Earthquake mechanism and its effect on ground motion and wave propagation

——with some comments on fundamental concepts

地震机制及其对地运动和波传播的影响

——兼对若干基本概念的讨论

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Abstract A tentative analysis of the mechanism of mantle circulation flow, continent drifting and earthquake origin is first clearly made, giving a simple mechanics- based explanation of the nature. Then the effects of earthquake mechanism on ground motion and wave propagation are delineated in a simple manner by accounting for the different types of earthquake source, break propagation, as well as the variations of rock property. It is shown on the basis of principles of mechanics that at least two physical parameters characterizing the seismic intensity must be specified because at the earthquake source two parameters, the stress jump and the velocity jump of particle motion, should act simultaneously whenever a sudden break occurs according to the discontinuous (jump) wave theory. While it is shown that the break propagation speed C_b together with the break plane area may be the third key parameter influencing definitely the time form of unloading function at the source. Since the fault break is an unloading process in the sense of mechanics and the break lead to stress jump and velocity jump so some concepts so far defined seem not exact or even of misunderstanding. Thus some comments on a number of basic concept in engineering seismology and earthquake engineering are made tentatively, aiming at arising an academic discussion.

Key words wave propagation, break propagation, source mechanism, ground motion, unloading wave, jump wave

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文 摘 首先对地幔对流、大陆漂移和地震起源的机制做了尝试性分析,给出一个简单的力学解释。然后,考虑不同的震源类型,破裂传播以及岩体性质,探讨了震源机制对地面运动和波传播的影响。根据间断(阶跃)波理论阐明了至少应该有两个物理参量才能表征地震烈度,因为在震源处同时有应力阶跃和质点速度阶跃发生。也阐明了断层的破裂速度连同断层面积一起应是第三个重要影响参量,因为它对震源处卸载的时间函数的形式有决定性的影响。由于断层破裂是一个瞬间卸载过程,并引起应力和速度阶跃,而现行惯用的一些概念均未考虑到这一点,所以笔者对工程地震和地震工程中若干概念提出了一些看法,意在引起学术界讨论。

关键词 波传播, 破裂传播, 震源机制, 地运动, 卸载波, 阶跃波
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1 Introduction

Up to the present, earthquake engineering and engineering seismology as two separate branches of science have made lots of remarkable progress and contributions. However, since earthquake is such a tremendously complex phenomenon that only occasionally occurs in the deep ground of the secret Earth, of which mankind's knowledge is far from sufficient yet, by unknown driving forces at unpredictable time, so almost all of the theories, hypotheses and methods etc, developed so far were, strictly speaking, come from indirect deduction approaches without direct verification. Some model tests made cannot match with the original large complicated earth's real conditions and the seismic observation data can represent only some indirect features of each particular event while post earthquake field investigations can only obtain some surface damage data whose interpretation, however, cannot be unique. Therefore we have to recognize that a number of definitions, such as magnitude, intensity and attenuation law etc, are only approximate with an unknown yet order of error. In other words, there are many respects needing refinement and innovative effort to contribute although we know our shortage of enough wisdom at present stage whereas what we can do our best would be based on the principles of modern sciences as widely as we learned.

In this paper we try to discuss some aspects of the effect of earthquake mechanism on ground motion and wave propagation and to present some comments aiming to evoke a new interest of investigation and to promote this science going further, based mainly on the principles of modern mechanics especially the discontinuous wave theory and some physical insight, by means of simplified reasoning, without the use of complicated mathematics and detailed computations.

2 Effect of mechanism of earthquake source

It is evident that the mechanism of earthquake source must have prime influence on ground motion and on human lives and property losses as well as building damages though they are a long distance apart, and should play a vital role to cause the response of upper earth strata, including surface soil layers.

2.1 Simplified reasoning of a source mechanism mode and the driving origin

Regarding the original actions that make earthquakes possible, so far nobody can say exactly that he has under

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– stood the truth already firmly, although there were many hypotheses such as continent drifting, plate movement, etc. But for the shallow focus earthquake, the fault break mechanism was most accepted from mankind's knowledge today. We believe that the driving action should be the motion of plate blocks rather than any given but randomly raised forces. The plate motions may be similar to those ice blocks drifting on river or sea surface in springtime and they compress and even collide or impact each other. Not definite kinds of force exist between the blocks except those induced by river flow (while for plate blocks maybe melt lava flow) and the blocks themselves. However, only when such forces or their combinations reach certain value of limit, i. e. the strength of material of the plate block, a fault break can occur.

In order to understand the possible origin of driving forces between the plate blocks, we present herein a new interpretation that may be regarded as a refinement to the hypotheses of plate motion and mantle circulation.

Regardless what was really the reason for the separation of the original continent into six main plates and each one then into many subplates again as well as why and how the mantle lava circulates, we deal with now two adjacent ones, as an illustrated example, to see how the forces happen between two blocks.

As shown in Fig. 1, two plate blocks (abbrev. as PB in the following) A and B drift on the earth mantle under circulation flow. The soft lava in mantle may be regarded as a viscoelastic liquid, such as Maxwell material whose viscosity may be dependent somehow on pressure and temperature. To simplify, here we consider only the effect of pressure. According to the viscoelastic theory, a laminar flow of such lava will induce shear stresses on base surface of PB, which are directly proportional to the flow velocity gradient (see e. g. Men, 1985)[1]. From geology and geography we know that PB– A and PB– B are uneven with quite large height and depth variation. Suppose PB – A (e. g. Euro – Asia Plate) contains large mountains and highlands above sea level (e. g. 4~ 6 km in average) and deep lower crust boundary (e. g. 30~ 40 km), shortly represented by large weight/ area ratio W_1/F_1, while PB– B (e. g. Pacific Ocean Plate) contains subsea thinner crust with small weight/ area ratio W_2/F_2, which means also the normal vertical stress on the base surface.

According to the direction of mantle circulation flow three cases may be encountered as follows.

Case 1. Mantle flow in same direction. Because depth h_1 is smaller than h_2 and from the continuity condition of flow discharge,

$$v_1 h_1 = v_2 h_2$$

we may obtain that v_1 is slightly larger than v_2. The pushing forces acted on the plate base surface T_1 and T_2 equal $\eta_1 F_1 \mathrm{d}v_1/\mathrm{d}z$ and $\eta_2 F_2 \mathrm{d}v_2/\mathrm{d}z$, respectively, when no slip occurrence between the plate base and the top of mantle; or fW_1 and fW_2, respectively, when slip occurrence, where η_1 and η_2 are viscosity of mantles; f is friction coefficient.

