Modeling transient and long-term postseismic deformation: A case study of 1995 M_W 9.5 Chile earthquake*

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Abstract

In this paper, we firstly use finite element method (FEM) with Burgers model to simulate the postseismic viscoelastic relaxation taking 1960 Chile earthquake as an example. The postseismic deformation modeled with Burgers model includes co-seismic deformation, transient postseismic deformation and long-term postseismic deformation. So if we apply Burgers model to calculate postseismic deformation of 1960 Chile earthquake, there is no discrepancy phenomenon due to different durations of postseismic deformations that happens in Maxwell model.

Key words: Chile earthquake; postseismic deformation; Burgers model; viscoelastic medium; FEM

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Introduction

Chile locates at the Andean subduction zone where Pacific Plate and South America Plate collide. It is one of the countries frequently suffered from serious earthquake hazards. The Valdivia, Chile M_W 9.5 earthquake occurred on May 22, 1960 is the largest earthquake ever recorded in the history, which produced an 850-km-long rupture and triggered a huge tsunami. The huge tsunami swept the coast of Pacific Ocean at a speed of hundreds kilometers per hour. Many cities were destroyed, such as Concepción, Talcahuano, Chillan and so on, and about 2 000 000 people were left homeless.

Since 1993, a large number of GPS stations were deployed in Chile by the German Research Center for Geosciences (GFZ). Since then the crustal deformation observation provides a plenty of data to study the geodynamics in this region. Klotz *et al* (1999, 2001) investigated the crustal deformation in Chile (22°S~42°S) by GPS observations. In his research, the main characteristic is that the deformation pattern in central section (26°S~37°S) is in consistence with the pattern that caused by the coupling of the thrust interface between the subducting Nazca and the overriding South America plates. While the deformation patterns in northern and southern section have large difference with that in the central section. Klotz *et al* (2001) attributed the difference to postseismic effects of 1960 Chile earthquake and 1995 M_W 8.1 Antofagasta earthquake (Figure 1). By in-

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version of fault model and geological model with GPS data, Lorenzo *et al* (2006) obtained the best-fitting viscosity was 1.0×10^{20} Pa·s.

Figure 1 Postseismic deformation of 1995 $M_W8.1$ Antofagasta earthquake and 1960 Chile earthquake (Klotz *et al*, 2001)

(a) Postseismic deformation of the 1995 $M_W8.1$ Antofagasta earthquake (Klotz *et al*, 2001); (b) Postseismic deformation associated with 1960 $M_W9.5$ Chile earthquake

Using GPS data, we obtained the best-fitting viscosity was 5.0×10^{18} Pa·s in northern Chile ($22^\circ\text{S} \sim 42^\circ\text{S}$) by grid-search method. Compared with the result of Lorenzo *et al* (2006), there are 2 orders of magnitude discrepancy in the viscosity. We cannot exclude the possibility that the crust behaviors were different because of scarcity of short-time observation data. However, from numerical modeling, we found that the observation time after the earthquake has crucial impact on the viscosity inversion.

This paper shows that the postseismic deformation modeled by Maxwell medium cannot explain the short- and long-term deformation simultaneously. While modeling with Burgers rheological model can interpret both of them.

1 Inversion of 1995 $M_W8.1$ Antofagasta earthquake

The Antofagasta, Chile $M_W8.1$ earthquake occurred on July 30, 1995 generated a 180-km-long surface rupture (Ruegg *et al*, 1996), co-seismic deformation exceeds 60 cm within $200 \text{ km} \times 300 \text{ km}$ area from InSAR and GPS observations. Maximum horizontal surface displacements up to 1m were recorded in Antofagasta city. The co-seismic slip mainly distributed at the depth from 5 km to 45 km. This paper utilized coseismic slip inferred by Xia *et al* (2003) based on their joint inversion of GPS and InSAR. The simulated and observed horizontal coseismic displacements are shown in Figure 3a.

