FINITE ELEMENT ANALYSIS
FOR GROUND MOTION OF 1976 TANGSHAN EARTHQUAKE

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SUMMARY

Numerical results obtained by using both the annual geodetic deformations as the ground surface constraints and the elastic constraint for other boundaries, show that the quasi-static stresses at the seismogenetic fault tip is built up more rapidly than that of other faults due to the speedup of the aseismic creep in and surrounding the seismogenetic fault. Once the stress level of the fault tip element reaches the rupture criterion, a dynamic finite element analysis is then carried out by reversing the shear stress of the ruptured element as the driving force and using the transmitting boundary condition to eliminate the reflection at the fictitious boundaries, no matter how the ground motion diminishes with the distance, both the rupture velocity and the local site effects, such as the thickness of deposits and the dynamically induced movement of each individual fault, are the most influential factors. The fault slipping processes and the stress-drop along the reactivated fault slipping processes and the stress-drop along the reactivated fault segment are not uniform, but depend on the localized normal stress acting on the segment and independend of earthquake magnitude.

INTRODUCTION

Recent progress in computer-simulation has significantly changed the methodology structure of seismology, unlike the early days, analytical procedures have been a principal method for research in seismology. Nowadays, we can construct a fairly realistic seismic model working numerically under plausible condition.

In predicting strong ground motion, 2- and 3-dimensional crustal model are required. Dynamic finite element models of fault rupture have been used (Ref. 12). Studies of farfield problems have enabled us to determine source parameters from remote station recording and more direct information on fault movement can be obtained if reliable observations are made in the vicinity of a fault origin, but this is not always possible. Calculating the near-field displacement instead of assigning arbitrarily a dislocation on fault segments and the fault depth discounting the weak superfield layer seismic effects in the fault vicinity are mainly responses to the motion of the nearest portion of the fault, and are due not to the whole fault surface. The ground motion is due mainly to faulting in the upper few kilometers.

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Since the stress state in the earth is believed to be the cause of an earthquake, it is desirable to know its space and time distribution accurately for the purpose of earthquake prediction. There are several approaches to estimating stress in a seismic region. One of these is to measure the deformation of the earth's surface to give the secular change in strain, which may be related to stress change. Geodetic data might be inverted to estimate the stress and strain near the active fault by using finite element method. The elastic rebound theory does not broach the original cause of earthquake, which lies in the source of the slow movements accumulating the elastic energy, but merely gives the mode of accumulation and liberation of earthquake energy. To obtain whole faulting process during earthquake, it is neccessary to use other more complex models, for instance, earthquake models (Ref. 9) proposed by seismologist are kinematic one, where slip theory on the fault is specified arbitrarily; and dynamic models, where slip is obtained from the solution of an appropriate stress relaxation problem. Kinematic models may be used in problem where the scales (wave length) of interest are longer than some characteristic dimension of the fault. In order to study the stress drop, the high frequency radiation, the physical processes at the rupture front and the strength, it is neccessary to use dynamic source models. It is clear that earthquake studies are shifting from geometrical or kinematic source models to mechanical and dynamic models (Ref. 8).

In numerical modelling of wave and transient dynamic problem, we have to replace the infinite boundary by finite distance. It is insufficient to prescribe zero displacement (or velocity) condition at large distance as done in static problems. It will raise up a serious problem of reflections at these boundaries. The usual practice is to place them as far as possible away from the structure if it is economically feasible. To solve this problem, some scholars put forward other boundary conditions to cancel the reflection. It is nature to introduce an artificial boundary which allows wave to pass through it without reflection and permit solution of the problem in a much smaller region. A simple viscous boundary will absorb body waves almost perfectly. However, surface waves required a special treatment with dashpot strengh varying with depth. This technique works satisfactorily for some problems of harmonic excitation but not for pulse loading and inability to handle high frequencies. Lysmer et al (Ref. 7) also aims at creating finite elements at a boundary which matches the impedance of the solid for a given frequency of disturbance, considering chiefly the horizontal propagation of waves across a vertical transmitting boundary. Robinson (Ref. 11) describe transmitting boundary for one dimension case. Arockiasamy (Ref. 1) incorparates viscous boundaries for including 3-dimensional effects and transimitting boundaries to minimize the required number of finite elements. Zienkiewiez et al. (Ref. 13) show a radiation boundary to assure that only outgoing waves are present so as to radiate all energy outwards. Haupt (Ref. 4) assigns macro-element and uses interaction-matrix to avoid using large amount of nodel point in complex inhomogeneous problems. Nelson (Ref. 10) points out that the results of transmitting boundary is very close to the analytic solution for a problem involving explosive loading. Recently, Cohen (Ref. 3) suggests extended-paraxial boundary for cancelling wave reflections.