Since $\eta_1 >$ or $= \eta_2$, $W_1/F_1 > W_2/F_2$, so $T_1 > T_2$ and a total pushing force $T = T_1 - T_2$ is resulted, which means that PB– A pushes PB– B to move further along the same direction as the mantle flow, and may induces some small to medium earthquakes.

Case 2. Mantle flow in opposite direction. As shown in Fig. 2 the flow direction is opposite, namely, the flow towards right. In this case T_1 and T_2 will be also in opposite direction. The total pushing force $T = T_1 - T_2$ now is towards right. So PB– A does not tend to push PB– B again, but will separate gradually from contact with PB– B. This fact may explain why some continents (e. g. South America And Africa) situated together in ancient time have drifted long distant apart like today's.

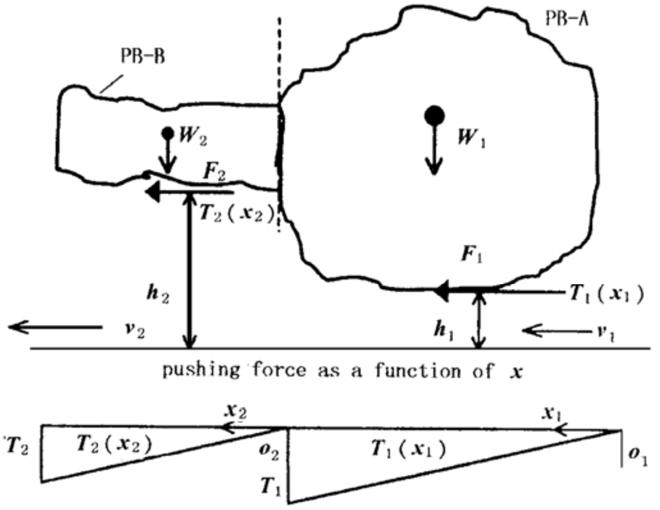

Fig. 1 Case 1

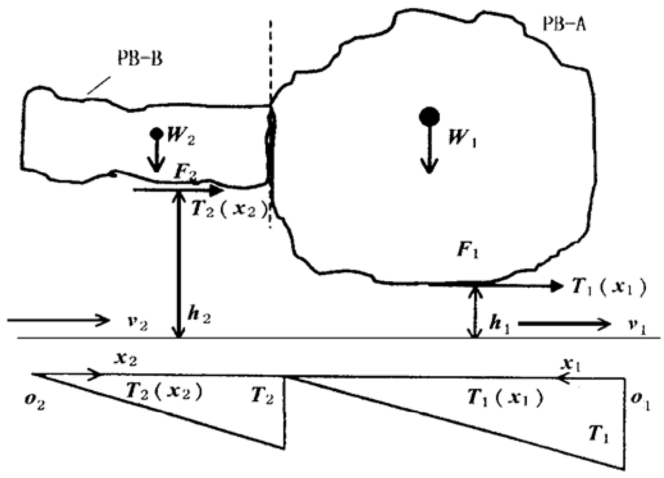

Fig. 2 Case 2

Case 3. Mantle flow in counter opposite direction. As shown in Fig. 3, if the flow directions under PB– A and PB– B are counter opposite as the modern hypothesis of mantle circulation supposed where the encountering position between Ocean Plate and Continent Plate just is the meeting position of the two mantle flow of counter opposite direction. In this case, T_1 and T_2 are also in opposite direction and the total pushing force, $T = T_1 +$

T_2 makes PB－ A and PB－ B compress and/ or collide more intensively, and thus may induce some earthquakes of large magnitude. Because among these three cases, at the contact location of two plates case 3 subjected the largest $T = T_1 + T_2$, whereas case 1 subjected only T_1.

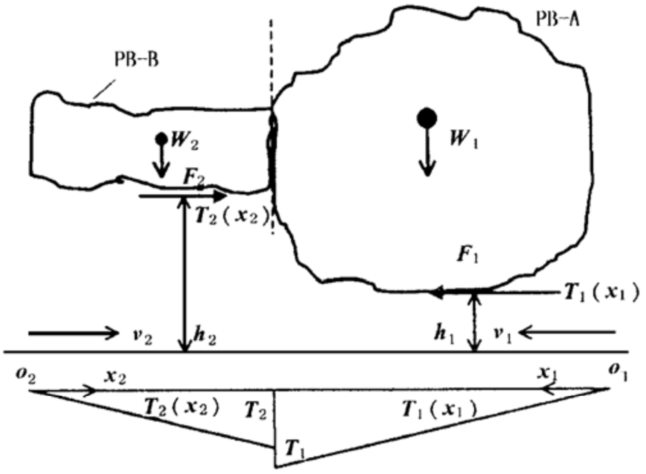

Fig. 3 Case 3

It must be pointed out that the pushing forces, equal shear stress times base area, is a function of the horizontal coordinate, x, of the point to be considered, as indicated in Figs. 1～ 2. From these function we may explain why earthquakes often occur in the meeting belt of two Plates. For example, in Fig. 1 only at point o_2 the pushing force is maximum, T_1, while at point x_2, $T = T_1 - T_2(x_2)$. A similar result may be find in Fig. 3.

Therefore, the analyses made above may satisfactorily explain the mechanism of continent drifting, plate motion and earthquakes origin, in principle. Considering the mutual interaction of many plates and the fact that within the spherical Earth the mantle flow direction and velocity, etc. may be not of same pattern, so the real situation will be more complicated but we believe that the above reasoning based on modern principle of mechanics gives a deeper understanding of the nature.

Of course, it can be estimated that except those forces caused by mantle circulation flow there may be other factors, which can cause not balance of forces among the plate's blocks. To the authors knowledge, they maybe, for instance,

a) Thermal stresses. Since the temperature and its variation in the underground of different plates should be different so thermal stresses have to be a major problem although so far we are still ignorant about its actual status.

b) Position of gravity centers which influences the tangential velocity and acceleration to Earth surface, and the horizontal forces of each plate. Those plates with large W and higher position of gravity centers will subject larger total force.

c) Other irregular agitation and disturbance coming from the mighty secret universe and/ or deep earth's interior.

