Elastic and Viscoelastic Models of Crust Deformation in Strike-slip Fault

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Abstract. The crust, when viewed over a long period, moves towards one another. Crusts might experience sudden slip on a fault plane and caused fractures or cracks. There are three different types of faults, normal, reverse, and strike-slip faults. Induced stress due to sudden rupture on fault planes capable of creating stress and need to be measured quantitatively to comprehend the earthquake process. To understand the stress that occurs in strike-slip faults in the earth's crust, the previous researchers study the use of elastic materials as the material of the earth's crust, so that the earth crust's deformation is elastic. However, elastic material has linear stress and strain relationship that results in reversible deformations or returns to their original shape. This material is not suitable for modeling the earth's crust's long-term deformation, where the deformation of the earth's crust can be permanent, so a model is needed to solve this problem. In this study, we will compare the stress in the strike-slip fault in the upper crust with elastic materials, while the lower crust and upper mantle have viscoelastic materials compared to purely elastic materials through numerical simulations. This comparison is made to see the comparison between the two approaches with the earth's layers' actual state. The two models is chosen to represent the different failure processes of the earth crust, i.e. the elastic deformation part describes the response to stress in a short period, and the viscous deformation can explain the response over a more extended period. The study of both materials above is based on plate tectonic theory, in which the lithosphere plates will relatively move to each other because the layer material underneath is solid but can flow like a liquid for a long period.

Keywords: Elastic, viscoelastic, numerical simulations, crustal deformation, strike-slip fault

1. Introduction

Displacements on faults occur continuously at tectonic velocities of tens of millimeters per year. When the crusts force overcomes the friction of the jagged edges of the fault, the stored up energy is released and will produce slip or sudden rupture on fault planes, causing more displacements to occur on faults during earthquakes and also fractures or cracks. A strike-slip fault is a fault along which the displacement is horizontal, which means no strain in the y-direction [Turcotte and Schubert, 1982]. A variant of strike-slip fault plays a significant role on plate tectonics. For example, Great Sumatra Fault...
(GSF), a 1650-km-long dextral strike-slip fault, is one of the strike-slip fault located in Indonesia. This fault zone poses major hazards, particularly to the highly populated areas on and around the active fault trace. Sumatra suffered from hundreds of earthquakes with Mw > 4 per year [Rafie et al., 2019]. The structure of strike-slip faults and its association with stress, strain, and displacement is an essential key to understanding intracontinental tectonic, including the process of the earthquake or its prediction and to define the seismic hazard along this fault.

The frictional strength of faults within the crust is an important factor that controls the earthquake mechanics; it governs the dynamics of earthquake nucleation and rupture propagation [Scholz, 2002; Kaneki and Hirono, 2019]. Several parameters affect the fault's frictional strength, such as normal stress, shear stress, rock type, fault orientation, displacement rate, coefficient of friction, and cohesion. Failure can occur along the fault plane when applied shear stress exceeds its resistance, particularly cohesion and coefficient of friction, which is remains the standard conceptual framework of faulting mechanics.

Strike-slip earthquakes and its deformation have been the subjects of intensive studies. Analog models (clay or sandbox experiments) are commonly used to study the long-terms evolution of faults. Still, they can not give quantitative constraints on the 3-D stress needed to understand the cause of crustal deformation [Dooley and Schreurs, 2012].

This study will model the tectonic loading in the strike-slip fault using 3-D numerical finite element code. This fault will be modeled on a crust with an elastic material as the upper crust overlying a visco-elastic material as the lower crust and upper mantle. These two materials are picked based on plate tectonic theory, where the lithosphere plates will relatively move to each other because the layer material underneath is solid but can flow like a liquid for a long period. For the elastic material, the material's behavior will produce reversible deformations or returns to their original shape due to their linear relationship between stress and strain. This kind of deformation can explain the response to stress in a short period. Meanwhile, the viscoelastic material yields viscous deformation that can explain the response over a more extended period [Stüwe, 2007; Bürgmann and Dresen, 2008].

