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Three Dimensional Investigation Into the Role of Increasing Edifice Pore-Pressures in Generating Volcanic Instability

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ABSTRACT

Volcano flank collapse events affect volcanic edifices where a range of different processes are at work. These processes and their complex interactions pose problems when trying to predict collapse mechanisms and timings. However, there is at least one mechanism of generating instability that may be present at all volcano collapse locations: increases of edifice pore fluid pressures from internal (gas) sources. Strangely, while the emission of volcanic gasses and their compositions are routinely monitored, the mechanical effects of the gas phase on the shear strength and structural integrity of the edifice have been mostly overlooked. Three-dimensional numerical modelling of edifice stability using $FLAC^{3D}$ provides a sophisticated means of undertaking a complex analysis of volcano instability promoted by internal pressurisation, in addition to previously recognised factors that may affect edifice stability. Five model geometries were examined over a pressure range of 0 to 20 MPa that allowed the sensitivity of gas pressure on structural stability to be assessed quantitatively. Significant reductions in stability were observed in all cases, with the most unstable edifice being a combination of 'weak' foundations and shallow regional gradient. Fully three dimensional modelling has additional advantages to the assessment of the risk posed by volcanic flank collapse. With the ability to incorporate real world topography within $FLAC^{3D}$ models, it is possible to provide valid estimates of collapse volumes, a feature not possible in even the most detailed of the conventional *2D* analyses, and a potential life-saver in the mitigation of the risk posed by volcanic flank collapse.

1. THE THEORY OF INTERNAL PRESSURISATION AND MODELLING WITH $FLAC^{3D}$

Although explosive eruptions and/or tsunamis are major consequences of volcano instability, *it is the processes that cause massive flank collapse that is the focus of this research*. Geotechnical engineers and geologists studying landslides are familiar with fluid pressurisation by water, and its modifying effects on the shear strength of soils and rocks (e.g. Voight, 1978; Bromhead, 1986). Ordinarily, this pressurisation is by groundwater of meteoric origin (external), and is rarely artesian, being hydrostatic and related to a ground water level within the slope. This leads to slopes which are stable against deeper-seated modes of failure (e.g. Bromhead, 1995). Recently, Voight and Elsworth (2000), have proposed a novel, highly non-linear instability mechanism for the hazardous collapse of lava domes, where dome failure is instigated by internal gas overpressure. Subsequent work in this area (Reid, 2004; Thomas *et al*., 2004; Vinciguerra *et al*., 2005a) has confirmed that, in principle, internal gas (fluid) pressurisation can play a critical role in promoting structural instability on a much larger scale, resulting in rapid destabilisation and massive sector collapse.

Although the specific dynamics of magma degassing are not under investigation, it is noteworthy that significant advances have been made in this field recently (Sparks, 2003; Gonnermann *et al*., 2007) and that the mode of failure proposed here is, in part a direct consequence of separation of gas from magma in addition to the heating and consequent boiling of hydrothermal systems. Steady degassing by itself need not result in deep failure of the edifice as gas may simply dissipate via fumaroles. However, a long-term or sustained high flux gas emission from depth increases the chances of developing significantly elevated pore pressures. Both these situations are likely at stratocones and also oceanic islands, where massive landslides have taken place without significant precursor eruptions.

As a first step towards understanding edifice failure we have modelled a destabilising mechanism involving gas pressurisation (e.g. Gerlach *et al*., 1996) that affects the interior of an edifice, and whose external expression is a deep-seated failure mode (landslip) that might be the cause of a catastrophic eruption. These models differ from many recent studies of volcano instability (e.g. Reid *et al*., 2001; Acocella, 2005) where the effects of internal fluid (gas) pressures are not considered and collapse is driven purely by gravity aided perhaps by regions of weak (hydrothermally altered) rock or the mechanical forces associated with direct intrusion of magma into the edifice.

