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INTERNAL REPORT
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International Atomic Energy Agency
and
United Nations Educational Scientific and Cultural Organization
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

STUDY ON THE CHARACTERISTICS OF CRUST STRESS FIELD IN EAST CHINA BY INVERSION OF STRESS TENSOR

Zhou Huilan*
International Centre for Theoretical Physics, Trieste, Italy
and
Ding Rugang
Princeton University, Princeton, New Jersey, USA.

ABSTRACT

This paper combines the search procedure with the optimization procedure to inverse the average stress tensor, and applies this method to study the crustal stress field using data of the solution of *P* wave first motion. By dealing with the data of Haicheng, Tangshan, Xingtai, Anyang, Liyang, Taiwan, Fujian and Guangdong areas, we obtain the characteristics of crust stress field of East China. The directions of the principal pressure stress always possess a small dip angle, but the azimuths vary from NEE (in north part of East China) to SEE (in the south part). This frame probably is related to the push-extrusive effects of the northwestern Pacific plate from NEE and the Philippine plate from SEE.

MIRAMARE – TRIESTE
December 1991

* Permanent Address: Academia Sinica, Graduate School, P.O. Box 3908, 100039 Beijing, People's Republic of China.

1.Introduction

In a given area, we can obtain two kinds of data about the direction of faulting.One is the fault striae from the field work of geologists; and the other is from the solution of the P wave first motion, which gives the two nodal planes perpendicular to each other,the fault plane being one of them and its slipping direction being the normal of the other.

If there is an average stress tensor in a not very large area and in a not very long time period, then the direction of its shear component on a given plane can be calculated. This direction should be consistent with the observed one.Thus,as an inversion problem,the average stress tensor can be determined by making the angle between the calculated and the observed directions as small as possible. This method of inverting stress tensor or fitting slipping direction was provided by Etchecopar ,et al.(1981) and Vasseur,et al.(1983), and applied to the data of China by Xu (1984,1985) and Gan, et al.(1988).

In this paper, we use this method and the data of the solution of P wave first motion to study the characteristics of the crust stress field in East China. For this purpose, we improve this method in two respects:

(1). On the Scopes of Area and Time

For a large earthquake sequence, the region related to the average tensor is the source area, i.e.the distribution area of main and after shocks. For an area, within which the seismic activity is high but no large events occurred,according to the time limit of the available data, we also estimate the average stress tensor by using this method. In this case, both of the time and area scopes are usually larger than the former .

(2). On the Details of calculation

We directly take the results from the search procedure (Gan, et al.,1988) as the initial value of the optimization procedure.This step makes the iteration fast. We change the type of the objective function to be easy to calculate. A complex case— the direction of the fault slipping is equal to or opposite to the direction of the normal of auxiliary plane,— is considered in our program.

2. Principles

The basic assumptions are: the stress tensor is relatively stable in a not very big area and in a not very long time period, the stress tensor is symmetric, and the slipping of fault results from the shear component of stress tensor **T**. σ_1, σ_2, and σ_3, are respectively the pressure, the middling and the tensive principal stress of stress tensor **T** in Principal Axis Coordinate— ox′y′z′, T′ and T are respectively the matrix of **T** in ox′y′z′ and in Ground Surface Coordinate— oxyz (ox—north, oy—east, oz—down vertically) (Fig.1). φ, θ and ψ are the three Euler angles as shown in Fig.1.

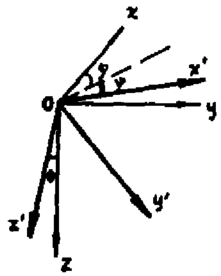

Fig.1 Principal Axis Coordinate ox′y′z′ and Ground Surface Coordinate oxyz. φ,θ, and ψ are the three Euler angles.