In summary, from the above statements the origin of interplate earthquake may be understandable more clearly. For intraplate earthquake we must consider yet the interaction of multi-plates and the possible distinctive tectonic-structure, discontinuous and nonhomogeneous of earth materials and stress concentrations, etc.

In this paper we adopt, so far, the most believable mode of focus mechanism, i. e. fault break caused by plate motion for earthquakes of shallow focus, to make discussion. It means that the driving action is the mutual compression and/ or collision and impact between the plate blocks and the focus is a fault break due to the resulting forces (stresses) exceeded the strength of the plate rocks there. Note here the forces (stresses), not the motion, play decisive roles. As we will clarify in what follows, the stress conditions at the fault plane should differ somehow from those understood previously and thus we have some new understanding and make some comments on fundamental concepts currently used in Earthquake Engineering and Engineering Seismology, based on simplified reasoning.

2.2 Stress and break conditions at source

As shown in Fig. 4 there maybe two types of fault break caused by plate pushing motion, one being caused directly by compression and another by shearing. The stress systems of them will be different somehow. For the plane fault break source mode, caused by compression forces we can see that once upon these forces equal the shear strength of the rock in some weaker cross section of the stratum a sudden break occurs (like the brittle fracture of rock specimen under compression) and a fault plane is formed. At the same time instant the shear stress at the break plane suddenly becomes zero, which is likely that a negative shear stress pulse applies on the fault plane instantaneously, and then recoveries a rest state due to a readjust of whole motion and force system acted around the source area, while on the part of fault plane that slipped out the normal stress becomes zero, which is equivalent to applying a negative normal (here i. e. tensile) stress on it.

So from the principles of Mechanics and the background clarified above, we can clearly write out the boundary condition and initial condition, which must be specified at first to solve a concrete problem and obtain its unique complete solution; However, the complete boundary conditions cannot be specified exactly except those on fault plane, which constitute the wave source. From viewpoint of Mechanics, the tectonic processes in the Earth are very slow, maybe ranging in 10^{-13} to 10^{-16} strain per second (Li 1977)[2] and at the source area of earthquake, either collision and subduction zones of interplate motion, or elastic rebound zones of intraplate motion, a suddenly intensive break occurrence must imply that the excessive stress, equal to the rock strength on the fault plane, is the main cause but not the displacement which must slowly develop before the break is started. At the time instant starting fault break of a fault plane, caused by shear action for example, the stress system should be as shown in Fig. 4, negative shear stress pulse, equal to the shear strength, acting on the whole break plane, and negative compression (i. e. tension) stress, equal to the compression stress at the break plane just before the break, acting on part of whole break plane, which slipped out and went free from contact as the fault slip performed. These equivalent stress systems cause a wave source in the sense of mechanics, not including thermal, electro-magnetic action, if any. In company with this, unloading waves will propagate away to long distance along different directions with different peak value and spectra.

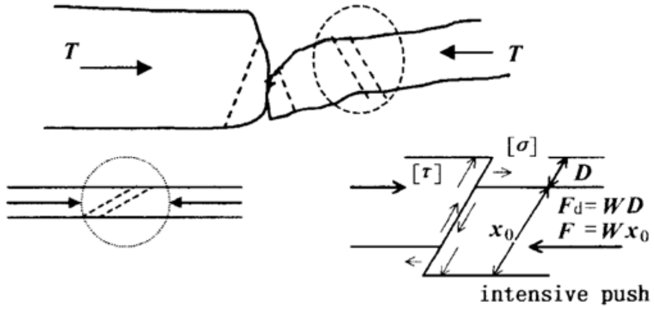

Fig. 4 Two types of fault break

Thus the initial condition may be of the form:

$$\left.\begin{aligned} &\sigma_r = \sigma_{st} (t = 0) \\ &\vec{u_r} = \vec{u}_{st} \approx 0 (t = 0), \dot{\vec{u_r}} = 0 (t = 0) \quad \text{for } r > 0 \end{aligned}\right| \quad (1)$$

while the boundary condition will be

$$\left.\begin{aligned} &[\sigma] = -\sigma_{st} U(t)\delta(r) && \text{on} \quad F_d \\ &[\tau] = -\tau_{sd}\delta(t) && \text{on} \quad F \\ &[v_p] = -[\sigma]/(\rho C_p) && \text{on} \quad F_d \\ &[v_s] = -[\tau]/(\rho C_s) && \text{on} \quad F \end{aligned}\right| \quad (2)$$

for an instantaneously occurred break surface, Fig. 5, and

$$\left.\begin{aligned} &[\sigma] = -\sigma_{st} U(C_b t)\delta(r - C_b t) && \text{on} \quad F_d \\ &[\tau] = -[\tau_{sd}]\delta(C_b t)\delta(r - C_b t) && \text{on} \quad F \\ &[v_p] = -[\sigma]/(\rho C_p) && \text{on} \quad F_d \\ &[v_s] = -[\tau]/(\rho C_s) && \text{on} \quad F \end{aligned}\right| \quad (3)$$

for a break surface performing with the speed of break propagation C_b, strictly speaking not a constant but varied with the break length in general, where $U(t)$ = Heaviside unit function or unit jump function.

Why these two coupled stress boundary conditions occur will be explained below.

It must be noted that at instant $t = 0$ the stress drop, being a strongly discontinuous (jump) unloading stress, must induce a jump of velocity for the boundary at the same time according to the theory of jump wave, which has been studied broadly in Physics and Magnetohydrodynamics (Jeffrey, 1964)[3] and for elastic wave we may obtain for the one-dimensional compression problem a relation as

$$[v] = -[\sigma]/(\rho C_p) \quad (4)$$

When the rocks of the source area are saturated with water or fluid the problem will be more complicated for the quake source mechanism. As in some previous papers (Men 1984, Men et al 1992)[4,5] we proved for a rock model of interconnected channel pores there may be four jump variables when $C_p > C_w$ and two jump variables when $C_p < C_w$. Omitting the detailed derivation we list only the final results in what follows for a given jump of normal stress in rock skeleton at boundary $[\sigma_z]$:

$$[\sigma_z] = -\frac{E}{C_p}[u_t], [u_t] = -\frac{n}{1-n}[U_t] - \frac{C_p}{(1-n)E_w}[\sigma_w]$$

$$[U_t] = -\frac{1}{C_p\rho_2}[\sigma_w] \quad (5)$$

for $C_p > C_w$.