$FLAC^{3D}$ (Fast Lagrangian Analysis of Continua in Three-Dimensions) is a three-dimensional explicit finite-difference program for engineering mechanics computation. $FLAC^{3D}$ is based on the long-serving numerical formulation used by the Itasca Consulting Group's two-dimensional program, *FLAC (Version 3.3, 1995)*. While *FLAC* has been shown to be a useful tool for modelling the complex system of volcanic collapse (Apuani *et al*., 2005), $FLAC^{3D}$ extends the analytical capability of *FLAC* into three dimensions, fully simulating the behaviour of soil and rock or any other materials that undergo plastic flow when their yield limits are reached.

2. MODEL GEOMETRIES

The three-dimensional modelling provides an examination of much more realistic (but still simplified) geometries than the standard two-dimensional limit equilibrium modelling. Five full three-dimensional geometries were examined (Fig. 1). A simple uniform cone on a horizontal substrate (a), A simple uniform cone on a weak horizontal substrate (b), A simple uniform cone on a dipping (1.5°) substrate (c), A composite cone consisting of a shallow lower cone and a steep upper cone (d) and a combination of all the four previously listed models (e). In each model the pressure source was defined as a cylindrical cavern with a 1500 m radius and a fixed height of 600 m (f).

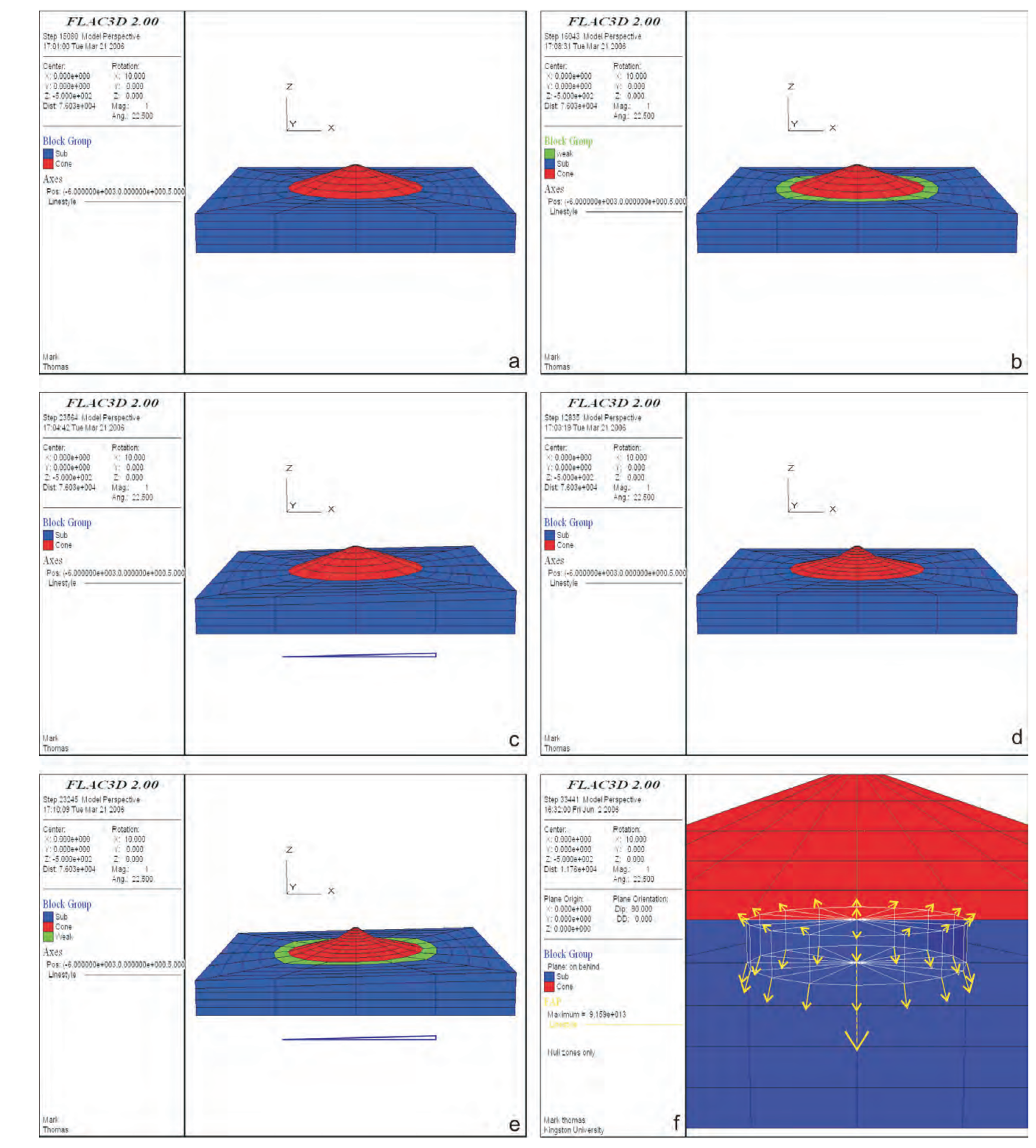