On the other hand, an external inertial force acting outward at the boundary with same direction to internal force coming to it is able to cancel the reflections. If we add an unknown boundary force which is proportional to itself the unknown boundary displacement, it behaves therefore as an external stiffness attached normally to the element, to allow the coming wave to transmit outwards. Dynamic calculation for stress distribution and ground motion is based on quasi-static analysis (Ref. 6) viscoplastically with the deformation map of 1972-1953 and leveling data of 1975-1972 nearby North China Bay. The laboratory results of Beyerlee (Ref. 2) is considered as a feasible fracture criterion to determine the stress-drop, slipping or stopping.

MODEL ANALYSIS

The central problem of earth science is to determine the structure and the properties of the earth, with which the wave propagation through geological media varies. Based on the data of seismotectonics, seismic monitoring, gravity survey and heat flow measurement, a 4-layer lithospherical profile, 350 km long and 40 km deep crossing northwesterly the North China Bay and consisting of sedimentary, granitic, basaltic layers and uppermost mantle with different thickness (fig. 1). Since the temperature strongly affects parameters and produces density gradients, the crustal temperature distribution computed numerically is used to adjust the rheological and mechanical parameters. Fault zone is made to behave in different means by simply changing the value of shear stiffness several times lower than their surrounding rock.

The fundamental link between rupture velocity, stress and slip has received much attention than in the past, leading eventually to a source model of self generating and propagating rupture which can also stop on its own.

Seismic stress drops due to frictional change along fault plane seem to be cohesive loss and are typically at least an order of magnitudle less than the ambient shear stress driving the faulting and are much smaller than the stress-drop resulting from stress release of fractured element in the front of the fault (Ref. 6).

In static calculation, it is assumed that the energy released along the pre-existing fault due to aseismic creep causes stress transferring to the surrounding rock, especially to the front of fault tip leading to a fracture. But, in dynamic calculation, the mainshock is followed by the rupture of fault plane due to dynamic stress added to the original static case. New rupture creating from fault end will stop at some later time either due to a strong barrier or due to the lack of strain energy.

In general, dynamic finite element equation can be described as following:

$$\underline{M}\ddot{u}_{t+\Delta t} + \underline{C}\dot{u}_{t+\Delta t} + \underline{K}u_{t+\Delta t} = \underline{P}_{t+\Delta t} \qquad (1)$$

where $\underline{M}$ is mass matrix, $\underline{K}$ is stiffness matrix, $\underline{u}$ is displacement matrix, $\underline{P}$ is load matrix, $\dot{\underline{u}}$ is velocity matrix.

To eliminate the reflection at the fictitious boundaries, the transmitting boundary is used which is equivalent to an outward going inertia force normal to these boundaries with equal magnitude and same direction of the internal inertia force coming to them. The boundary condition which causes such an additional "stiffness" is one where transition force occurs. Unknown outward normal inertia is considered as boundary force and is related to the acceleration of the same boundary nodes which can be described as:

$$\underline{T} = \rho(\ddot{u})_n = \int \rho \underline{N}^T \left(\frac{\partial N}{\partial x} n_x + \frac{\partial N}{\partial y} n_y\right) \underline{\ddot{u}}ds = \int \rho \underline{N}^T \underline{Nn} \, ds \, \underline{\ddot{u}} \qquad (2)$$

in which, $\underline{n}$ is outward normal vector, n_x and n_y is direction cosine, $\underline{N}$ is shape function matrix, $(\ddot{u})_n$ is the outward normal acceleration of boundary, $\underline{\ddot{u}}$ is the boundary nodal acceleration, and ρ is mass.

Dynamic equation can be rewritten by combining eq. (2) with eq. (1) as:

$$\underline{M}' \, \underline{\ddot{u}}_{t+\Delta t} + \underline{C} \, \underline{\dot{u}}_{t+\Delta t} + \underline{Ku}_{t+\Delta t} = \underline{P}_{t+\Delta t} \qquad (3)$$

where

$$\underline{M}' = \underline{M} + \underline{M}_s = \sum_m \int \rho \underline{N}^T \underline{N} \, dv + \sum_{m'} \int \rho \underline{N}^T \underline{N} \, \underline{n} \, ds$$

m' is the number of boundary elements.