For a center-symmetrical case of point source we can get a similar solution of the jump relationships even for visco-elasto-plastic materials (Perzyna, 1959)[6]. The main one is

$$[v_r] = -[\sigma_r]/\rho C \quad (6)$$

where σ_{st} – initial stress before earthquake, which may be equal to the long-term static tectonic plus self weight stresses for the far field, and may be approximately replaced by $2\tau_{sd}$ at focus and near field; $\tau_s = \tau_{sd}$ = shear strength; [ ] = symbol denoting a jump value; C_p = dilatational wave velocity of source rock; C_w = dilatational wave velocity of pore water; v = velocity of point at the break plane; ρ = material density of the rock; u = displacement of rock; $u_t = v$; U = displacement of pore water; U_t = velocity of pore water; σ_w = pore water pressure; $\delta( )$ – Dirac delta function; n = porosity of rock; C_s = shear wave velocity.

It must be pointed out here that we showed the jump relations among the discontinuous waves only for the one-dimensional condition, including also the spherically symmetrical condition, since those for multi-dimensional condition, which would be just the case for the line or plane source, will be not easy to treat by using the characteristics method. However, we can reasonably use the above relations as a first approximation in considering the reason stated later in 3.1.

2.3 Causes of fault break and their consequence

It would be evident that the real break details of the shock-generated fault plane including the original type of straining, orientation, break length and area, speed of break propagation, etc. must definitely affect the details of ground motion and wave propagation.

From the viewpoint of solid mechanics it may be concluded that the types of straining or stress causing fault planes to occur would be compression-tension, bending or folding, shearing, torsion, and any of their combinations such as tension-torsion, compression-bending etc. As the measurement data of in-situ underground rock stresses indicated the horizontal rock pressure is multi-times of the vertical one. And pushing forces caused by mantle flow would be the essential origin, as clarified in subsection 2.1. So we believe with confidence that the movement and break of ground strata would be caused mainly by the horizontal straining and stressing. Therefore, those compression-tension and shearing types would be dominant for the common earthquakes. Since rock masses always possess very small tensile strength so the break due to tension would be very seldom, if not impossible, and shear breaks must prevail even under compression because of small shear strength of rocks.

2.4 Effect of source break on wave propagation and ground motion

Since a slow mantle flow will be inducing strain and stress at certain coming source area and thus generates internal force with time, whenever this force is beyond some limit of the rock strength a break plane may be started to form (instantaneously or at a speed of break propagation). At the same time as the break made the stresses at the break plane drop to zero or other small value, as usually called as residual strength, so unloading waves will also start to propagate away from this plane. As is well known, earth materials are of the property that the stress-strain relations are different for loading and unloading stages. Therefore the speed of wave propagation from the break source follows the speed of elastic waves because the unloading stress-strain relation may be regarded as elastic for many rocks; thus the unloading waves follow nearly the theory of elastic wave. This must be why the elastic wave theory basically validates in seismology dealing with earthquake-induced wave problems. However, a complicated situation deviating from purely elastic phenomena may be also caused by some source break of complicated mechanism, affected by other conditions. Meanwhile, during the sudden break a release of the accumulated energy was accomplished and therefore a strong motion must be accompanied to the stress drop, doing the work of ascertain quantity following the principle of energy conservancy. Because the stress drop is a jump pulse so the velocity pulse is also a jump. We have derived the relation, which also validates for shear, as follows,

$$[v_s] = -[\tau]/\rho C_s \qquad (7)$$

on the basis of the theory of discontinuous wave, by the characteristics method.

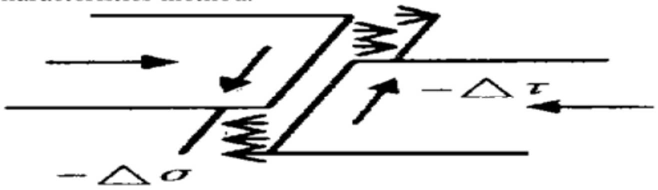

Fig. 5　Coupled unloading normal stress when shear fault moves

It may be noted therefore that two types of impulse excitation occur initially at $t = 0$ and at the break plane of the quake source and at the same time instant induce two types of wave propagation from there, one being a unloading stress wave and following the elastic wave theory while the other, a velocity wave which maybe a loading-unloading wave or a loading wave, dependent on the magnitude and the criterion of yield velocity which so far we are of no sufficient knowledge of them, or in other words the velocity wave may be elastic or inelastic in accordance with how high its value is beyond the yield limit or not. This value, in turn, relates indirectly to the value of stress jump as given in the above equation. There may be two possible situations, namely

(1) $[v]$ does not exceed the yield value of the rock and/or the movement does not resist by other neighboring strata so that one unloading stress wave and the other loading velocity wave are originally emitted from the source with elastic wave speed for the former and almost elastic wave speed for the latter.

(2) $[v]$ exceeds the yield value of the rock or resists by neighboring strata so that one unloading stress wave and one elastic-plastic loading velocity wave are there with a varying elastic-plastic wave speed for the latter and consequently cause a more complex wave pattern both in nearfield and farfield.

Pursuant to the equations 4~ 7 the stress drop really plays a major role at the source while the rock property responding velocity imput is also a factor of considerable influence, deciding what type the source and its action will be. For ideal perfect elastic materials the stress wave and the velocity wave shall have indeed same phase and form with only different peak value. However, since rocks are not really perfect elastic even when the unloading stage so that the velocity wave may differ from the stress wave in many cases, particularly whenever fluid-saturated, highly inelastic and plastic media with complicated damping mechanism, etc are available in the wave path, and they should normally be regarded as two independent wave types initially excited at the source and then propagate away therefrom. Therefore, it would be evident that for earthquake engineering problems at least two ground motion parameters instead of only one acceleration for measurement of earthquake intensity should be specified since there are two types of excitations at the quake source as explained above, and as a consequence two independent variables must play part everywhere. Furthermore, in aseismic design of structures we noted that at an interface between subsoil and foundation of building there must be two continuity conditions, i. e. stress and displacement ones. So we must know simultaneously these two variables or their alternatives in soils caused from the quake. As we will discuss later that a third parameter characterizing the source nature may be the speed of break propagation together with the break (fault) area. It must be pointed out that the above statement is valid for dry rock conditions. In contrary, for those rock conditions at the source that fluids exist, making rocks saturated or surrounded with water or other kind of fluid, at least an additional parameter must be specified, which we attempt not state further herein.