that is

$$T' = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix} \qquad (1)$$

and

$$T = AT'A = (T_{ij}). \qquad i,j = 1,2,3$$

here, A is the matrix of the coordinate transform, and

$$A = (A_{ij}), \qquad i,j = 1,2,3$$

$$A_{11} = -\sin\varphi\cos\theta\sin\psi + \cos\varphi\cos\psi$$
$$A_{12} = \cos\varphi\cos\theta\sin\psi + \sin\varphi\cos\psi$$
$$A_{13} = \sin\theta\sin\psi$$
$$A_{21} = -\sin\varphi\cos\theta\cos\psi - \cos\varphi\sin\psi$$
$$A_{22} = \cos\varphi\cos\theta\cos\psi - \sin\varphi\sin\psi \qquad (2)$$
$$A_{23} = \sin\theta\cos\psi$$
$$A_{31} = \sin\varphi\sin\theta$$
$$A_{32} = -\cos\varphi\sin\theta$$

$$A_{33} = \cos\theta$$

and

$$T_{11} = A_{11}\sigma_1 + A_{12}\sigma_2 + A_{13}\sigma_3$$
$$T_{21} = A_{21}\sigma_1 + A_{22}\sigma_2 + A_{23}\sigma_3$$
$$T_{31} = A_{31}\sigma_1 + A_{32}\sigma_2 + A_{33}\sigma_3 \qquad (3)$$
$$T_{12} = T_{21} = A_{11}A_{21}\sigma_1 + A_{12}A_{22}\sigma_2 + A_{13}A_{23}\sigma_3$$
$$T_{13} = T_{31} = A_{11}A_{31}\sigma_1 + A_{12}A_{32}\sigma_3 + A_{13}A_{33}\sigma_3$$
$$T_{23} = T_{32} = A_{21}A_{31}\sigma_1 + A_{22}A_{32}\sigma_3 + A_{23}A_{33}\sigma_3$$

The shear component $\vec{F}$ of **T** on plane N which with normal $\vec{n}$, is

$$\vec{F} = \mathbf{T}\cdot\vec{n} - (\vec{n}\cdot\mathbf{T}\cdot\vec{n})\vec{n} \qquad (4)$$

Let

$$\mathbf{T}_1 = \lambda\mathbf{T} + \mu\mathbf{I} \qquad (5)$$

here,

I—the unit tensor

λ,μ—arbitrary positive constants

Substituting $\mathbf{T}_1$in (4), and marking its shear component as $\vec{F_1}$, we have

$$\vec{F_1} = \lambda\vec{F}.$$

The unit vector of $\vec{F_1}$ or $\vec{F}$ is written as :

$$\vec{f} = \vec{F_1} / |\vec{F_1}| = \vec{F} / |\vec{F}|$$

which means that the direction of $\vec{F_1}$ is the same as that of $\vec{F}$.

Let

$$\lambda = 1/(\sigma_1 - \sigma_2)$$
$$\mu = -\sigma_3/(\sigma_1 - \sigma_3)$$

from (5), we obtained the matrix T'_1 of $\mathbf{T}_1$ in ox′y′z′ as following:

$$T'_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

here, $R = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ is called the bias ratio of the principal stress.

From (1), the matrix T_1 of $\mathbf{T}_1$ in oxyz is:

$$T_1 = AT'_1A = (t_{ij})$$

here,

$$t_{11} = A_{11}^2 + RA_{12}^2$$
$$t_{22} = A_{21}^2 + RA_{22}^2$$
$$t_{33} = A_{31}^2 + RA_{32}^2 \quad (6)$$
$$t_{12} = t_{21} = A_{11}A_{21} + RA_{12}A_{22}$$
$$t_{13} = t_{31} = A_{11}A_{31} + RA_{12}A_{32}$$
$$t_{23} = t_{32} = A_{21}A_{31} + RA_{22}A_{32}$$

From (6) we can see, that the direction of the shear component of the stress tensor only contains information on the parameters φ,θ,ψ, and R, i.e., for the stress tensor, we can only determine the directions of three principal axes and the bias ratio R, by fitting the direction of the shear component in the observed direction of the slipping of fault.

