11 WCEE

Copyright © 1996 Elsevier Science Ltd
Paper No. 304. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

DYNAMIC SOURCE INVERSION OF SEISMIC FAULT BY SUPERPOSITION METHOD

Sumio SAWADA

School of Civil Engineering, Kyoto University,
Yoshida-honmachi, Sakyo-ku, Kyoto, 606-01, Japan

ABSTRACT

Dynamic Rupture Model is a promising tool for estimating the barrier and asperity effect because the rupture process and ground motions can be directly calculated from physical parameters such as stress or strength on the fault. However it takes enormous computer time and power, particularly for inversion analysis. In order to improve the effectivity, a new procedure for inversion analysis of seismic fault parameters is proposed based on the dynamic rupture model.

KEYWORDS

Dynamic rupture model; Waveform inversion analysis; Fault rupture; Finite element method

INTRODUCTION

The empirical Green function method is often applied for simulation of seismic ground motion in the seismic response analysis of important structures such as nuclear power station. This method is classified as kinematic model which assumes the source time functions and propagation of rupture on the fault without considering the stress and strength distribution. Although the fault rupture process and resulting ground motion are strongly affected by barrier and/or asperity on the fault plane, it is difficult to infer the spatial distribution of barrier or asperity by kinematics model. In addition, the empirical Green function is not applicable for simulation of seismic ground motion near the fault because the relative position between the source and the observation point exerts great influence on the Green function.

the dynamic rupture model is a realistic and promising tool for simulation of seismic ground motion, in which physical parameters such as stress and strength distribution on the fault plane are involved in the analysis of the fault rupture process. Moreover, in the case of the dynamic model, it is relatively easy to consider the effects of barrier and asperity on the seismic rupture process and seismic ground motion. Miyatake(1980) utilized the finite difference method to analyze the fault rupture process by the dynamic rupture model. Toki and Sawada(1988) simulated rupture process of a thrust fault by finite element method. In the dynamic rupture model, the rupture automatically proceeds and the ground motion near the fault can be calculated by assuming the distribution of strength, initial stress and residual stress on the fault. Eventually the propagation of rupture, source time function and other fault parameters are obtained as a result of computation of the rupture on the fault. However the analysis is a forward analysis, in which the distributions of stress and strength are to be known before the simulation.

In order to determine the distribution of stress and strength on a fault plane, an inversion analysis is needed by making use of seismic records obtained during actual earthquakes. The kinematic models have been used so far for inversion analyses and the distribution of dislocation and rupture front of major earthquakes of the past have been inferred from seismic records. The kinetic model, however, cannot determine the distribution of stress and strength on the fault plane.

The dynamic rupture model can infer the stress and strength distributions on fault plane but the repeated computations for above mentioned forward analysis are needed and the demand for computer power is so much that it is expected to develop much faster algorithm of computation of fault parameters by the dynamic rupture model. Then in the present paper, we propose a method for inversion analysis of fault parameters, which can reduce the computer time.

METHOD OF ANALYSIS

Fig.1 shows the stress-time history of a point on a fault plane to be analyzed.

(1) The initial stress throughout the fault plane is same and denoted as σ^I.

(2) Applying the lateral tectonic force to the entire fault plane model, the stress on the fault plane is increased and that of the origin reaches to the yield stress σ^Y.

(3) The slip takes place at the origin and the stress drops to the residual stress σ^R and the strain energy at the point is released.

(4) The released strain energy generates the stress waves and transmitted to adjacent area of the fault plane.

(5) The transmitted energy increases the stress level of the neighbor area and the slip of the adjacent area takes place again.

(6) This process is repeated and the rupture occurs successively on the fault plane.

Then the rupture occurs automatically and the dislocation is eventually obtained. The process is much more realistic than that of the kinematic model.

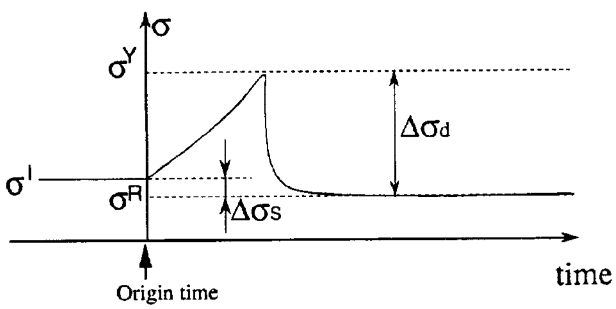


Fig.1 Time history of the stress on a fault.