In addition, it is reasonable to note that for shear type of break mechanism two companion P waves, one unloading tensile stress wave and one compressional velocity wave would be performed soon after the shear break plane was totally resulted because the shear slip motion must make the originally existed compression stress decrease to some extent, which likely apply a jump tension stress to the break plane and induce a jump velocity at the same time. Naturally, the energy loss of this type may be smaller than that due to the shear break and will depend largely on the slip displacement of the two branches of the broken stratum, see Fig. 5. This might explain why for the quakes of shear type we might also record P waves and the peak value of primary P wave was always smaller than that of S wave in seismic records.

2.5 Effect of break propagation speed on ground motion

To clarify such effect we use a simple but clear-sight manner to make a discussion. For an instantaneous break plane source (i. e. $C_b = \infty$) the boundary conditions would be likely as shown in Fig. 6 where a jump stress, and a jump velocity are applied to the whole plane, $F = x$ h, at the time instant $t = 0$. While the waves start to propagate there to every direction. i. e.,

$$\left.\begin{aligned} \tau &= [\tau] = -\tau_s\delta(t) && \text{on } F \\ v_s &= -[\tau]/(\rho C_s) = \tau_s\delta(t)/(\rho C_s) && \text{on } F \end{aligned}\right| \quad (8)$$

and

$$\left.\begin{aligned} \sigma_p &= -\sigma_{st}U(t) \sim \sigma_{st}\delta(t) - \sigma_{st} && \text{on } F_d \\ v_p &= -\frac{\sigma_p}{\rho C_p} \sim \frac{\sigma_{st}\delta(t)}{\rho C_p} && \text{on } F_d \end{aligned}\right| \quad (9)$$

For a progressive break plane source with break propagation speed, C_b, the boundary conditions would be likely as shown in Fig. 7 where a jump stress drop and the corresponding jump velocity are time functions in $x - t$ plane, i. e.,

$$\left.\begin{aligned} \tau &= -\tau_s\delta(x - C_bt) && \text{on } F \\ v_s &= \tau_s\delta(x - C_bt)/(\rho C_s) && \text{on } F \\ \sigma_b &= -\sigma_{st}U(t)\delta(x - C_bt) && \text{on } F_d \\ v_p &= -\sigma_{st}\delta(C_bt)\delta(x - C_bt)/(\rho C_p) && \text{on } F_d \end{aligned}\right| \quad (10)$$

where $x_0 =$ the length of break plane; $h =$ the height of break plane; $F = hx_0$; and $F_d = hD$.

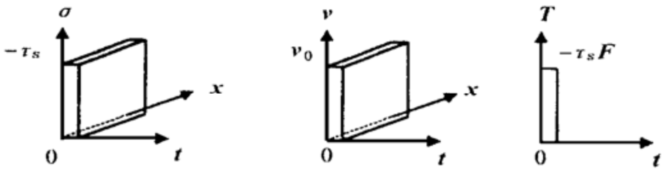

Fig. 6 Jump conditions at source with $C_b = \infty$

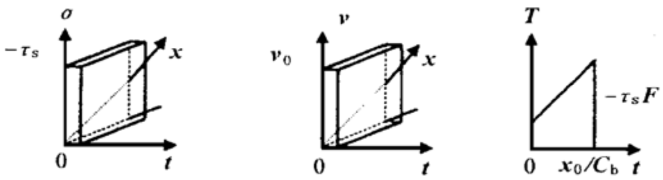

Fig. 7 Jump conditions at source with C_b = constant

Since the straining energy accumulated will release totally or partly through forming the break plane and other types of dissipation such as thermal, and even chemical in certain cases, so the mechanical energy released would be equal to the work done by the force exerted on the break plane and the corresponding displacement of rock point on the plane at $t = 0$. We thus can estimate it approximately as follows:

$$\left.\begin{aligned} W_s &= \int_0^t Tv_s\mathrm{d}t - f\sigma_{st}FD = -\left[\frac{\tau_s^2}{\rho C_s} + f\sigma_{st}D\right]F \\ W_p &= \int_0^t T_pv_p\mathrm{d}t - T_pD\cos\alpha = -\left[\frac{\sigma_{st}^2}{\rho C_p} + \sigma_{st}D\cos\alpha\right]F_d \end{aligned}\right| \quad (11)$$

for $C_b = \infty$; and

$$\left.\begin{aligned} W_s &= \int_0^t Tv_s\mathrm{d}t = -\tau_sF\frac{C_bt}{x_0}v_s - f\sigma_{st}FD\frac{C_bt}{x_0} \\ W_p &= -F_d\left[\frac{\sigma_{st}^2}{\rho C_p} + \sigma_{st}D\cos\alpha\right]\frac{C_bt}{x_0} \end{aligned}\right| \quad (12)$$

if C_b is a constant, with T denoting the total shear force drop on the break plane, i. e. $T = -\tau_sF$, $T_p = -\sigma_{st}F_d$, $f =$ friction coefficient, $D =$ slipped displacement, and $\alpha =$ inclination angel of fault plane.

It can be seen that both W are a time function and vary with C_b for the progressive break plane. Therefore W has the same total magnitude for a specific quake of same $-\tau_s$, F, F_d, C_s and C_b but has different form of time function, which leads consequently to different frequency spectra. Then we may conclude that five parameters, $-\tau_s$, F, F_d, C_s, and C_b would be important for fully characterizing the mechanism of an earthquake. This conclusion is almost coincided with that of Haskell (1964)[7] but a little difference is still existed. We deem that $-\tau_s$ is of primary importance and it may be taken nearly the break strength of rock at the source instead of D, the slip displacement, of Haskell.