3. Methods of Calculation

The nodal planes N and M from the solution of the P wave first motion are shown in Fig.2, $\vec{n}$ and $\vec{m}$ are the unit vectors of the normal corresponding to N and M, respectively. Usually, we do not know which nodal plane is the fault plane except some large earthquakes.If N is the fault plane, then $\vec{m}$ is the slipping direction; otherwise, M is the fault plane and $\vec{n}$ is the slipping direction.

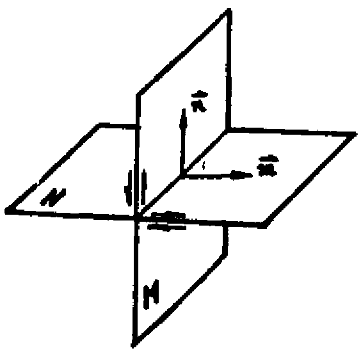

Fig.2 Two nodal planes determined from the solution of the P wave first motion

(1). Method of searching the stress tensor

By separating the definition domain of φ, θ, ψ (all $\in [0,\pi]$)and R ($\in [0,1]$), we set up a great quantity of stress tensor with the parameter group(φ, θ,ψ,

R). For each tensor and each event,we calculate the shear component on the N plane, and the angle between it and m ; and then do the same for the M plane:

$$\alpha_{N_i} = \cos(\overline{f_{N_i}} \cdot \overline{m_i})$$
$$\alpha_{M_i} = \cos(\overline{f_{M_i}} \cdot \overline{n_i}) \quad i = 1,2,\ldots,L \quad (7)$$

here, L is the number of events.

If a group parameters satisfy that:

$$\alpha_j = \min(\alpha_{N_j}, \alpha_{M_j}) \leqslant \alpha_0, \quad j = 1,2,\ldots,L-k \quad (8)$$

then this group of parameters φ , θ , ψ and R,is one of trying solution.Here, α_0 is a given constant , k is a given number to allow that a few events (k) do not satisfy (8). Obviously,the smaller α_0 or k,the smaller the number of trying solutions. In this procedure, if all solutions give $\alpha_N < \alpha_M$ for a fixed event, then the fault plane of this event is N ; otherwise, it is M.

(2). Method of optimizating the stress tensor

We set up the object function Q as follows:

$$Q = \sum_{i=1}^{L} (\cos^{-1}(\overline{f_i} \cdot \overline{S_i}))^2 \quad (9)$$

here, $\overline{s_i}$ is the unit vector of the slipping direction of the fault plane determined by the search procedure for the event i (e.g., if N is the fault, $\overline{s_i}$ is $\overline{m}$); $\overline{f_i}$ is the calculated one. Thus, the problem of theoptimization is to find a tensor (with parameters φ,θ,ψ and R),which gives a minimum Q. For this purpose, the simple acceleration type of the optimization was used in this study.

(3). Combination of two methods

Since the object function Q is nonlinear and its minima are very concentrated, the selection of the initial values for the optimization is very important. A selection in error may lead to a sub-minimum and obtain a meaningless result. To avoid this possibility, Gan, et al.(1988) considered a large number of initial points (5 x 10^4).Their method needs large memory and long time for the calculations.

In this paper, we combine the optimization with the search. Each trying solution from the search procedure is taken as an initial value in the optimization procedure. After iterations, final parameters φ,θ,ψ and R, and a final value of Q, are obtained, correspondingly. This proceeding is applied to all trying solutions.Comparing these final values of the object function Q, a minimum can be found, and the corresponding final values of the parameter φ,θ,ψ and R are considered as the result.

The computing time of our method is only one fiftieth of Gan' et al.'s for the same data.

4. Data and Results of Inversion

(1). Haicheng area (in Liaoning Province)

We collected the data of the solutions of the P wave first motion for the earthquake Haicheng (Feb. 4,1975, Ms 7.3) and its aftershocks. According to the distributions of these 57 events, we divided them into A,B and C sub– regions (Fig.3), and inverted their stress tensors by using the methods mentioned above. The results are listed in Table 1, and the directions of σ_1 are marked in Fig.3 .