Difference between eq. (3) and (1) is that eq. (3) is applicable to the unknown boundary condition, which is useful to handle complex geological problems.

COMPUTATION PROCEDURES

In literature, most researchers assume the crack tip moving a given velocity or displacement, accually it is unknown. In this paper, the initial motion is determined by using the static stress state of the element in the front of fault and an appropriate fracture criterion.

(1) at t = 0, assuming that the stress of the element in the front of the fault reaches its peak value and releasing its shear stress with reversing sense as the driving force to calculate the dynamic stress and

ground motion by using eq. (3). It is neccessary to use a suitable factor less than unity in order to make the tentative driving force be only a portion of the stored elastic energy and to match the measured ground motion.

(2) friction force f along the fault segments at any time interval is obtained by adding the calculation dynamic normal stress to the initial static ones to induce a tangential traction across the plane.

If the shear stress τ equals to or greater than f, slip starts; if $\tau < f$, slipping segments will stop.

(3) repeat step (1) and (2) until $\Delta t = t$ (t is assigned calculation time period).

(4) compare calculation results with the estimated strong motion data and adjust stress drop factor until calculated results are satisfied.

(5) during coseismic period, calculating the maximum stress drop on the pre-existing fault surface and the newly developed fracture plane as well as the total energy released.

RESULTS AND DISCUSSION

(1) Ground motion during earthquake is related to the slipping velocity of fault segments, the frictional coefficients of contact surface and the initial static stress before mainshock.

Fig. (2) shows ground motion function varying with slipping velocity, because the slipping velocity is proportional to the released elastic stress which is in turn related to the ground motion. It indicates that no matter how the ground motion diminishes with the distance, both the slipping velocity and local site effects, such as the thickness of deposits and the dynamically induced movement of each individual faults, are the most influential factor.

(2) Fig. (3A) is obtained without consideration of the other faults reactivated during seismic faulting and shows the normal intensity change with epicentral distance. But Fig. (3B) describes the abnormal intensity, not decreasing with epicentral distance. It is supposed that an important cause of abnormal intensity may come from the induced motions of other reactivated faults.

(3) non-uniform fault slipping processes and the stress-drop have been obtained basing on the elasto-viscoplastic calculation (Fig. 4). Clearly, non-uniform slipping and stress drop characteristics are caused by initial static stress distribution and they describe similar visco-slipping process as obtained in laboratory (Ref. 5).

From above results, we suggest that: Faults are often very heterogeneous,this is reflected in random ground motion. Stress state along faults may be highly non-uniform, both in time and space.

A source model containing a fault plane with unbroken barriers or with fault tips to simulate major earthquakes must have the distinguishing between tectonic stress and self stress due to irregular slip function along fault plane. The stress drops to a low value on the aseismic slipping segment, but may be elevated considerably near the unbroken barriers to cause large shocks. The tectonic stress in the fault zone drops only a small amount and is diminished by healing and stress relaxation.

Accelerated fault slip before earthquakes may cause observable precursory deformation fields. A key problem is the condition for rupture initiation. We have the capacity of numerically solving the direct problem, but there are many uncertainties in specifying the initial stress, kinematic friction, final stress and rupture energy distribution on the fault plane. They have large fluctuations in space and are largely unknown.

