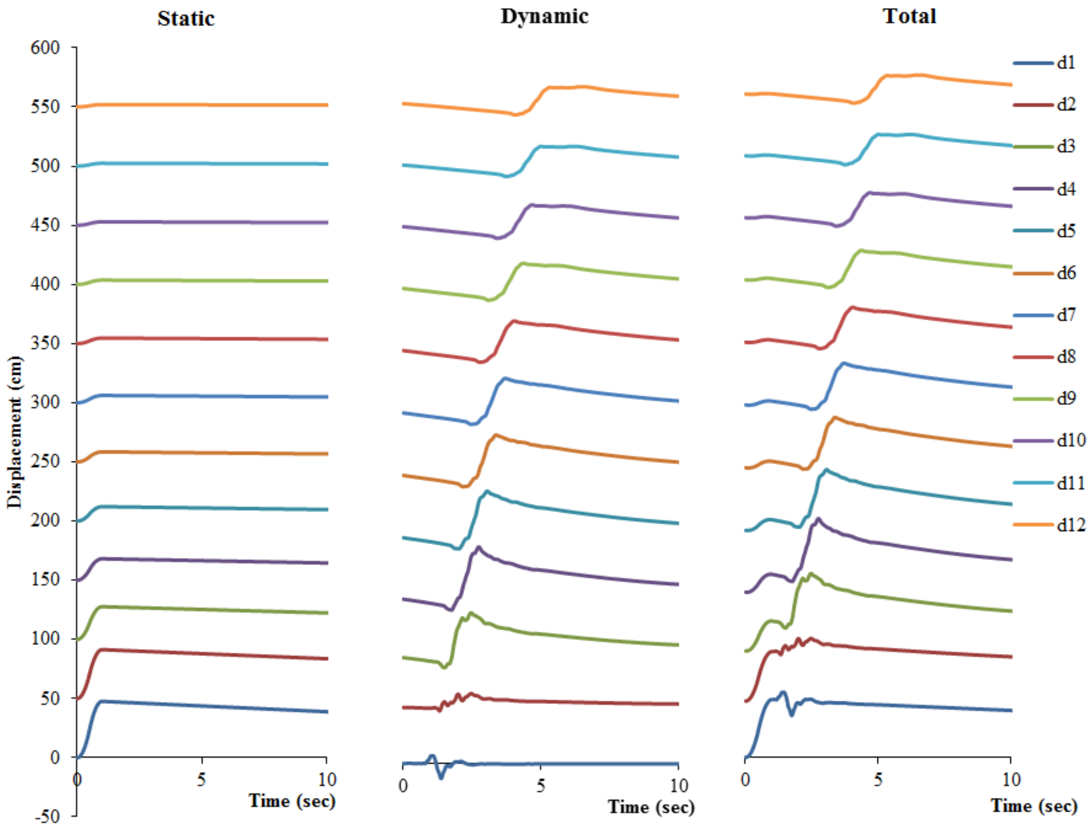


Fig.2 (a) strike-slip model with surface faulting and 12 observation points; (b) Slip distribution; and (c) Slip velocity function



(a) Static (b) Dynamic (c) Total

Fig.3 Results along fault-parallel direction at 12 observation points

In terms of the fault model which is shown in Fig.1(a), ground motions of 12 observation points on the free surface along a line perpendicular to the fault plane are calculated. Point 1 is 0.1 km away from the center of the surface fault, and point 2 is 0.5 km away. Similarly, points 3-12 are 1.5-10.5 km away from the fault at 1-km intervals. Because of the symmetry of the model and the pure strike slip, the fault-normal components are zero, and the vertical components are negligible compared to the fault-parallel components. As shown in Fig.2(b), the maximum slip of the fault is 1m, including the shallowest sub-faults which break the free surface, and tapers at both edges and at the bottom of the fault. The slip velocity function is an isosceles triangle with a 1-sec duration as shown in Fig. 2(c).

Material properties of the layered half-space are listed in Table 1. The rupture velocity is infinite that means rupture simultaneously occurs on the fault plane; we use the homogeneous half-space with the physical properties of as shown in Table 1.

The static term is calculated by using the proposed representation theorem, Eq.(5), and the dynamic term is simulated by adoption of statistical Green's function.

The calculated displacements along fault-normal direction have been shown in figure 3. When observation points are close to the fault (e.g., points 1 and 2), we see the strong fling effects, which means, the large static offsets in displacement. From point 1 to 12, the static terms decay rapidly with distance from the fault, the fling effects disappear for observation points away from the fault (e.g., points 11 and 12). While as for the dynamic terms in figure 3(b), they become dominant far from the fault, the same tendency as for the total displacement.