It must be pointed out that C_b in reality may be not a constant. From fracture mechanics of metals we can see that

$$C_b = C_r(1 - a_0/a) \quad (13)$$

In which $C_r =$ critical speed of crack propagation, close to Rayleigh wave speed of metals or the less; $a_0 =$ initial length of the crack; $a =$ transient length of the crack at t.

Since up to now the fracture mechanics of rocks is still in its infancy state so we do not know exactly to what extent this relation holds for the rocks. A rather more complex relation maybe expected for rocks due to their complicated properties. We thus could imagine that various $T - t$ relations dependent on various, $C_b - a$, relation may be resulted for rocks as shown in Figs. 8~9 for examples. In conclusion we may see that C_b affects largely the time figure of the total force drop caused by the energy release at the source and determines the original frequency spectrum and duration of the quake at the source, and is thus one of very important parameters specifying the mechanism of quake, for same a magnitude.

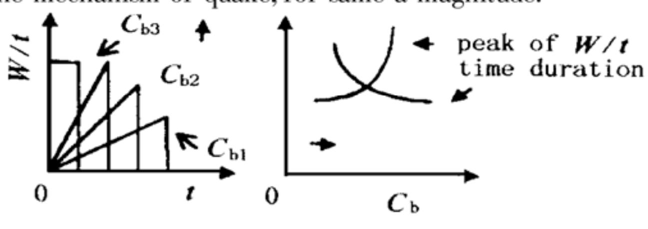

Fig. 8 $W/t - t$ relation and quake duration to C_b

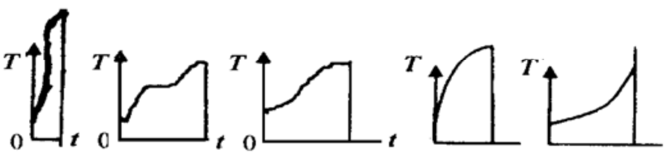

Fig. 9 $T - t$ for variable C_b

3 Wave propagation path

Wave path plays an intermediate role to transmit the shock at focus to the buildings. On the basis of the foregoing sections we may make some further simplified reasoning of this topic. For earthquakes of shallow focus the main types of fracture would be shear slip fault and we thus put emphasis on this type of focus in what follows.

3.1 Correlation between ground motion and source mechanism

Firstly, let us see some features when waves propagate in bedrock. Omitting those commonly known fact such as reflection, refraction, etc., we only want to point out one thing herein i. e. the direction of slip motion of fault plane and the inclination angel of the broken stratum are of importance to decide the status of ground motion. To simplify and limited by space, we take only two simple cases, one dip slip and one strike slip focus in an originally horizontal stratum as examples to show the basic differences. As is well known from geology and rock mechanics, since the large plate blocks are always separated further into sub-blocks by long-term existed tectonic fractures, such as fault, crack, joint planes, etc, and they, usually, can not withstand tensile stress so it is reasonable to take out a certain body of rock rather than a semi-infinite one as follows.

As shown in Fig. 10, a dip slip fault of sufficient length (perpendicular to the plane xz) occurred in a horizontal level rock stratum will make the pair $[\tau]$, $[v_\tau]$ and $[\sigma]$, $[v_\sigma]$ propagate mainly in direction of x. A three component seismometer placed on the rock surface along the symmetric, centric line may obtain (a) horizontal motion due to normal stress jump; and (b) vertical and horizontal motions due to shear stress jump; (c) motions along y axis would be null or almost null for this ideal symmetric example. This case likely induces only an in-plane motion in a near field. In this case the shear waves can also make vertical motion possible, even of great quantity depending on dip angel and break shear stress.

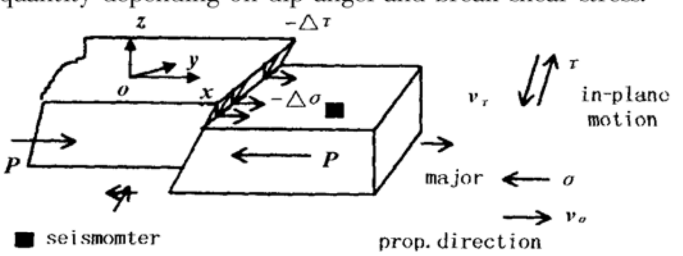

Fig. 10 Dip slip focus and wave motion

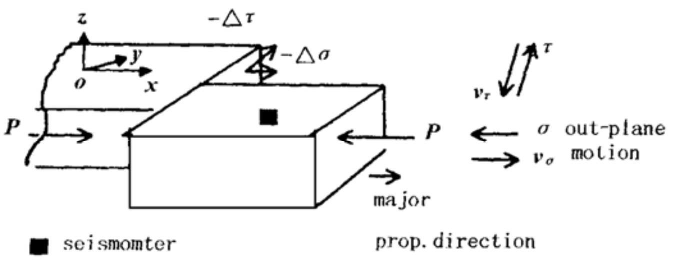

Fig. 11 Strike slip focus and wave motion

Fig. 11 shows a strike slip fault source occurred in a horizontal level rock stratum will cause the pair $[\tau]$, $[v_\tau]$ and $[\sigma]$, $[v_\sigma]$. Only horizontal motion in x direction due to normal stress and horizontal motions in y and x directions can be induced in this case, while no vertical motion occurs on the rock surface.

Generally, a dip slip fault induces SV, P, and smaller SH (only when the stratum has not horizontal plane) wave, while a strike slip one induces SH, P, and a smaller SV (under the same condition mentioned just above) at the source firstly.

For other more irregular stratum configurations, the ground motion will be somehow more complicated. Besides, since the plane source must be limited in size so the geometrical attenuation has come into effect especially in the far field. But a directional effect, e. g. major and minor propagation direction, has to be recognized from the dip angel and strike angel and the inclination angel of the strata, even roughly from the Saint Venant′s Principle in theory of elasticity. The exact expression of geometrical attenuation cannot yet be given here at once. Although there were quite a number of publications giving out formulae of wave motion induced from some typical source, point, single couple, double couple, etc, based on ideal elastic theory, in reality the shallow earth crust is consisted of lots of irregular forms and qualities of lock blocks separated by different fault, joint, and crack planes. It cannot indeed be regarded as part of an elastic semi-space and thus makes those formulae soundless and inaccurate too beyond the source area. In addition, the material damping of bedrock will also play some part but we think that in unloading stage it might be smaller than what in loading stage.

