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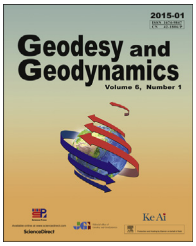

Numerical simulation of influences of the earth medium's lateral heterogeneity on co- and post-seismic deformation

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ABSTRACT

Many studies revealed that the Earth medium's lateral heterogeneity can cause considerable effects on the co- and post-seismic deformation field. In this study, the three-dimensional finite element numerical method are adopted to quantify the effects of lateral heterogeneity caused by material parameters and fault dip angle on the co- and post-seismic deformation in the near- and far-field. Our results show that: 1) the medium's lateral heterogeneity does affect the co-seismic deformation, with the effects increasing with the medium's lateral heterogeneity caused by material parameters; 2) the Lame parameters play a more dominant role than density in the effects caused by lateral heterogeneity; 3) when a fault's dip angle is smaller than 90°, the effects of the medium's lateral heterogeneity on the hanging wall are greater than on the footwall; 4) the impact of lateral heterogeneity caused by the viscosity coefficient on the post-seismic deformation can affect a large area, including the near- and far-field.

1. Introduction

The rapid development of modern space geodetic techniques and the study of dislocation theory have brought new opportunities to seismological research. The finding that most tectonic earthquakes occur on faults is one of the largest advances in seismology in the 20th century. Steketee [1] first introduced the dislocation theory to seismology, and since then, dislocation theory has seen significant development. Chinnery [2,3] derived the expressions for the surface displacements and stress near vertical strike-slip faults; Maruyama [4] extended these expressions to dip-slip faults. Chen et al. [5,6] discussed the general inversion method with semi-infinite space dislocation theory and ground deformation data, and inverted the source processes of the 1966 Xingtai earthquake and the 1976 Tangshan earthquake.

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Okada [7] reviewed and analyzed the closed analytical expressions that describe the surface deformation due to shear faulting in a half-space, and presented a suite of expressions for the surface displacements, strains, and tilts due to inclined shear and tensile faults in a half-space for both point and finite rectangular sources. Wang et al. [8] attempted to develop the formulations in a more realistic earth model, which includes the effect of crustal layering.

However, a realistic earth model is very complex, possessing not only crustal layering but also medium lateral heterogeneity, such as is found in the Longmenshan Mountains area [9–11]. According to Rybicki et al. [12–14], lateral heterogeneity can sometimes cause considerable effects on the co-seismic deformation fields. Li et al. [15] demonstrated, using numerical simulation, that the medium's lateral heterogeneity has influences on the co-seismic deformation. However, issues such as how the medium's lateral heterogeneity affects co- and post-seismic displacements, which parameters control the effects, whether a fault's dip angle has influences on the effects, and whether the effects are the same in the near- and far-field are yet to be addressed sufficiently. In this study, using numerical simulation through detailed analysis, we present the effects of the medium's lateral heterogeneity on the co- and post-seismic deformation fields in detail.

2. Model construction

A finite element model was constructed in the Cartesian coordinate system. The intersection of the fault plane and surface coincides with the Y-axis; the X-axis is perpendicular to the Y-axis and the Z-axis is perpendicular to the OXY plane. The region of the finite element model is: -200 km $\leq X \leq 200$ km, -200 km $\leq Y \leq 200$ km, -310 km $\leq Z \leq 0$ km. In the case of vertical strike-slip faults, the region of the fault is:$X = 0$ km, 0 km $\leq Y \leq 20$ km, -20 km $\leq Z \leq 0$ km. After designing the region and slip distribution, the fault plane was embedded into the finite element model. Then, the region was divided into connected tetrahedral mesh.

The finite element model was divided into three layers, the first layer being the upper crust, the second layer the lower crust, and the third layer the mantle. The upper crust was separated by a fault plane, which could be set to possess different material properties on both sides of the fault plane, causing it to become laterally inhomogeneous. In addition, we assumed the fault to only be present in the upper crust. For the co-seismic problem, the material is three-dimensional isotropic elastic, and can thus be described by only three material properties, λ, μ, and ρ; λ and μ are the Lame parameters. The values of all the parameters were from Dziewonski and Anderson's preliminary reference Earth model [16].

3. Simulation and analysis

3.1. Impact of λ on co-seismic deformation

To study the impact of λ, μ, ρ and the other parameters should be kept constant. Here, we kept μ as 2.7×10^{10} Nm^{-2} in all the experiments. Ten groups of experiments, listed in Table 1, were designed. Each group had three cases; all the parameters of case 2 and case 3 were the same, except for λ; the value of λ in case 2 was the same as that of the footwall in case 1; the value of λ in case 3 was the same as that of the hanging wall in case 1.

The ten groups of experiments were designed to determine the impact of the medium's lateral heterogeneity caused by the λ on co-seismic deformation. As a consequence of the differences in the λ, the material in case 1 of each group was laterally heterogeneous. On the contrary, the material in case 2 and case 3 of each group was homogeneous. Therefore, subtracting the co-seismic displacements of case 2 from the co-seismic displacements of case 1 gave the impact of the medium's lateral heterogeneity, caused by the λ of the hanging wall, on the co-seismic deformation (Fig. 1). Likewise, subtracting the co-seismic displacements of case 3 from the co-seismic displacements of case 1 gave the impact of the medium's lateral heterogeneity, caused by the λ in the footwall, on the co-seismic deformation (Fig. 1).

Fig. 1(a) Impact of lateral heterogeneity caused by the λ of the hanging wall on the co-seismic deformation in the X-axis direction; 1(b) Impact of the hanging wall in the Y-axis direction; 1(c) Impact of the hanging wall in the Z-axis direction; 1(d) The square root of the impact of the hanging wall in all directions; 1(e) Impact of lateral heterogeneity caused by the λ of the footwall on the co-seismic deformation in the X-axis direction; 1(f) Impact of the footwall in the Y-axis direction; 1(g) Impact of the footwall in the Z-axis direction; 1(h) The square root of the impact of the footwall in all directions. In the figure, the X-axis and Y-axis represent the area of the area of the earthquake.

In the numerical simulation results, the impact of the medium's lateral heterogeneity caused by λ on the co-seismic deformation was different in the three directions of the surface coordinate system. In the experimental results for the 10th group, the biggest change in the X-axis, Y-axis, and Z-axis directions was 5.3 mm, 7.6 mm, and 9.0 mm, respectively. Moreover, the rate of the biggest change in the Z-axis direction was just 3.25%.

As shown in Table 1, the parameter of λ in the hanging wall varied from 3.75×10^{10} Nm^{-2} to 6.0×10^{10} Nm^{-2} in steps of 2.5×10^{9} Nm^{-2}. The co-seismic displacement was observed to increase with an increase in λ. In addition, the increments of the co-seismic displacements were not linear; they were diminishing.

3.2. Impact of μ on co-seismic displacement

To study the influence of μ, λ, ρ, and the other parameters should be kept constant. Here, λ was set at 4.0×10^{10} Nm^{-2} in all the experiments. Ten groups of experiments, listed in Table 2, were designed. Each group had three cases; the parameters of case 2 and case 3 were the same, except for the μ; the value of μ in case 2 was the same as that of the footwall in case 1; the value of μ in case 3 was the same as that of the hanging wall in case 1.

The ten groups of experiments were designed to determine the medium's lateral heterogeneity caused by the μ on the co-seismic deformation. As a consequence of the differences of μ,