Earthquakes did not occur frequently before the $M_W8.1$ earthquake (Figure 2 shows the seismicity of this region one year before the earthquake). However, aftershocks were highly activated with a rate as high as 250 one day and lasted for three months (Sobiesiak, 2000). After that, the seismicity went back as before (Figures 2b and 2c). From then on the observed postseismic deformations were mainly caused by viscoelastic relaxation, and had no relationship with aftershocks. The best-fitting viscosity inverted by grid-search method is 5.0×10^{18} Pa·s. The observed

Figure 2 Earthquake distribution before the 1995 M_W 8.1 Chile earthquake (earthquake catalogue comes from ISC)

(a) Earthquake distribution one year before the event; (b) Aftershock distribution. Solid circles represent aftershocks occurred in three months after the earthquake (1995-07-30~1995-10-30) and open circles denote aftershocks occurred in three months after the earthquake (1995-10-30~1996-10-30)

Figure 3 Coseismic deformation of 1995 M_W 8.1 Antofagasta earthquake (a); Postseismic deformation of 1995 M_W 8.1 Antofagasta earthquake (b)

Figure 4 Deviations for different sets of viscosity by grid-search method

and calculated postseismic deformations are shown in Figure 3b. Figure 4 is the data fitting curve between viscosity and deviation.

2 Postseismic deformation analysis of 1960 M_W 9.5 Chile earthquake

Based on Maxwell rheological model, Lorenzo *et al* (2005) inverted the dislocation and viscosity by postseismic displacements. They

found the best-fitting viscosity was 1.0×10^{20} Pa·s. By adopting the optimal fault model and inverted geological model, we calculated the time-dependent postseismic displacements in Puerto Montt (41.4°S , 73.1°W) (Figure 5). The result shows that when the viscosity gets higher, deformation varies almost linearly with time, which is disagree with the result of Barrientos *et al.* (1992), who demonstrated that the postseismic strain rate decays time-dependently. On the other hand, if the viscosity is lower, postseismic deformation will get steady in 35 years and there are no measurable postseismic displacements today. The postseismic horizontal strain rate of 1960 Chile earthquake is shown in Figure 6. Obviously, the strain rate has no clear difference between the 1962 and 1995 when viscosity is set at 1.0×10^{20} Pa·s. However, when adjusting the viscosity to 1.0×10^{18} Pa·s, the viscoelastic relaxation is close to steady in 1995. The results reveal that it is difficult to model the long- and short-term postseismic deformation simultaneously by Maxwell rheological model.

Figure 5 Postseismic displacement at Puerto Montt (41.4°S , 73.1°W)
(a) Postseismic displacement in E-W direction; (b) Postseismic displacement in N-S direction

3 Postseismic deformation modeling with Burgers rheological model

3.1 Constitutive equation in differential form

As shown in Figure 7, a Burgers body consists of a Maxwell element in series with a Kelvin element. The constitutive equation in differential form can be obtained from model theory.

$$\sigma + \left(\frac{\eta_2}{k_1} + \frac{\eta_1}{k_1} + \frac{\eta_2}{k_2} \right) \frac{\partial \sigma}{\partial t} + \frac{\eta_1 \eta_2}{k_1 k_2} \frac{\partial^2 \sigma}{\partial t^2} = \eta_2 \frac{\partial \varepsilon}{\partial t} + \frac{\eta_1 \eta_2}{k_1} \frac{\partial^2 \varepsilon}{\partial t^2} \quad (1)$$

Where, ε is strain; σ is stress; η is viscosity; k is elastic modulus; the subscripts are corresponding to that in the schematic illustration

Loading a constant stress σ_0 , the strain response can be shown as

$$\varepsilon(t) = \frac{\sigma_0}{k_2} + \frac{\sigma_0}{k_1} (1 - e^{-t/\tau_1}) + \frac{\sigma_0}{k_2} \frac{t}{\tau_2}$$

Where $\tau_1 = \eta_1/k_1$ and $\tau_2 = \eta_2/k_2$. The strain response includes three different effects, transient elastic response, initial rapid exponential decay and steady state of linear increase.