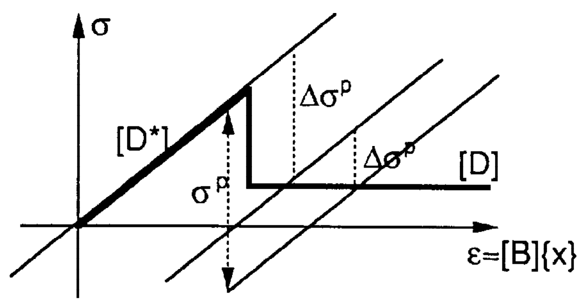


Fig.2 Constitution law of joint element.

Toki and Sawada (1988) introduced the joint element for modeling the fault in simulation of fault rupture process by finite element method. Fig.2 shows the constitution law of the joint element. The behavior of the model is governed by a nonlinear equation of motion. However, nonlinear motion is limited on the fault plane so that the equation is transformed to a linear equation by making use of the modified Newton-Raphson method.

The superposition method is applicable in case of linear system and the response analysis based on the Green function is a superposition method. Then we propose a calculation method of the equation of motion by making of use of the unit step response function. The schematic diagram of the proposed process is shown in Fig.3. The process is consisted of 4 steps as follows;

<u>Step 1:</u> Integrated Green Functions are obtained, which are the response time functions of the stress on the fault plane and the ground velocity at the observation point to the unit impulse at a point on the fault plane. The response $\{x^S(t)\}$ of the system subjected to a single couple force with unit intensity is governed by Eq.1.

$$[M]\{\ddot{x}^S(t)\}+[C]\{\dot{x}^S(t)\}+[K^*]\{x^S(t)\}=[B]^T\begin{Bmatrix}0\\ \vdots\\ 1\\ \vdots\\ 0\end{Bmatrix}=\begin{Bmatrix}0\\ \vdots\\ 1\\ -1\\ \vdots\\ 0\end{Bmatrix} \tag{1}$$