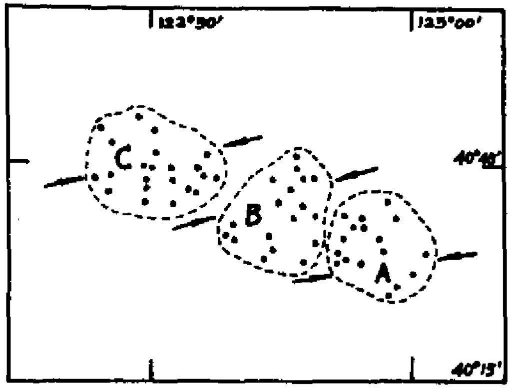

Fig.3 Distribution of events and the 3 sub–regions divided for Haicheng area. Arrow represents the direction and azimuth of principal pressure stress σ_1 inversed by this study.

(2) Tangshan area (in Hebei Province)

The data are the same as those used by Gan,et al., The 60 events are the aftershocks of the big earthquake Tangshan (July 27, 1976, Ms 7.8) , and are divided into 5 groups instead of Gan's 3 groups. The corresponding sub–regions and the directions of σ_1 are shown in Fig.4, and the results in the Table 1.

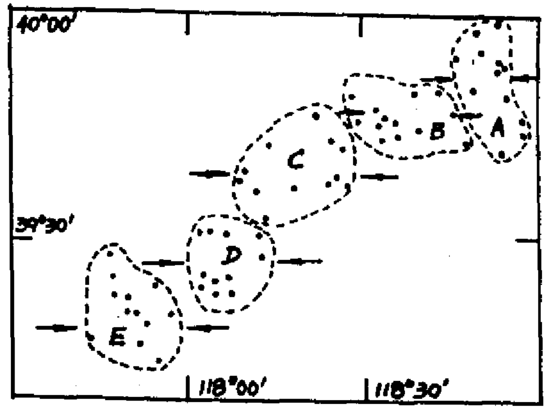

Fig.4 Distribution of events and the 5 sub–regions used for the Tangshan area. The direction and the azimuth of σ_1 obtained in this paper are marked by arrows.

(3). Xingtai area (in Hebei Province)

For this area, we have collected 40 events— the aftershocks of the earthquake Xingtai (Mar. 8, 1966, Ms 6.8), and have divided them into 3 groups(Fig.5). The results are listed in Table 1, and σ_1 is marked in Fig.5 .

Table 1

		Tangshan					Haicheng			Xingtai		
		A	B	C	D	E	A	B	C	A	B	C
σ_1	Az	-105.2	-105.3	-85.9	95.0	-90.0	-95.2	-100.2	-95.1	-102.3	-98.7	-100.3
	Dip	6.0	14.7	-0.6	4.0	30.0	19.6	31.5	15.5	17.1	28.7	29.0
σ_2	Az	-25.9	-41.8	7.5	-91.4	-90.0	-10.9	-98.6	92.9	-151.6	-130.9	-95.6
	Dip	-64.5	-61.2	-80.6	86.0	-60.0	9.2	-58.5	4.5	-64.8	-57.1	-60.9
σ_3	Az	-10.4	-6.6	4.0	3.0	0.0	3.97	-9.8	2.8	-18.0	-17.0	-9.8
	Dip	24.7	24.1	9.4	0.3	0.0	-28.6	0.72	-0.63	-18.0	-14.7	2.0
R		0.41	0.55	0.87	0.40	0.06	0.99	0.36	0.51	0.37	0.41	0.12

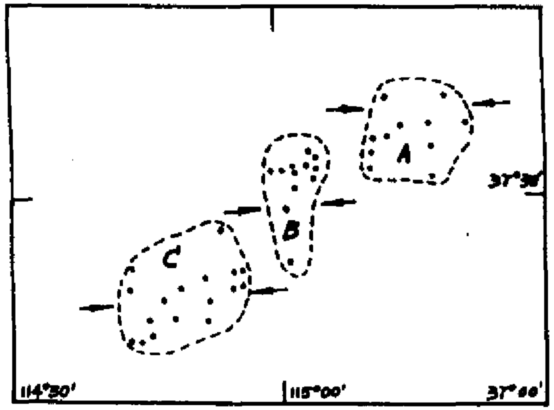

Fig.5 Distribution of events and the 3 sub–regions used for the Xingtai area. Arrows point out the direction and azimuth of σ_1 given by this study

(4). Anyang area (in Henan Province)

Here the collected 14 events are considered as one group, although their distribution area is relatively large. The result is in Table 2.