(2) Example 2:Dip-slip model with surface faulting in a homogeneous half-space

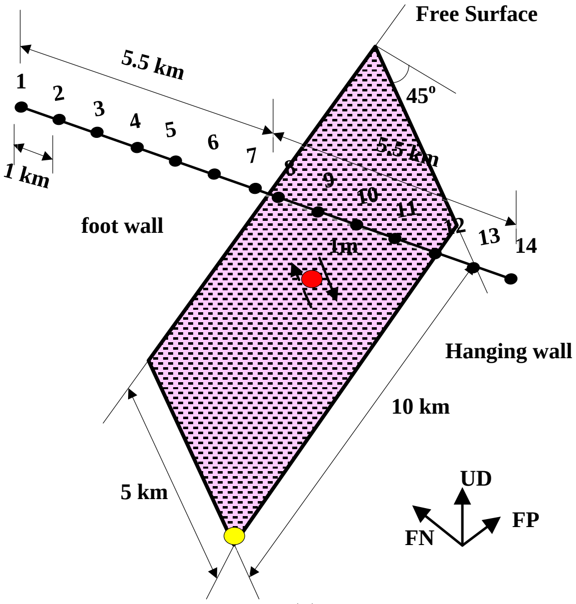
Next, we calculated the near-fault strong motions using a dip-slip model with surface faulting. The fault model is shown in Fig.3. The dip and rake angles are 45°and 90°, respectively. Other source parameters are the same as the model in example 1(see Fig. 1), and the same homogeneous half-space with the physical

Table 2 Material properties of the layered half-space

Number of layer	1
Density (g/cm^3)	2500
Vr (km/s)	infinite
V_p (km/s)	5.0
V_s (km/s)	3.0
Q_p	200
Q_s	100
Thickness (km)	0

properties as shown in table 1. Here, 14 observation points are located on the free surface along the line perpendicular to the fault; points 1–7 are located on the foot-wall side, and points 8–14 are on the hanging-wall side. The points closest to the fault trace are points 7 and 8, 0.1 km away from the surface fault trace. Figure 4a, b shows the fault-normal and up–down components of the displacements at the 14 observation points respectively.

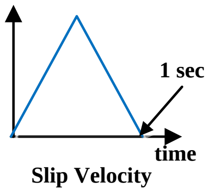
the fault model, the points 1 to 7 are located on the foot-wall, and points 8 to 14 are located on the hanging-wall. Compared with the foot-wall(points 1-7), the displacements on hanging wall (points 8-14) have large values, especially along the up-down direction. As for all the observation points, the static terms are all larger than the dynamic terms, and the static terms take dominant parts. The distance become farther from the fault traction, the static terms attenuated very fast, then



(a)

0.2	0.5	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.2
0.2	0.5	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.2
0.2	0.5	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.2
0.2	0.5	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.2
0.2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.2

(b)

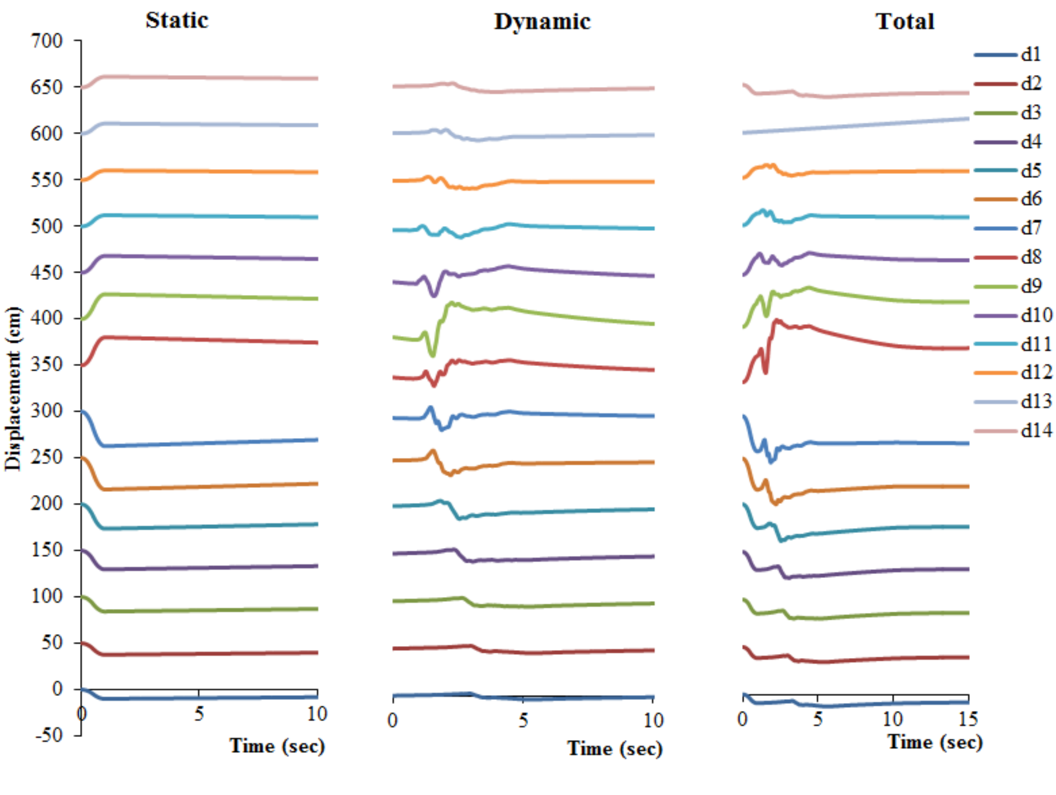


(c)