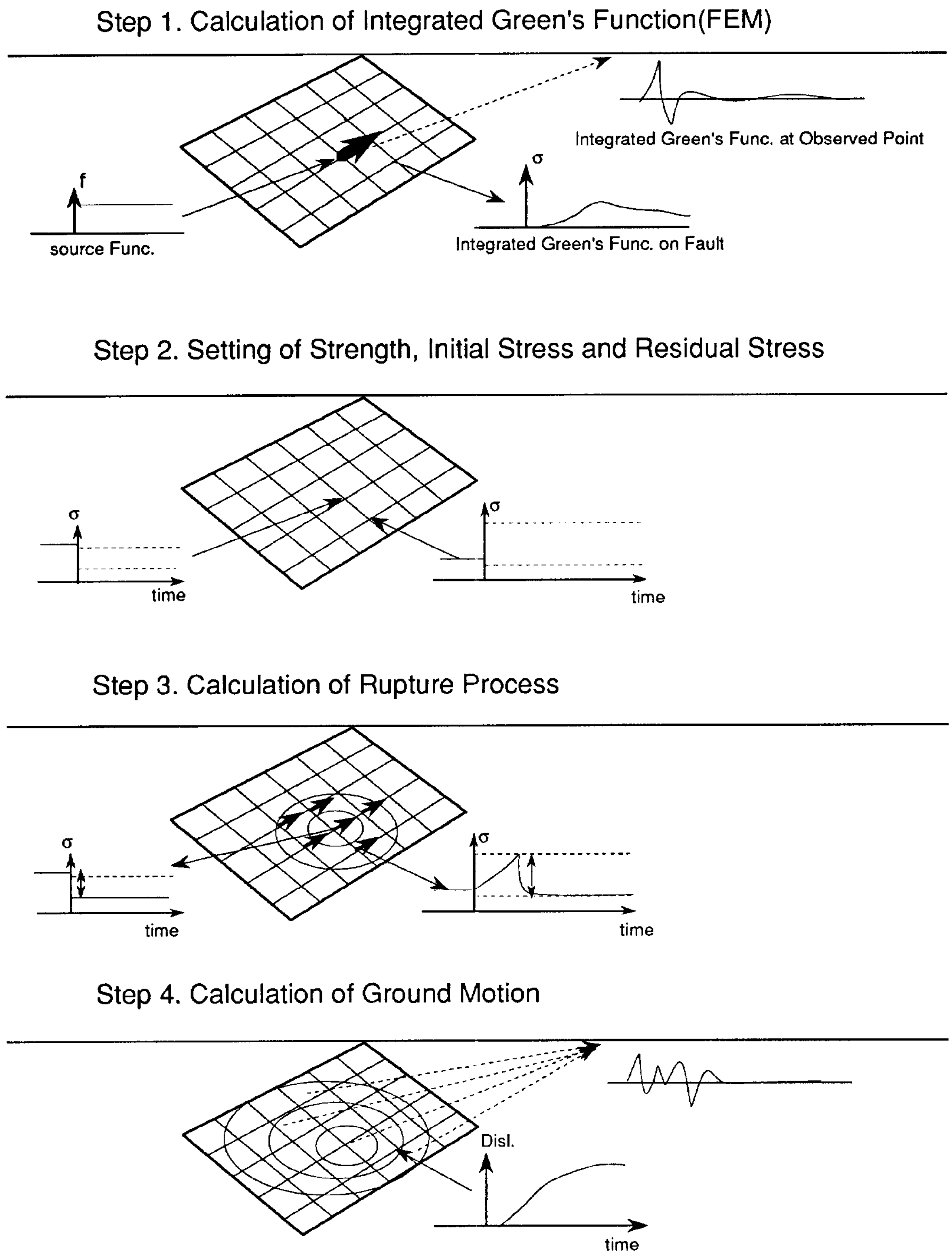


Fig.3 Steps of calculation.

The initial conditions are

$$\{x^S(0)\}=\{\dot{x}^S(0)\}=\{\ddot{x}^S(0)\}=\{0\}.$$

Then, the response time function of stress on the fault $\sigma^S{}_{ij}(t)$ is given by Eq.2.

$$\sigma^S_{ij}(t)=[D^*][B_{ij}]\{x^S(t)\} \qquad (2)$$

where i and j are the relative position parameter on the fault. The position of i=j=0 corresponds to the point where an impulse of unit intensity is applied.

Step 2: The distribution of strength $\sigma^Y{}_{ij}$, initial stress $\sigma^I{}_{ij}$ and residual stress $\sigma^R{}_{ij}$ are assumed.

Step 3: Dynamic Rupture process under the assumed stresses distribution can be calculated by summation of $\sigma^S{}_{ij}(t)$. In this calculation, as the balanced condition is applied only to the fault plane, the number of calculation is the order of two dimensional analysis. The time history of the stress on the fault $\sigma_{ij}(t)$ and the time history of plastic stress $\sigma^P{}_{ij}(t)$ are obtained by Eq.3 and 4.

$$\sigma_{ij}(t)=\sum_k \sum_l \sum_{t_0=1}^{t-1} \sigma^S_{(i-k)(j-l)}(t-t_0)\sigma^P_{kl}(t_0)+\sum_{t_1=1}^{t-1}\sigma^P_{ij}(t_1) \qquad (3)$$

$$\sigma^P_{ij}(t)=\sigma_{ij}(t)-\sigma^R_{ij} \qquad (4)$$

In Eq.3, $\sigma^S{}_{(i-k)(j-l)}$ is assumed to be approximately same with the stress response at the point (i,j) when an unit step stress is applied at point (k,l) as shown in Fig.4. This assumption is acceptable if the rock blocks are homogeneous and the points (k,l) and (i,j) are far enough from boundaries.

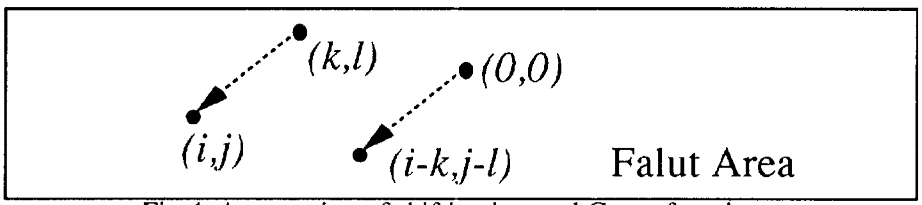


Fig.4 Assumption of shifting integral Green functions.

Step 4: The observed ground motion is obtained by summing up $\{x^S(t)\}$ according to the rupture process given by $\sigma^P{}_{ij}(t)$. The process in this step is the same as that of the kinematic model. In this summation, the integrated Green function for ground motion must be modified according to the direction and distance from the source to receiver. The time history at the receiver site $U(t)$ is determined by Eq.5.