3.2 Constitutive equations

Because it is difficult to calculate the high order differential form of displacement, we utilize the integral representation of constitutive equation instead of differential form. Boltzmann's superposition theorem is used to represent the accumulative effect of the viscoelasticity. The constitutive equation can be written as (ZHOU *et al.*, 1995; Carcione *et al.*, 1988)

Figure 6 Postseismic strain rate of 1960 $M_W 9.5$ event with different viscosity
 (a) Strain rate with Maxwell rheology in 1962 ($\eta=1.0 \times 10^{20}$ Pa·s); (b) Strain rate with Maxwell rheology in 1995 ($\eta=1.0 \times 10^{20}$ Pa·s); (c) Strain rate with Maxwell rheology in 1962 ($\eta=1.0 \times 10^{18}$ Pa·s); (d) Strain rate with Maxwell rheology in 1995 ($\eta=1.0 \times 10^{18}$ Pa·s)

Figure 7 Schematic illustration of simple mechanical analogues for Burgers rheology

$$\begin{aligned}\sigma_{ij}(t) &= 2 \int_0^t G(t-\xi) \frac{\partial \varepsilon_{ij}(\xi)}{\partial \xi} d\xi + \left\{ \int_0^t \left[G'(t-\xi) - \frac{2}{3} G(t-\xi) \right] \frac{\partial \varepsilon_{kk}(\xi)}{\partial \xi} d\xi \right\} \delta_{ij} \\ &= 2G(t) * \dot{\varepsilon}_{ij}(t) + \left(K - \frac{2}{3} G(t) \right) * \dot{\varepsilon}_{kk}(t) \delta_{ij} \quad i, j = x, y, z\end{aligned}\quad (2)$$

Where the relaxation modulus of Burges rheology is shown as

$$\begin{aligned}G(t) &= \frac{1}{\sqrt{p_1^2 - 4p_2}} [(\alpha q_2 - q_1)e^{-\alpha t} + (q_1 - \beta q_2)e^{-\beta t}] \\ \alpha, \beta &= \frac{p_1 \pm \sqrt{p_1^2 - 4p_2}}{2p_2}\end{aligned}$$

set $\Phi(t) = \dot{G}(t)$, as $G(t) * \dot{\varepsilon}_{ij}(t) = \int_{-\infty}^t G(t-\xi) \frac{\partial \varepsilon_{ij}(\xi)}{\partial \xi} d\xi = G(0)\varepsilon_{ij}(t) + \Phi(t) * \varepsilon_{ij}(t)$, equation (2) can be written as

$$\sigma_{ij}(t) = 2G(0)\varepsilon_{ij}(t) + \left(K - \frac{2}{3} G(0) \right) \varepsilon_{kk}(t) \delta_{ij} + 2\Phi(t) * \varepsilon_{ij}(t) - \frac{2}{3} \Phi(t) * \varepsilon_{kk}(t) \delta_{ij} \quad (3)$$

In order to overcome the numerical problem caused by convolution, the expression of the relaxation modulus was rewritten as the summation of two components:

$$G(t) = G_1(t) + G_2(t) \quad (4)$$

Where,

$$G_1(t) = \frac{1}{\sqrt{p_1^2 - 4p_2}} (\alpha q_2 - q_1) e^{-\alpha t}, \quad G_2(t) = \frac{1}{\sqrt{p_1^2 - 4p_2}} (q_1 - \beta q_2) e^{-\beta t}$$

accordingly

$$\Phi(t) = \Phi_1(t) + \Phi_2(t) \quad (5)$$

Where

$$\Phi_1(t) = \dot{G}_1(t) = \frac{1}{\sqrt{p_1^2 - 4p_2}} [-\alpha(\alpha q_2 - q_1) e^{-\alpha t}], \quad \Phi_2(t) = \dot{G}_2(t) = \frac{1}{\sqrt{p_1^2 - 4p_2}} [-\beta(q_1 - \beta q_2) e^{-\beta t}]$$

The first derivative of $\Phi_1(t)$ and $\Phi_2(t)$ are

$$\dot{\Phi}_1(t) = -\alpha \frac{1}{\sqrt{p_1^2 - 4p_2}} [-\alpha(\alpha q_2 - q_1) e^{-\alpha t}] = -\alpha \Phi_1(t) \quad (6)$$

$$\dot{\Phi}_2(t) = -\beta \frac{1}{\sqrt{p_1^2 - 4p_2}} [-\beta(q_1 - \beta q_2) e^{-\beta t}] = -\beta \Phi_2(t) \quad (7)$$