Fig.3 (a) Dip-slip model with surface faulting and 14 observation points;
(b) Slip distribution; and (c) Slip velocity function

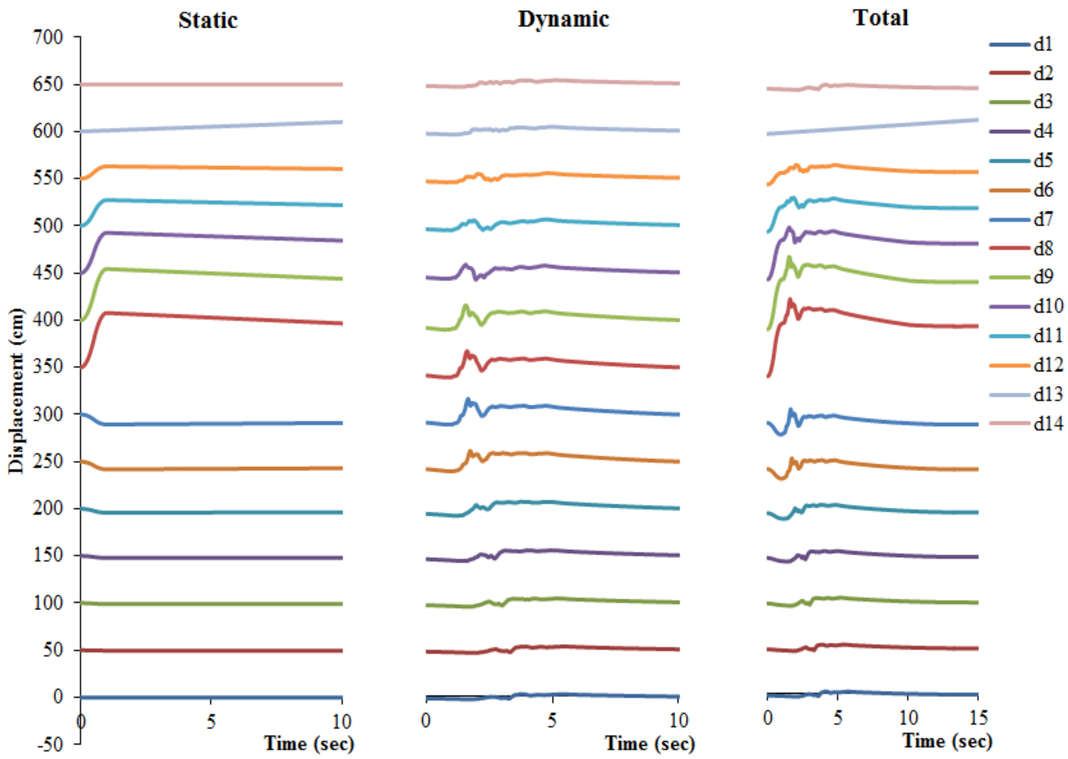
Fig.5 (a) and (b) shows the fault normal and up-down displacements, including the static terms, dynamic terms, and the total components, respectively. As for

the dynamic component take the dominant parts. The results and various tendency are almost the same as the method calculated with Hisada's theoretical method 6),



(a) Static (b) Dynamic (c) Total

Fig.5 Displacement along fault normal direction



(a) Static (b) Dynamic (c) Total

Fig.6 Displacement along up-down direction

which demonstrate that the method is applicable.

4. CONCLUSION

In this paper, we proposed a hybrid method to simulated strong ground motions near fault zone. What we had done and obtained results are:

(1) A hybrid method combined statistical Green's function and theoretical Green's function was proposed to simulate the displacement of strong ground motion, which synthesizes the static and dynamic terms.

(2) Displacements near the fault were calculated for a simple strike-slip fault model by using this method. From the results of 12 observation points located along the fault normal direction, the static term-induced displacements were dominant in the time history along the near fault area, while the dynamic term-induced displacements were dominant along the further distance from the fault line.

(3) Displacements near the fault were also calculated for a simple dip fault model by adopting this method. The displacements along fault-normal and fault-parallel direction of 14 observation points showed that the fling-step was much obvious and dominant in the hang-wall, and the same tendency occurred in strike-slip fault along the distance from the fault trance on the surface.

(4) According to the proposed method, we can simulate near-fault displacements. The displacements obtained can be applied for the design input ground motion of, for example, a road bridge across the active fault.

5. DISCUSSION

As this proposed method considers only a simple combination of dynamic term by adoption of statistical Green's function method, and static term using theoretical Green's function method, while some other factors, such as the multi-faults, time delay, different types of slip velocity, slip distribution and multi-time windows, have to be considered in the future research. Also, much more observation points and the ground with multiply layers must be taken into consideration. Moreover, we have to conduct a comparison between the calculated and observed results and verify the accuracy of the method.

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