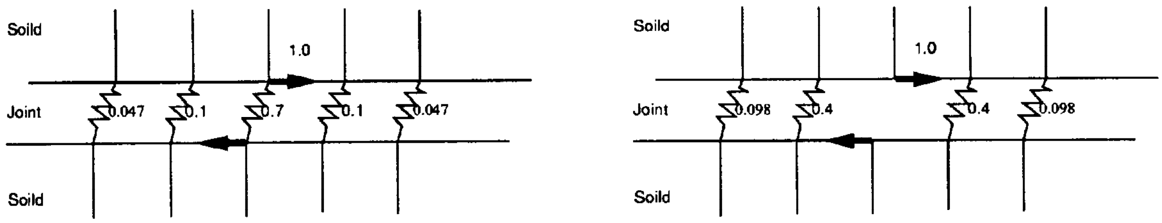
$$U(t)=\sum_i \sum_j \frac{r_{00}}{r_{ij}}[R_{ij}]^T[F_{ij}][R_{00}]u(t)\otimes\sigma^P_{ij}(t) \qquad (7)$$

where $\otimes$ is the operator of convolution, $u(t)$ the displacement of receiver site, r_{ij} the distance from the source to receiver, $[R_{ij}]$ the conversion matrix from model coordinate to ray coordinate which is defined by straight ray from the source to receiver and $[F_{ij}]$ the radiation pattern ratio matrix as follows;

$$[F_{ij}]=\begin{bmatrix} \frac{f^P_{ij}}{f^P_{00}} & 0 & 0 \\ 0 & \frac{f^{SV}_{ij}}{f^{SV}_{00}} & 0 \\ 0 & 0 & \frac{f^{SH}_{ij}}{f^{SH}_{00}} \end{bmatrix}$$

where $f^P{}_{ij}$, $f^{SV}{}_{ij}$, $f^{SH}{}_{ij}$ are the radiation pattern factors on the ray coordinate.

In the present paper, the modified Newton-Raphson method is used for numerical integration of equation of motion and the iterative computation is needed. In the step of iteration, large mount of the applied force is transmitted to the spring of joint element to which the force is applied and small mount of the applied force is transmitted to adjacent elements(Fig.5(a)). For this reason, iterative calculation must be done with increasing the applying force until the transmitted force becomes 1.0. In the proposed method, the force is applied only to an element, the spring of the joint element can be removed. Taking the procedure, iteration is not need because all the applied force is transmitted to adjacent joint elements as shown in Fig.5(b).



(a) Ordinary method. (b) Proposed method.
Fig.5 Applying force to joint element.

In the Inversion analysis using the dynamic rupture model, once the integrated Green functions are calculated by Step 1, only Step 2,3 and 4 are necessary for a forward calculation. Thus, proposed method can greatly reduce the CPU time for a forward analysis. In the case of IBM RS/6000-550 computer, the CPU times needed are compared as shown in Table 1.

Table 1 Comparison of CPU time

Method	CPU time
Ordinary nonlinear FEM	1,800 min
Calculation of Step 1(Green function)	180 min
Calculation of Step 2,3,and 4	2 min

MODEL ANALYZED

The model analyzed is shown in Fig.6. This model has the dimension of 40km by 20km by 19 km and 40 x 20 joint elements for strike-slip type fault, which is shaded in Fig.6. the viscous boundary is applied to five boundaries except the free field to reduce the reflection of waves. The rock blocks of the model have shear wave velocity of 2 km/sec, Poisson's ratio of 0.3, density of 2.0. P1, P2 and P3 in Fig.6 is the receiver sites. Fig.7 is a Green function at P2, which represents the ground motion to an unit force.

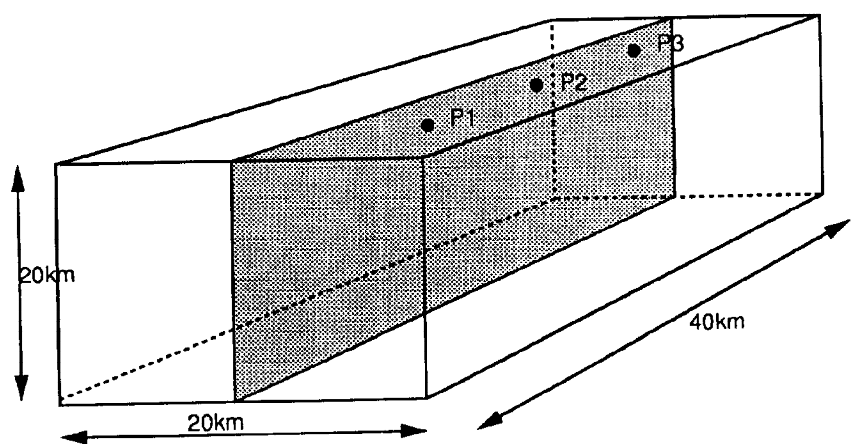


Fig.6 Model analyzed.