Figure 1. The five studied model geometries (a-e) and a wireframe outline of the defined region of the pressures source (f)

3. RESULTS

The state of stress within any volume can be expressed in terms of the maximum and minimum principal stresses σ_1 and σ_3. This stress state, in general, will plot as a circle, "a" with a radius r_a, on a Mohr diagram (Fig. 2).Failure will occur if this circle touches the failure envelope (Fig 2.). A *failure index* or *factor of safety* can be defined from the ratio of the radii of the two circles (r_b/r_a) shown in Figure 2, and can be defined as:

$$Fs = {r_b}/{r_a} = \frac{\sigma_3 - \sigma_{1f}}{\sigma_3 - \sigma_1}$$

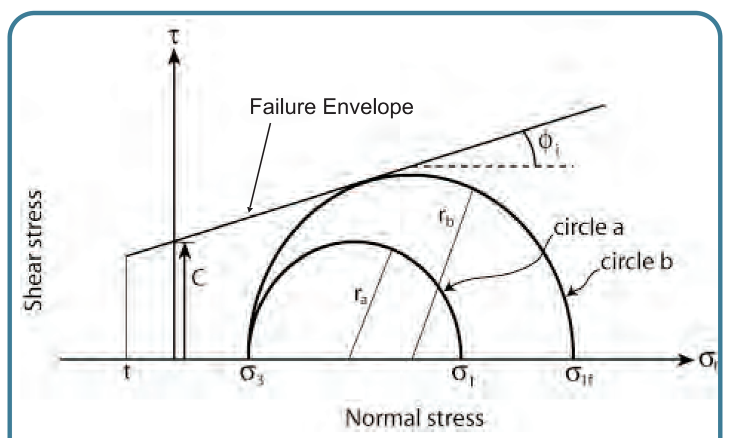

Figure 2.

Five pore pressurisation regimes, 0 MPa, 1 MPa, 5 MPa, 10 MPa and 20 MPa, were simulated for each model geometry. The applied pore fluid pressure for each stage was applied across the boundary of the defined pressure source (Fig. 1) and allowed to dissipate radially away from the source region. The results show an ubiquitous reduction in flank stability with each increase in the magnitude of the simulated pore fluid pressures. Figure 3 shows *Factor of Safety* plots for geometries (a) and (f) at simulated pore fluid pressures of 0 MPa and 20 MPa. The reduction in stability can clearly be seen from the volume of the model edifi with relatively low Factor of Safety values (Reds and Yellows) in the 20 MPa plot.