2. Methodology

The process of measuring the perturbation of stress on a fault can be carried out using a numerical modeling method using the finite-element mesh. The finite-element mesh is a method used to divide a model into very small domains, which can be called elements. Element is an area where a series of equations will be applied. This equation represents the equation of the mesh (equation of interest) through a set of polynomial functions assigned to each element. Since these elements are made very small, the calculated solution will approximate the actual solution.

In this research, the 3-D finite-element mesh method is the right method for modeling the movement or deformation of shear faults in the earth's crust. This modeling is made by including several fault model parameters and crust material properties. This modeling is done using Coreform Cubit 2020.2 to generate the mesh model and Pylith [Aagaard et al., 2013, 2017] to produce modeling of the earth's crust with certain parameters.

3. Results and discussion

This research is on-going research. This study has already succeed in modeling the effect of rock strength parameters on the displacement around the fault in elastic materials. The parameters that are being studied are cohesion and coefficient of friction.

The mesh used in this modeling is a hexahedron mesh with a length of 6 km, a width of 6 km, and a height of 4 km (Figure 1). This mesh consists of two layers, namely upper crust and lower crust, and a
fault as an interface with model parameters that support this material, such as density of a 2500 kg/m$^3$, velocity of compressional wave (Vp) 3000 m/s and velocity of shear wave (Vs) 5291.5026 m/s.

The boundary conditions applied to this mesh are quasi-static Dirichlet boundary conditions. Axial displacements are applied on the $-x$ and $+x$ faces to maintain normal stress on the fault, and velocity displacements are applied in $-y$ and $+y$ directions on the same faces to yield a left-lateral sense of shear. This modeling uses a static friction fault with parameters in the form of a friction coefficient of 0.6 [Byerlee, 1978] and cohesion of 2 MPa [Andrews, 2005] to cause slip on the fault. This model was simulated for 200 years. From the result of modeling with applied parameters, it is known that the fault will generate slip at a period of 125 years (Figure 2).

Observations from this modeling are done by varying the value of the coefficient of friction and cohesion against the strike-slip fault to see the distribution of the displacement resulting from the modeling. From the variation of the coefficient of friction carried out on the crust model, it is known that the higher the coefficient of friction used, the longer the stress accumulates in the fault, which results in slip so that the slip that occurs will also take longer. This is shown in Figure 3, where each model with different coefficient of friction produce slips in different period. Model with friction coefficient 0.6 will slip at period 125 years, model with friction coefficient 0.85 will slip at period 145 years.
years, model with friction coefficient 0.2 will slip at period 85 years and model with friction coefficient 0.4 will slip at period 105 years.

Figure 3. Each model with different coefficient of friction produce slips in different period: (a) Friction coefficient 0.6: 125 years, (b) Friction coefficient 0.85: 145 years, (c) Friction coefficient 0.2: 85 years, (d) Friction coefficient 0.4: 105 years.

In addition, this research also varied the cohesion value used. The higher the cohesion value in a rock, the longer the stress accumulation in the fault can produce slip, so that rocks that have a lower cohesion value will experience slip first than rocks with a higher cohesion value. This is shown in Figure 4, where each model with different cohesion produce slips in different period. Model with cohesion 2 MPa will slip at period 145 years, model with cohesion 5 MPa will slip at period 185 years, and model with cohesion 1 MPa will slip at period 105 years.
4. Conclusions
We model a simple numerical modeling represent the tectonic load at the model boundary and the frictional strength of the fault. Model of strike-slip fault with coefficient of friction 0.6 and cohesion 2 MPa will slip in the period of 125 years. The variation of frictional strength parameter affects the fault reactivation, the higher the coefficient of friction and cohesion is used, the longer the stress accumulates in the fault which result in the longer slip of the fault will occur. The further study of this research is to apply the modeling concept developed in this study to explain the observed major events along Great Sumatra Fault (GSF).

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