From equations (5~7), equation (3) can be written as

$$\begin{aligned}\sigma_{ij}(t) = & 2G(0)\varepsilon_{ij}(t) + \left(K - \frac{2}{3}G(0)\right)\varepsilon_{kk}(t)\delta_{ij} + \\ & \Phi_1(t) * \left(2\varepsilon_{ij}(t) - \frac{2}{3}\varepsilon_{kk}(t)\delta_{ij}\right) + \Phi_2(t) * \left(2\varepsilon_{ij}(t) - \frac{2}{3}\varepsilon_{kk}(t)\delta_{ij}\right)\end{aligned}\quad (8)$$

Note time-dependent items as memory variable, which is shown as

$$r_{ij1}(t) = \Phi_1(t) * \left(2\varepsilon_{ij}(t) - \frac{2}{3}\varepsilon_{kk}(t)\delta_{ij}\right) \quad (9)$$

$$r_{ij2}(t) = \Phi_2(t) * \left(2\varepsilon_{ij}(t) - \frac{2}{3}\varepsilon_{kk}(t)\delta_{ij}\right) \quad (10)$$

So, the constitutive equation can be expressed as

$$\sigma_{ij}(t) = 2G(0)\varepsilon_{ij}(t) + \left(K - \frac{2}{3}G(0)\right)\varepsilon_{kk}(t)\delta_{ij} + r_{ij1}(t) + r_{ij2}(t) \quad (11)$$

By making the first time derivative at both hand of equation $r_{xy1}(t) = 2\Phi_1(t) * \varepsilon_{xy}(t)$, we have

$$\frac{\partial r_{xy1}(t)}{\partial t} = \frac{\partial}{\partial t} 2 \int_{-\infty}^t \Phi_1(t-\tau) \varepsilon_{xy}(\tau) d\tau = 2\Phi_1(0)\varepsilon_{xy}(t) - \alpha r_{xy1} \quad (12)$$

We can obtain the same expression of other memory variables using the same method

$$\dot{r}_{ij1}(t) = \Phi_1(0) \left(2\varepsilon_{ij}(t) - \frac{2}{3}\varepsilon_{kk}(t)\delta_{ij}\right) - \alpha r_{ij1}(t) \quad (13)$$

$$\dot{r}_{ij2}(t) = \Phi_2(0) \left(2\varepsilon_{ij}(t) - \frac{2}{3}\varepsilon_{kk}(t)\delta_{ij}\right) - \beta r_{ij2}(t) \quad (14)$$

So that, equations (11), (13) and (14) are the constitutive equations used in this work. Though we just modified the expression of the equations, the difficulties in calculation can be avoid effectively in finite element modeling, which are mainly caused by complexity of the model.

3.3 Finite element modeling

Okada's analytic solution (Okada, 1985; 1992) have explained many seismic deformation problems, however, due to the constraints of half-space model, it is too simplified to represent real conditions. Cummins *et al* (1998) indicated the difference between half-space model and layered model. Wang *et al* (2006) and Pollitz (2005) have modeled and explained postseismic deformation using semi-analytic method. In their models the parameters can only vary vertically while the real geophysical behavior varies both in vertical and horizontal direction. Although it is quite effective to explain the postseismic deformation, there are still many difficulty in using semi-analytical method with arbitrary discontinue transect. For this reason finite element modeling were applied extensively (Deng *et al*, 1998; Freed and Burgmann, 2004; ZHU and CAI, 2006; Sheu and Shieh, 2004; Masterlark and Wang, 2000; Wang *et al*, 2006), though it may consume more compute time (Deng *et al*, 1998; Freed and Burgmann, 2004; ZHU and CAI, 2006; Sheu and Shieh, 2004; Masterlark and Wang, 2003; Wang *et al*, 2006).