3.2 Two types of soil base excitation

In addition to the very important factor of tectonic force types such as shearing, compression, torsion, and bending or folding etc., which decide what kind of stress and deformation will play the principal part for that particular quake, we divide two types of soil base excitation to define the wave path in soil deposits overlaying the bedrock, taking account of the above statements.

(1) For intra-plate earthquake or other interplate earthquake but with simpler tectonic structure under simple strike slip condition, an unloading stress wave and a velocity wave start to propagate soon as the breaking starts to spread. Because a dislocation spread speed of 2~3 km/s was estimated by Trifunac (1974, 1989)[8], we may regard, approximately, the break as an instantaneous for the far fields. As unloading waves propagate with elastic wave speed which for bedrock may be of order 2~3 km/s in shear and 4~6 km/s in compression (Finn, 1995)[9], so the disturbances at the source may propagate through bedrock with a velocity ratio about 4~10 to the overlying soil layers. It can be noted thus that stress waves in bedrock are much more fast than those in soil layers and we, therefore, can consider the whole bedrock moves horizontally in one same phase and gives excitations at the

rock surface to the overlying soils as an commonly considered one-dimensional problem. In this case the unloading stress waves and velocity waves are the original ones, while to simplify, we may consider it be under a displacement excitation and a stress excitation inputted up on soils base for every particular location of perfect elastic bedrock's. However, for a dip slip condition, the above statements is valid but the base excitations have to use SV waves and something representing a horizontal motion caused by a smaller SH wave.

(2) For interplate earthquake and other earthquake with complicated tectonic structure in the source area, an unloading elastic stress wave and a velocity wave may also start to propagate from the break zone firstly, but some secondary complicated collisions and breaking between the broken blocks and plates and their neighbors may cause additional loading stress and displacement waves which are elastic-plastic in nature and generally with a lower propagation speed than the unloading elastic waves. These might make more complicated secondary wave motions and a longer duration. Consequently, the base excitations would be more complicated, dependent on many conditions. So the base excitations of bedrock can not always identify as simple as an one-dimensional excitation cited above, due to the existence of unloading and loading elastic-plastic waves interaction and phase interference between stress and velocity waves in bedrock and soil strata. An example has been shown in a previous paper (Men et al, 1998)[10].

In summary, we are intending to evoke attention that earthquake source types and features are one vital origin of building damages regardless the geometrical and soil material damping as well as multiple wave reflection, scattering etc. through the complex geological paths. Because bedrocks show quite different mechanical behavior under loading and unloading stages, especially for cyclic loading condition, and of the much different geologic structures there will be many different types of earthquake excitations in reality that can not be described simply by the attenuation laws so far specified, which only taken account of the epicentral distance and magnitude. The late well-known Prof. Li Shi-Guang (1977) had pointed out that "those two points of even long distance but located in same a tectonic unit would be likely most closer than those of even short distance but located in two different tectonic unit", which correctly described one aspect of the drawback of the empirical attenuation laws.

Wave propagation in ground during earthquakes, both observational and theoretical, have extensive publications in the literature. However, an absolutely majority of them was based on the elastic wave theory. As we have pointed out above that the elastic wave theory was valid only for earthquake of simple unloading ruptures, whereas for quakes of complex unloading and loading and/or reloading only the precursor or the initial motion may exactly follow the elastic theory while for soil deposits in far field, usually, we may regard them as subjecting to loading waves which follow the inelastic wave theory.

4 Comments on some problems in engineering seismology and earthquake engineering

Based on the source break model given above and the loading conditions at the source we may sum up the explanations made already in the foregoing sections and present some comments on several problems and make them understandable more clearly.

(1) Why for such tremendously great earthquake loading at the source, which can make a fault break occur instantly and emit stress and velocity waves in highly inelastic rocks, can the elastic wave theory still nearly correctly hold.

As we have mentioned this is because the fault break at the source makes an unloading state at the source and then propagates far away in form of unloading waves. Since the unloading at source is normally an impulse form and the unloading stage of rocks may be regarded nearly as an elastic so elastic wave theory is basically valid in bedrock, except some complicated conditions near the source make yet certain loading and/or reloading conditions prevail. However, elastic wave theory may not fully valid for reflected waves and in top soil layers because they may subject loading waves from the bedrock as we explained in the section on wave propagation path.

Besides, though seismic waves in bedrock basically obey the elastic theory, those solutions for point, single couple, double couple, dipole, etc. (see e.g. Roy, 1965 or many others)[11,12], derived on the basis of semi-infinite homogeneous elastic media would be not sufficiently valid since, as we have mentioned before, the huge rock masses of plate blocks are separated by many fault, crack, joint system, etc, and, consequently, part of them can break in form of a limited fault plane in local zone as many earthquakes showed, while it would be impossible in a homogeneous and continuous media. Therefore, strictly speaking, all of these solutions are approximate with an unknown yet order of error, although we recognize their contributions at the same time and should point out their limitations in describing the real earth problems.

(2) One of the reasons why we can always record out P and S wave phases together even for an earthquake of purely shear slip focus.

As we have explained before, this is due to the fact that a drop of normal stresses at the fault plane will occur as soon as the two branches of faulted stratum slip a distance one to another no matter how the transition of wave types may occur or not via the wave propagation path up to the recording seismometer. Since the slip distance is usually smaller than the length of fault plane so the peak value of P wave would be smaller than that of S wave in seismogram.

(3) A comment on velocity record of earthquake.

Since the velocity at the source possesses a jump value at $t = 0$ so it must have also a jump in the velocity records at distant locations at least for those recording velocity meters fixed in rock or rock surface. Only those that placed on the surface of thick soil deposits may this jump diminish or even vanish due to the non-linear soil properties. From this fact we doubt the soundness of those velocity records for bedrock, obtained via integration of accelerogram and letting $v = 0$, at $t = 0$.

(4) A comment on the magnitude of earthquake.