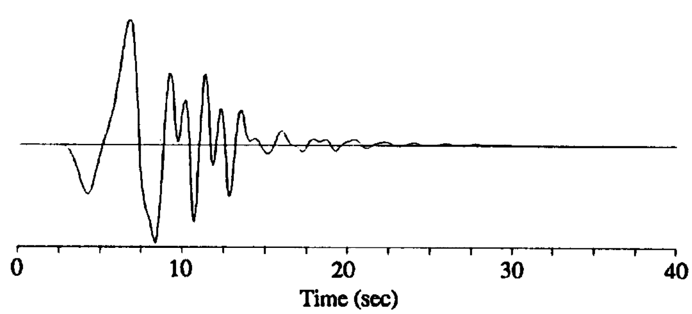


Fig.7 Integrated Green function for Velocity at P2.

The area of 24 by 16 km of the fault is assumed as the potential rupture area by setting strength σ^Y to 70 bar, initial stress σ^I to 65 bar and residual stress σ^R to 10 bar. The rupture propagation is shown in Fig.8 which is obtained by Step 3. An example of the time history of plastic stress $\sigma^P{}_{ij}(t)$ obtained by Step 3 is shown in Fig.9. It is very similar with the source time function used by Irikura(1988). This shows the adequacy of the proposed method.

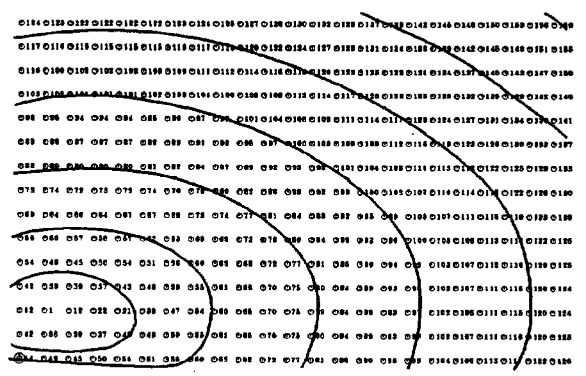


Fig 8 Development of rupture front.

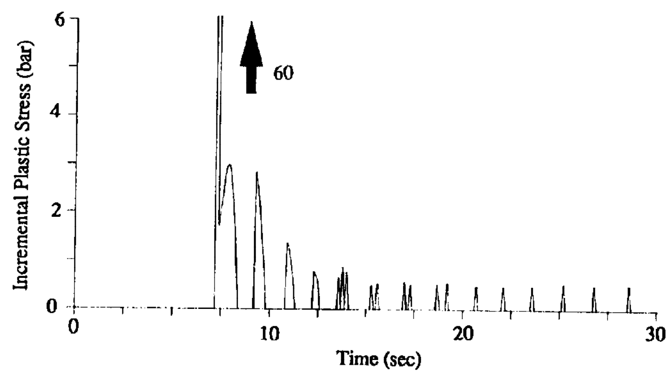


Fig.9 Time history of applied plastic stress.

RESULTS OF DYNAMIC SOURCE INVERSION

Three cases of inversion analyses are performed. The distribution of strength is inferred in Case 1 and the residual stress is treated in Case 2. In Case 3, both the strength and residual stress are detected.

Case 1 is set up to know whether the inversion analysis can detect the barrier on the fault to be analyzed. A block of the strength σ^Y of 80 bar and two blocks of the strength σ^Y of 75 bar are set on the rupture area of the fault plane as shown in Fig.10(a). Then the ground motion at P1, P2 and P3 is calculated, which are the target ground motion. The inversion analyses are carried out to compare the ground motion with target ground motion, with iterative calculation modifying the strength on the fault. In the iterative calculation, the maximum number of iteration limited to 25 because of CPU power.