(5). Liyang area (in Jiangsu Province)

As for the Anyang area, we handle the 12 events as one group. The result is shown in Table 2.

Table 2

	σ_1		σ_2		σ_3		R
	Az	Dip	Az	Dip	Az	Dip	
Anyang	-91.9	4.7	-178.7	-34.1	-8.8	-5.55	0.5
Liyang	-89.6	29.4	-89.7	-60.6	0.41	-0.06	0.2

(6). Taiwan area (in Taiwan Province)

We collected and compiled 57 events' solutions of the P wave first motion. These events occured in this area from thirties to eighties. Three groups are divided and shown in Fig.6. Table 3 lists the results.

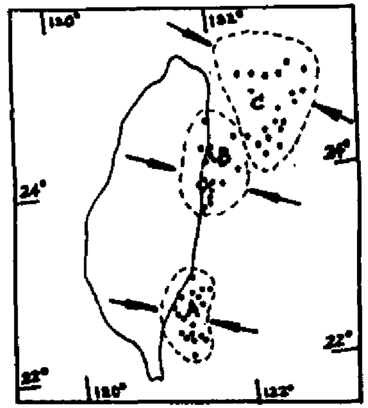

Fig. 6 Distribution of events and the 3 sub–regions used for the Taiwan area. The arrows points out the direction and the azimuth of σ_1

(7). Fujian area (in Fujian Province)

For this area, 20 events are divided into Ao and Bo groups (Fig.7), and the results are shown in Table 3.

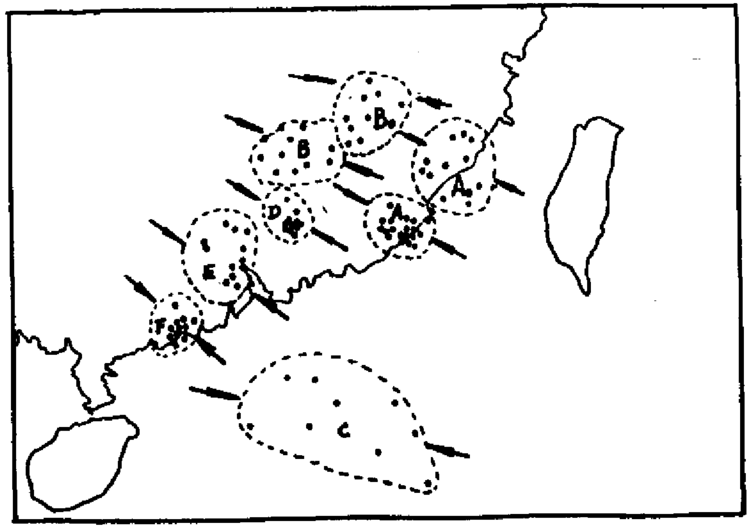

Fig.7 Distribution of events and sub–regions used for the Fujian area (Ao and Bo) and the Guangdong area (A,B,C,D,E and F). The arrows point out the direction and the azimuth of σ_1

(8). Guangdong area (in Guangdong Province)

Here the collected 73 events are divided into 6 groups (A,B,C,D,E and F) shown in Fig.7, and the results are in Table 3.