The virtual work equation can be obtained from constitutive equation based on virtual work theory

$$\begin{aligned}
& \int_V \left[\left(K + \frac{4G(0)}{3} \right) \varepsilon_{xx} \delta \varepsilon_{xx} + \left(K - \frac{2G(0)}{3} \right) \varepsilon_{yy} \delta \varepsilon_{xx} + \left(K - \frac{2G(0)}{3} \right) \varepsilon_{zz} \delta \varepsilon_{xx} + \right. \\
& \left(K - \frac{2G(0)}{3} \right) \varepsilon_{xx} \delta \varepsilon_{yy} + \left(K + \frac{4G(0)}{3} \right) \varepsilon_{yy} \delta \varepsilon_{yy} + \left(K - \frac{2G(0)}{3} \right) \varepsilon_{zz} \delta \varepsilon_{yy} + \\
& \left(K - \frac{2G(0)}{3} \right) \varepsilon_{xx} \delta \varepsilon_{zz} + \left(K - \frac{2G(0)}{3} \right) \varepsilon_{yy} \delta \varepsilon_{zz} + \left(K + \frac{4G(0)}{3} \right) \varepsilon_{zz} \delta \varepsilon_{zz} + \\
& 4G(0) \varepsilon_{xy} \delta \varepsilon_{xy} + 4G(0) \varepsilon_{xz} \delta \varepsilon_{xz} + 4G(0) \varepsilon_{yz} \delta \varepsilon_{yz} + \\
& r_{xx1} \delta \varepsilon_{xx} + r_{xx2} \delta \varepsilon_{xx} + r_{yy1} \delta \varepsilon_{yy} + r_{yy2} \delta \varepsilon_{yy} + r_{zz1} \delta \varepsilon_{zz} + r_{zz2} \delta \varepsilon_{zz} + \\
& 2r_{xy1} \delta \varepsilon_{xy} + 2r_{xy2} \delta \varepsilon_{xy} + 2r_{xz1} \delta \varepsilon_{xz} + 2r_{xz2} \delta \varepsilon_{xz} + 2r_{yz1} \delta \varepsilon_{yz} + 2r_{yz2} \delta \varepsilon_{yz} \left. \right] dV \\
& = \int_V (f_x \delta u + f_y \delta v + f_z \delta w) dV + \int_{\Gamma} (T_x \delta u + T_y \delta v + T_z \delta w) dT
\end{aligned} \quad (15)$$

where strain $\varepsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$.

The differential form of memory variability can be written as $\frac{\partial r_{ij}}{\partial t} = \frac{r_{ij}^{n+1} - r_{ij}^n}{\Delta t}$, where,

$r_{ij} = \frac{r_{ij}^{n+1} + r_{ij}^n}{2}$, n is the time step, so that, the following recursive relationship can be obtained from equations (13) and (14)

$$r_{ij1}^{n+1} = \frac{4\Phi_1(0)\Delta t}{2 + \alpha\Delta t} \varepsilon_{ij}(t) - \frac{4\Phi_1(0)\Delta t}{3(2 + \alpha\Delta t)} \varepsilon_{kk}(t) \delta_{ij} + \frac{2 - \alpha\Delta t}{2 + \alpha\Delta t} r_{ij1}^n \quad (16)$$

$$r_{ij2}^{n+1} = \frac{4\Phi_2(0)\Delta t}{2 + \beta\Delta t} \varepsilon_{ij}(t) - \frac{4\Phi_2(0)\Delta t}{3(2 + \beta\Delta t)} \varepsilon_{kk}(t) \delta_{ij} + \frac{2 - \beta\Delta t}{2 + \beta\Delta t} r_{ij2}^n \quad (17)$$

3.4 Theoretical analysis

Taking a strike-slip event as an example, we discussed the difference of Maxwell and Burgers rheological model. Parameters of earth model are shown in Figure 1. From modeling results, there are incompatible problems in fitting long-term and short-term postseismic deformation with Maxwell rheological model, which means Maxwell rheological model cannot explain the viscoelastic relaxation with different time scales. While the postseismic deformation induced by Burgers rheology exhibits both transient adjustment and long-term steady deformation, as shown in Figure 8.