From the quake model of jump wave clarified above we may arrive a definition of the mechanical work, i. e. not involving the thermal and chemical energy dissipated, to measure the quake intensity of the focus, simply as

$$W_t = \tau_s^2 F/(\rho C_s) + \sigma_{st}^2 F_d/(\rho C_p) + \sigma_{st} D(fF + F_d \cos\alpha) \tag{14}$$

To know W_t we only need fault plane area F, shear strength τ_s, slip distance D, residual shear resistance or friction resistance, and original compression stress which may be taken nearly as $\sigma_{st} \approx 2\tau_s$.

(5) A comparison between earthquake and underground explosion.

Underground explosion emits spherically symmetrical positive pressure in a loading stage for surrounding rocks in all directions whereas earthquake of shear slip type emits anti-symmetrical plane minus pressure and shear stress in an unloading stage for the rocks and has an extremely strong directional effect. The stress- time form of both them would be an impulsive. However, the former has a steep increasing curve (i. e. short rise time) starting from the origin $t = 0$ and propagates away, following elasto-plastic wave theory, while the latter has a jump at $t = 0$ and has a coupled jump $[v]$ at the same time, following nearly elastic wave theory. These features show clearly that the two types of excitation are fundamentally different and consequently we cannot use the data of one to replace that of another in research work of engineering seismology.

So far, though some authors have made works to use explosion data for solving problems in earthquake engineering, we are of opinion that these two are fundamentally different loading types and have not any common features. Only for deep explosions below layered strata their P waves may transform to generate other form of P waves and S waves through the interfaces and boundaries of different media, but they can generate only SV, not SH waves, and their wave pattern, stress and strain conditions cannot be identity with those of earthquakes. We can see also that the use of any controlled explosions (array of explosions) cannot simulate exactly the earthquake, especially they cannot generate shear jump waves at the source.

(6) The ratio of vertical to horizontal ground motion.

As we have explained in detail in a foregoing section, and some really existed observation records showed there were not few with a greater ratio, even beyond 1 (see e. g. Tokuji, 1987, Elnashia, 1996)[12, 13] so we may conclude that one of the reason of vertical component of ground motion may be greater than the horizontal one for dip slip focus depends on the dip angel of dip slip surface, beyond 45 degree to horizontal direction. Of course, there may be yet other reasons in complicated situations.

(7) A more complete criterion of earthquake intensity.

To measure more completely the intensity we have to use altogether, at least, two parameters, stress and velocity, or their alternatives. Besides, the frequency spectrum and the duration time due to the forced vibration phase (i. e. the response to only the impulsive source action) are also useful to represent indirectly the influence of C_b and fault length of the source. Those responses due to self vibration might be of some different features and should consider additionally.

(8) In comparison with the model of Haskell (1964) our model included the jump contributions at time $t = 0$, and the coupled actions of negative shear and normal stresses on the fault plane. Besides, in our opinion the slip distance is the combined consequence of loading conditions at focus and the environment conditions of the quake-generated plate and its neighbors, not only a direct function of the shear stress on the fault plane because this displacement comes to the end only when the total earthquake process (including farfield response) ceased to act, so it seems not suitable to regard D as an independent parameter. Only when compute the total work we need it.

(9) Why large earthquakes usually are uneasy to occur repeatedly at one local position.

Because large quakes must be caused by a new fault with big shear strength and mechanical work while, then afterward, the possible fault break could occur only along the old fault with much less shear resistance due to friction, usually about 3 to 10 times smaller than τ_s and consequently 9 to 100 times smaller in work W. So this indicates that large earthquake should occurs in different zones within a longer time period if the crust motion is normal.

(10) The so-called stress drop used so far in focus study would be actually equal to the shear strength minus the friction resistance on fault plane during fault slipping. This friction resistance depends on many factors and would be largely smaller than the shear strength of intact rock. The commonly used estimation from slip distance D seems not reliable enough because D depends on many factors other than the shear stress and shear modulus only. And it does not much influence the original disturbance causing waves generation at focus.

(11) Some doubts in mantle circulation flow.

May the flow patterns differ from that so far assumed? For instance, may all the flows are in one direction as the Earth evolves? or may the flow velocities change with time somehow and cause the change of pushing force? May the so-called subduction of ocean plates into beneath continent plates at ocean valley (pit) be soundless? but, in fact, only because they collide and break into small blocks and then washed and erosioned away by seawater?

5 Conclusions

From the above statements it would be reasonable to conclude that

(1) The current broadly-accepted plate motion and continent drifting might be validated by a simple analysis based on modern mechanics, as we tried first in the paper. The still existed unknowns may be the circulation pattern (velocities, flow directions at different locations, etc.) and other types of disturbance sources, which no one can surely know at present.

(2) The source mechanism is of vital importance to excite waves and ground motion as well as buildings damage. At the instant when the break plane starts to perform a minus stress jump and a plus velocity jump, two waves occur simultaneously and propagate away therefrom. Only for purely elastic materials and one-dimensional propagation may these two waves have same form while for rocks, quite far from purely elastic, these two waves would have different forms soon after their leaving the source. So there are at least two original independent waves, stress and velocity one, in the ground before wave types transition may occur under certain geologic and soils conditions. Therefore, to measure the intensity of earthquake for engineering design we must choose also at least two independent parameters, instead of only the acceleration currently used in aseismic design.

(3) The break propagation speed C_b has also a decisive significance to specify the mechanism and the wave form of ground motion. Its value and variation form together with the fault plane area determine the original pulse form as a time function of the released energy at source and greatly influence the spectrum content and duration of ground motion. Unfortunately, knowledge of C_b is much far lack at present in reality.

(4) Usually, for the break slip caused by shear, unloading tensile waves may be induced also in companying with the shear waves as soon as the two branches of broken plate slipped a distance from one to another at the source. This could explain why we can always record P and S waves in seismograms of earthquakes consequently.

(5) Such parameters as τ_s, C_b, C_s, C_p, D, f, and F (particularly, τ_s, C_b, F, f and D) may fully describe a quake source of fault break type and the jump wave theory has to be used to analyze wave propagation taking account of the nature of instantaneously unloading of stress at the break plane. Whereas strike and inclination direction of the slip plane will have also some effects on ground motion especially for the far field.

(6) Based on this focus mode in which we first clearly noticed the unloading nature, stress and velocity jump, P and S waves together from the break plane and the significance of C_b, some comments on some fundamental concepts are made, aiming at attracting academic discussion and prompting new progress, though our opinions may be not totally correct.

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