Table 3

		Taiwan			Fujian		Guangdong					
		A	B	C	A	B	A	B	C	D	E	F
σ_1	Az	-83.6	-84.0	122.4	124.0	-76.2	-62.6	-68.9	-80.0	-50.2	132.4	-41.3
	Dip	27.2	12.7	22.8	-28.6	-11.4	19.4	24.5	-10.3	27.7	22.9	15.0
σ_2	Az	-106.0	-140.0	-12.9	133.2	167.8	-111.[illegible]	-73.9	62.5	-170.0	-154.[illegible]	-98.3
	Dip	-60.9	-68.1	53.9	61.1	-65.8	-7.05	-5.47	-77.2	17.9	-16.9	-63.8
σ_3	Az	1.49	1.86	44.4	36.9	18.3	-20.2	16.1	8.49	-90.0	-70.6	42.8
	Dip	-9.5	-17.6	-26.3	3.47	-21.6	-7.85[illegible]	-.48	7.63	-25.9	20.5	-20.9
R		0.65	0.800	0.00	0.87	0.67	0.67	0.52	0.55	0.22	0.99	0.19

5. Characteristics of the Stress Field in East China

In order to investigate the characteristics of the crust stress field of East China, we estimate the average azimuth and dip angle of σ_1 in the Haicheng, Tangshan, Xingtai, Fujian, Taiwan, East Guangdong and South Guangdong areas, and list them in Table 4 together with those of the Anyang and Liyang areas. All these σ_1 are plotted with their azimuths in Fig.8 .

Table 4

		Haicheng	Tangshan	Xingtai	Anyang	Liyang	Taiwan	Fujian	Guangdong	
No.		1	2	3	4	5	6	7	8a (A.B.D)	8b (C.E.F)
σ_1	Az	-96.8°	-93.9	-100.4	-91.4	-89.6	-75.1	-66.1	-59.7	-57.2
	Dip	22.2°	11.1	24.9	4.7	29.4	20.9	-20.0	23.9	16.1

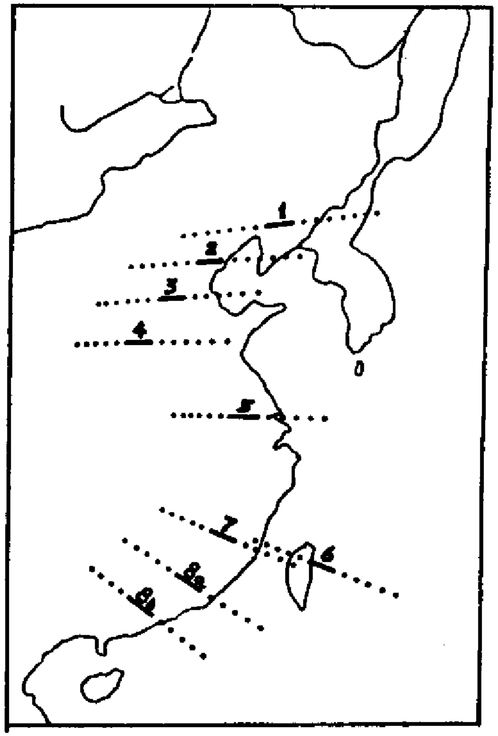

Fig.8 The average azimuths of σ_1 in the 9 areas of East China.The number in this figure is the same as in Table 4. (1.— Haicheng area, 2.— Tangsha area, 3.— Xingtai area, 4.— Anyang area, 5.— Liyang area, 6.— Taiwan area, 7.— Fujian area, 8a.— East Guangdong area, 8b.— South Guangdong area)

From Table 4 and Fig.8, we can see a remarkable character of stress field. In East China, from north to south, the azimuth of the principal pressure stress σ_1 varies from NEE to SEE, but always with a small dip angle.

These characteristics probably mean that:

(1). The crust stress field of whole East China is outstanding with a nearly horizontal pressure stress, and this is probably related with the push–extrusive effect of the Pacific plate from the east.

(2). In the north part of East China, the effect of northwestern part of the Pacific plate from NEE is more remarkable; and in the south part of East China, the effect of Phillippine plate (the west part of Pacific plate) from SEE is more remarkable.

Acknowledgments:

We would like to thank Professor Adbus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste, Italy. We also would like to thank Professor Giuliano Francesco Panza, and the Institute of Geodesy and Geophysics of the University of Trieste, for valuable discussions and kindly providing calculation condition. This work is a part of joint projects for IDNDR directed by Professor G.F.Panza.

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