Some Insights into Topographic, Elastic and Self-gravitation Interaction in Modelling Ground Deformation and Gravity Changes in Active Volcanic Areas

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Abstract—Surface displacements and gravity changes due to volcanic sources are influenced by medium properties. We investigate topographic, elastic and self-gravitation interaction in order to outline the major factors that are significant in data modelling. While elastic-gravitational models can provide a suitable approximation to problems of volcanic loading in areas where topographic relief is negligible, for prominent volcanoes the rough topography could affect deformation and gravity changes to a greater extent than self-gravitation. This fact requires the selection, depending on local relief, of a suitable model for use in the interpretation of surface precursors of volcanic activity. We use the three-dimensional Indirect Boundary Element Method to examine the effects of topography on deformation and gravity changes in models of magma chamber inflation/deflation. Topography has a significant effect on predicted surface deformation and gravity changes. Both the magnitude and pattern of the geodetic signals are significantly different compared to half-space solutions. Thus, failure to account for topographic effects in areas of prominent relief can bias the estimate of volcanic source parameters, since the magnitude and pattern of deformation and gravity changes depend on such effects.

Key words: Topography, self-gravitation, displacement, gravity change.

Introduction

Surface ground deformation and gravity changes are associated with mass movement and stresses in volcanic regions. An important topic in the study of active volcanoes is the correlation of the subsurface magma movement with such surface effects, not only in order to understand the internal volcano processes, but also to detect precursors of volcanic activity. Volcano monitoring includes analysis and interpretation of such precursors through theoretical models. These are key methods for inferring the geometrical and dynamical parameters characterizing buried magma
bodies. Therefore, realistic models of magma-induced deformation and gravity changes are of great importance for the forecasting of volcanic hazards (Gudmundsson, 1986; Bianchi et al., 1987; Dvorak and Dzurisin, 1997).

The deformation due to an expanding/contracting magma chamber has frequently been modelled as a dilatational source in an elastic half space. The most commonly used volcanic deformation model corresponds to a spherically symmetric point source of dilatation in a homogeneous elastic half space (Mogi, 1958). The Mogi model does a reasonably good job in explaining vertical displacement in many cases. However, this model poses difficulties in simultaneously modelling the observed displacement and gravity changes (e.g., Kisslinger, 1975; Rymer, 1996). Rundle (1980) studied the effect of the medium properties in modelling and solved the equations that represent the coupled elastic-gravitational problem for a stratified half-space of homogeneous layers. This type of model goes one step further since it allows considering the geologically meaningful superposition of a pressurized cavity and the mass intrusion within an elastic-gravitational medium. Moreover, most deformation models assume the Earth surface as flat and use half-space solutions. While such models have been quite successful at fitting surface measurements, it is clear that local topographic relief can introduce misinterpretation into source parameter estimation.

McTigue and Stein (1984) and McTigue and Segall (1988) studied the effect of topography by means of a two-dimensional model. Cayol and Cornet (1998) and Williams and Wadge (1998, 2000) calculated the effect of the volcanic relief caused by a dilatational source in a purely elastic medium. Folch et al. (2000) considered a viscoelastic medium in order to study the effect of topography. Trasatti et al. (2003) considered topographic effects on an axisymmetric volcano shape applied to Mt. Etna. Lungarini et al. (2005) used a numerical finite-element technique to model realistic 3-D topographic effects of ground displacement at Mt. Etna. In general, the conclusion reached by these authors is that topography has a significant effect on the deformation field. Thus, approximating the Earth by a flat horizontal half space can lead to an erroneous interpretation of observed ground deformation.

The following is a study of the relative importance of elasticity, self-gravitation and topography in modelling volcanic ground deformation and gravity changes before discussing a numerical technique for including realistic topographic relief. It is expected that although self-gravitation could produce significant changes in the value and pattern of predicted gravity changes, the topographic effect can mask elastic-gravitational coupling. Thus, while elastic-gravitational models can be a far more suitable approximation to problems of volcanic loading in which topographic relief is negligible, for prominent volcanoes the ground irregularities could affect deformation and gravity changes to a more significant extent than the self-gravitation effects. This fact allows one to simplify the elastic-gravitational approach when topography is significant.