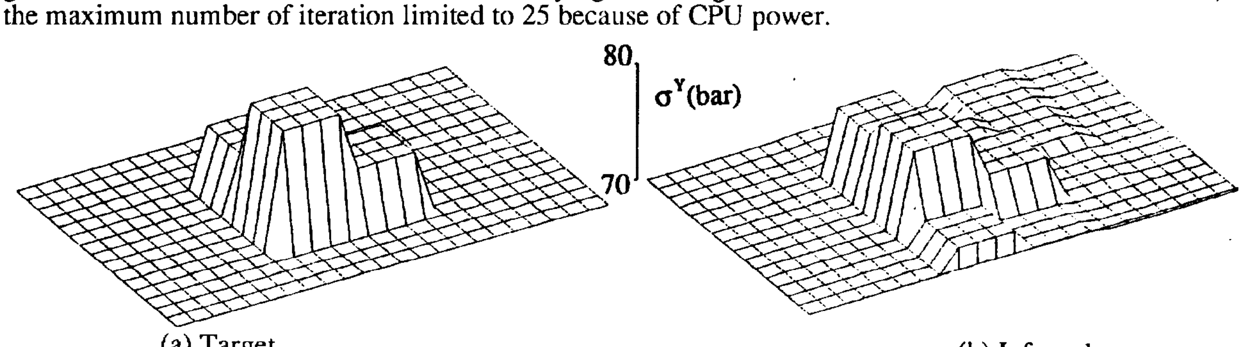
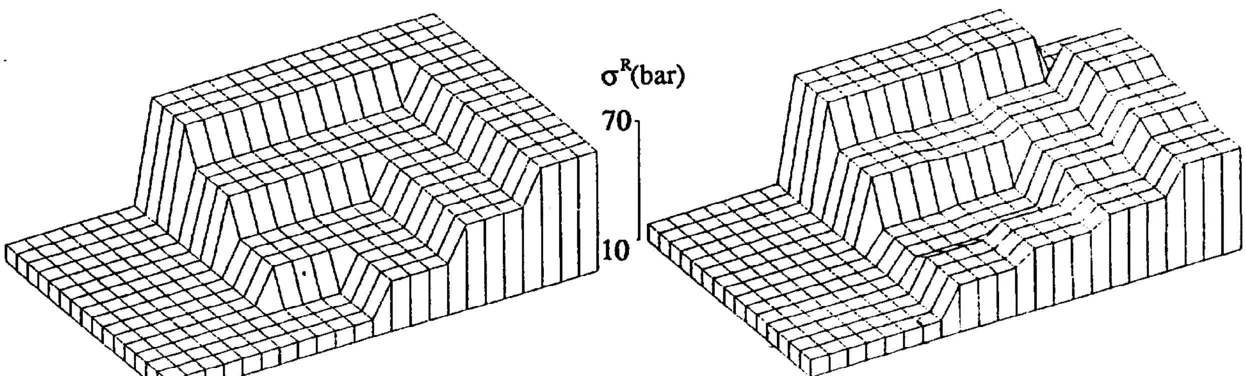


Fig.10 Distribution of strength (Case 1).

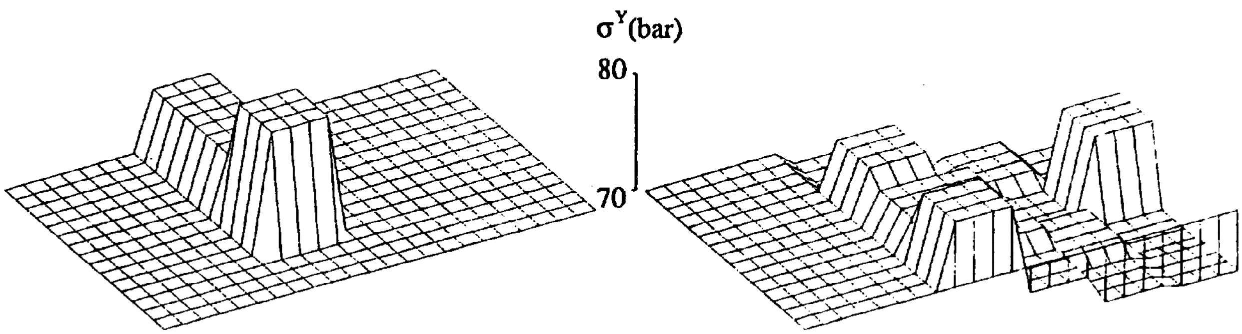
The resulted distribution of strength σ^Y on the fault is shown in Fig.10(b) to compare with the target shown in Fig.10(a). Although the position of barrier is obtained correctly, the magnitude of strength at the barrier are evaluated slightly smaller than that of the assumed one.