3.5 Short-term and long-term postseismic deformation of 1960 Chile event

Utilizing the best-fitting fault model and earth model inverted by Lorenzo *et al* (2006), we calculated and analyzed the postseismic effect of 1960 $M_w 9.5$ Chile earthquake with Burgers

Table 1 Parameters of material (in Burgers model)

Layers	Depth/km	K/Pa	$k_1, k_2/\text{Pa}$	$\eta_1/\text{Pa}\cdot\text{s}$	$\eta_2/\text{Pa}\cdot\text{s}$
Upper crust	0~10	4.8×10^{10}	3.0×10^{10}	1.0×10^{30}	1.0×10^{30}
Lower crust	10~20	8.0×10^{10}	4.5×10^{10}	1.0×10^{18}	1.0×10^{20}
Mantle	20~	1.5×10^{11}	7.0×10^{10}	1.0×10^{20}	1.0×10^{20}

Figure 8 Postseismic surface deformation of Maxwell and Burgers model

(a) Maxwell model ($\eta=1.0\times10^{20}$ Pa·s) for lower crust; (b) Burgers model ($\eta_1=1.0\times10^{18}$ Pa·s, $\eta_2=1.0\times10^{20}$ Pa·s) for lower crust

Figure 9 A model section showing element division

rheology, of which the two viscosities are 1.0×10^{18} Pa·s and 1.0×10^{20} Pa·s. The finite element mesh is shown in Figure 9. We utilized 341 550 irregular elements in the mesh with $92\times75\times495$ cells in northeast, northwest, and vertical direction holding a coverage of $1\ 280\text{ km}\times900\text{ km}\times450\text{ km}$. From modeling result (Figure 10), strain rate in 1962 has the same order of magnitude as that calculated from Maxwell rheological model with lower viscosity (1.0×10^{18} Pa·s); While in 1995, the order of

magnitude of strain rate is similar to the strain rate from Maxwell rheology with higher viscosity (1.0×10^{18} Pa·s). As a result, the long-term and short-time viscous deformation can be reflected effectively by Burgers rheology.

Figure 10 Postseismic displacement rate (mm/a) of the Chile $M_w9.5$ earthquake calculated by using Burgers model ($\eta_1=1.0\times10^{18}$ Pa·s, $\eta_2=1.0\times10^{20}$ Pa·s)

(a) Displacement rate in 1962; (b) Displacement rate in 1995

4 Discussion and conclusions

In 1960 and 1995, two large earthquakes occurred in Antofagasta (M_w 9.5) and Valdivia (M_w 8.1), Chile. Although the two regions exhibiting similar geological behavior, the viscosity of lower crust reveals 2 orders of magnitude discrepancy using the same inversion method. By analyzing the phenomenon, we consider that the difference maybe caused by the observation time from the earthquake, *i.e.*, the surface deformation data can be classified by long-term and short-time.

Taking 1960 M_w 9.5 Chile earthquake as an example, we modeled the postseismic deformation with Maxwell rheology, utilizing the optimal fault model and geology model obtained by Lorenzo *et al* (2006) from inversion. Results show that when the viscosity is higher, deformations almost change linearly with time, which is disagree with Barrientos *et al* (1992), who consider that the postseismic strain rate decays with time. On the other hand, if the viscosity is lower, postseismic deformation will get balance in 35 years. It is difficult to model the long- and short-term postseismic deformation using Maxwell rheology.

Based on finite element modeling, we calculated the postseismic deformation with Burgers rheology for the first time. We used integral representation of constitutive equations based on Boltzmann's superposition theorem, and solved the problem caused by convolution effectively by introduction of memory variability. As shown by numerical calculation, Burgers rheology can model both long-term and short-term deformation, which solved the incompatible problem in fitting the long-term and short-term post-seismic deformation from using Maxwell rheology.

With the development of observation techniques and accumulation of data, long-term and short-time postseismic deformation will be considered more and more in analyzing seismic deformation problems. With more detailed information as constraint, we can build a more accurate model to understand the geodynamic process and further make clear the deformation of crust and mantle both in long and short terms, which will help us to understand the different time scales activity of seismicity.

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