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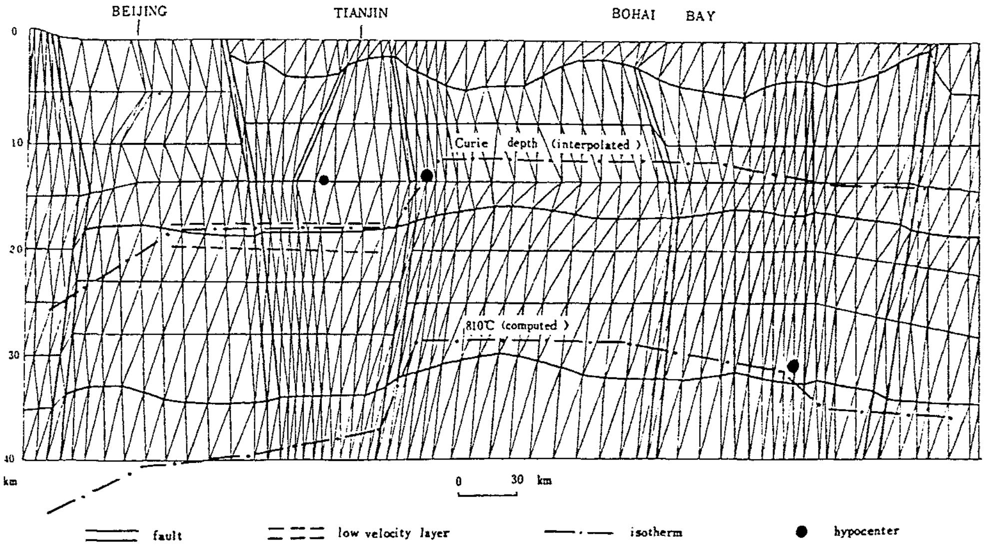
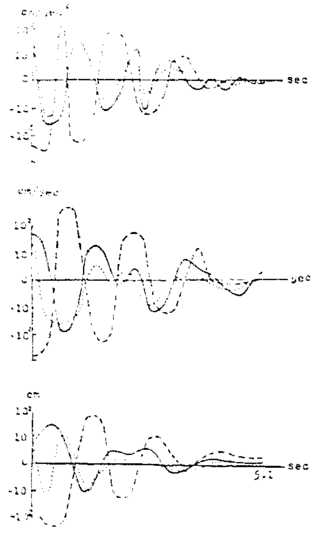


FIG. 1 FINITE ELEMENT MESHES OF A PROFILE CROSSING BOHAI BAY AREA NORTHWESTERLY



----- TRANSIENT SLIPPING OF EARTHQUAKE FAULTING PLANE
..... SLIPPING VELOCITY OF INDIVIDUAL SEGMENTS

FIG. 2 GROUND MOTION AT DIFFERENT SLIPPING VELOCITY

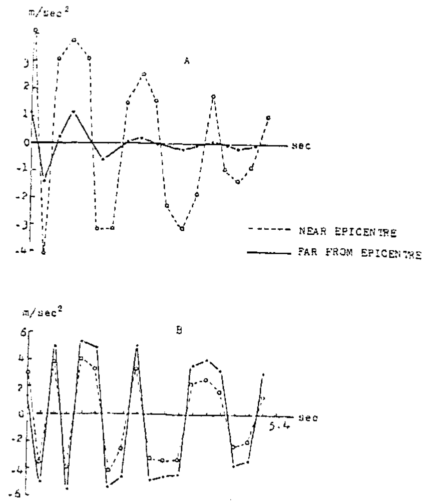
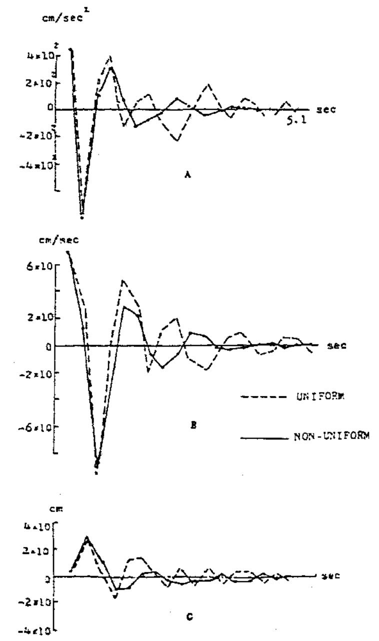
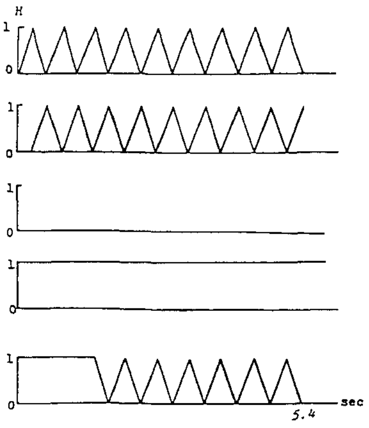


FIG. 3 GROUND MOTION WITH (B) OR WITHOUT (A) CONSIDERATION OF OTHER INDUCED FAULT MOVEMENT





D -SLIPPING PATTERNS

H 1 MEANS FAULT SEGMENTS MOTIVATED
H 0 MEANS FAULT SEGMENTS LOCKED

FIG. 4 GROUND MOTION DUE TO DIFFERENT PROCESSES AND PATTERNS OF FAULT SLIPPING SEGMENTS