Case 2 is for checking whether the inversion analysis can infer the distribution of asperity on the fault. The assumed distribution of residual stress σ^R is shown in Fig.11(a). The result of inversion analysis is shown in Fig.11(b). Although the inferred magnitude of σ^R is smaller than that of the assumed one in the opposite region of the origin, the difference is not significant in the region near the origin. The result of the inversion analysis is acceptable



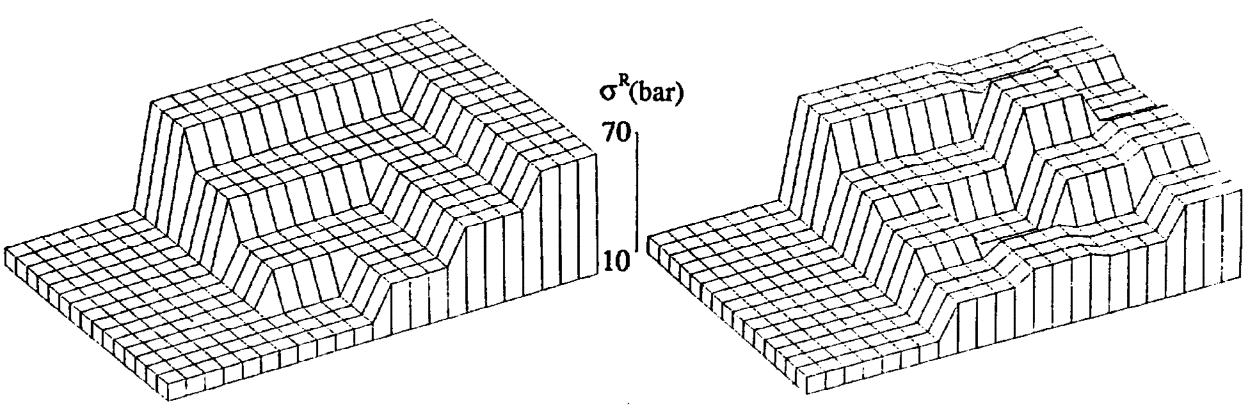
(a) Target (b) Inferred

Fig.11 Distribution of residual stress (Case 2).



(a) Target (b) Inferred

Fig.12 Distribution of strength (Case 3).



(a) Target (b) Inferred

Fig.13 Distribution of residual stress (Case 3).

Case 3 is prepared to know whether the inversion analysis can detect both the asperity and the barrier on the fault. Increasing strength and increasing residual stress have similar effect for making rupture slow. Consequently, it is not easy to separate the barrier and asperity from the waveform inversion analysis. The assumed and inferred distribution of strength σ^Y is shown in Fig.12, and those of residual stress σ^R in Fig.13. The result of inference of residual stress is acceptable but the result for the strength is not so good as that of Case 1. However, general tendency of the stresses is acceptable.

CONCLUSION

(1) Superposition technique can decrease drastically the number of calculation of the dynamic rupture model.
(2) Proposed method using superposition technique can enable inversion analysis using the dynamic rupture model.
(3) Numerical experiments indicate the possibility of inversion analysis using the dynamic rupture model based on the observed ground motion.
(4) Inversion analysis using the dynamic rupture model can estimate each effect of barrier and asperity.

REFERENCES

Irikura, K. (1988). Prediction of Strong Acceleration Motions Using Empirical Green's Function, *Proc. 7th Japan Earthq. Eng. Symp.*, Tokyo, 151-156.

Miyatake,T. (1980). Numerical Simulations of Earthquake Source Process by a Three-Dimensional Crack Model. Part I. Rupture Process: *J. Phys. Earth*, 28, 565-598.

Miyatake, T., T.Mikumo and N.Mikami (1991). Dynamic Fault Rupture Process Recovered From the Results of Waveform Inversion, *Abstracts of Seismological Society of Japan*, No.2, 119-121 (in Japanese).

Toki, K. and S.Sawada (1988). Simulation of the Fault Rupture Process and Near Field Ground Motion by the Three-Dimensional Finite Element Method, *Proceedings of Ninth World Conference on Earthquake Engineering*, II, 751-756.