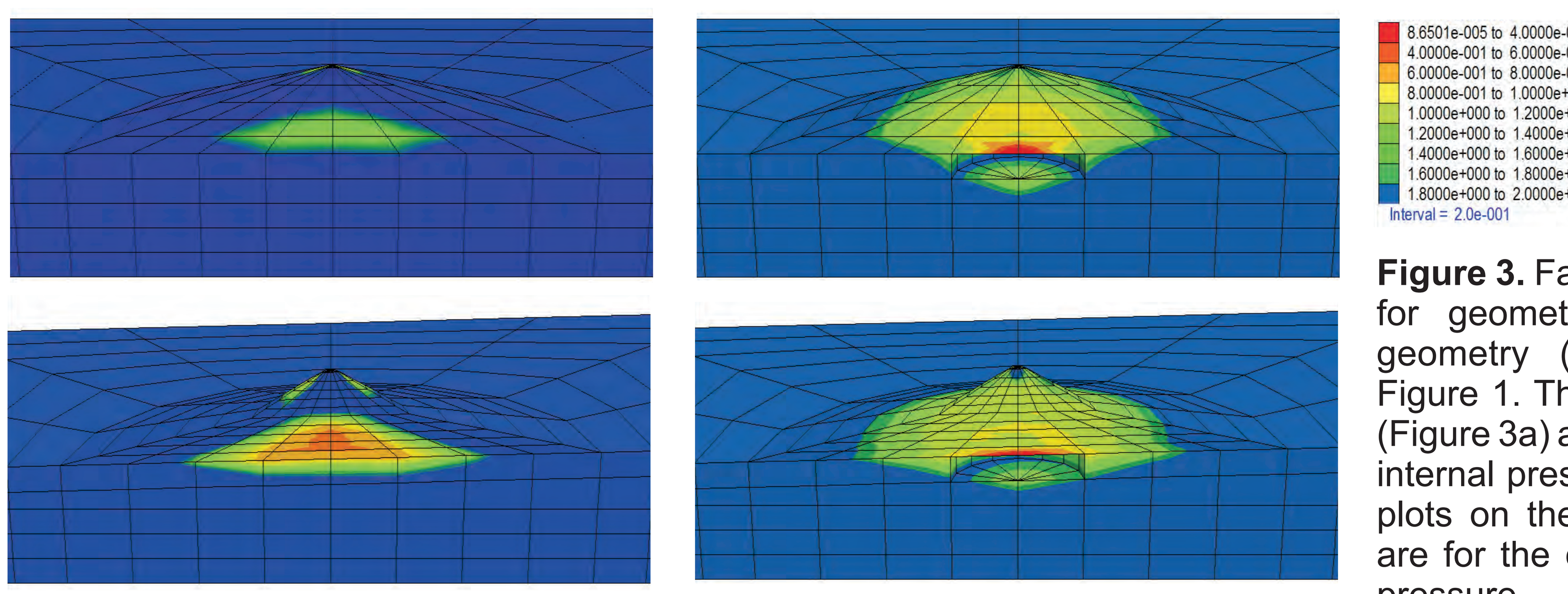

Figure 3. Factor of safety plots for geometry (a) (top) and geometry (f) (bottom) from Figure 1. The Plots on the left (Figure 3a) are for a case of no internal pressurisation and the plots on the right (Figure 3b) are for the case of a 20 MPa pressure.

4. WHAT NEXT ?

The latest addition to the $FLAC^{3D}$ program suite, 3D*Shop*, is a geometry modelling and automatic meshing option for $FLAC^{3D}$. It allows the relatively routine use of real world topography to generate the finite difference grid. This combined with detailed mapping of any particular feature and the use of geophysics to interpret the internal structure allows the potential for a new level of realism and accuracy in hazard prediction.

Shown below is a $FLAC^{3D}$ geometry created in 3D*Shop* showing real world topography of a section of slope. Superimposed on the slope is displacement magnitude after a 0.34g earthquake with a duration of 55 seconds. This demonstrates (a) the ability of $FLAC^{3D}$ to model complex real world geometries, and (b) its applicability as a hazard prediction

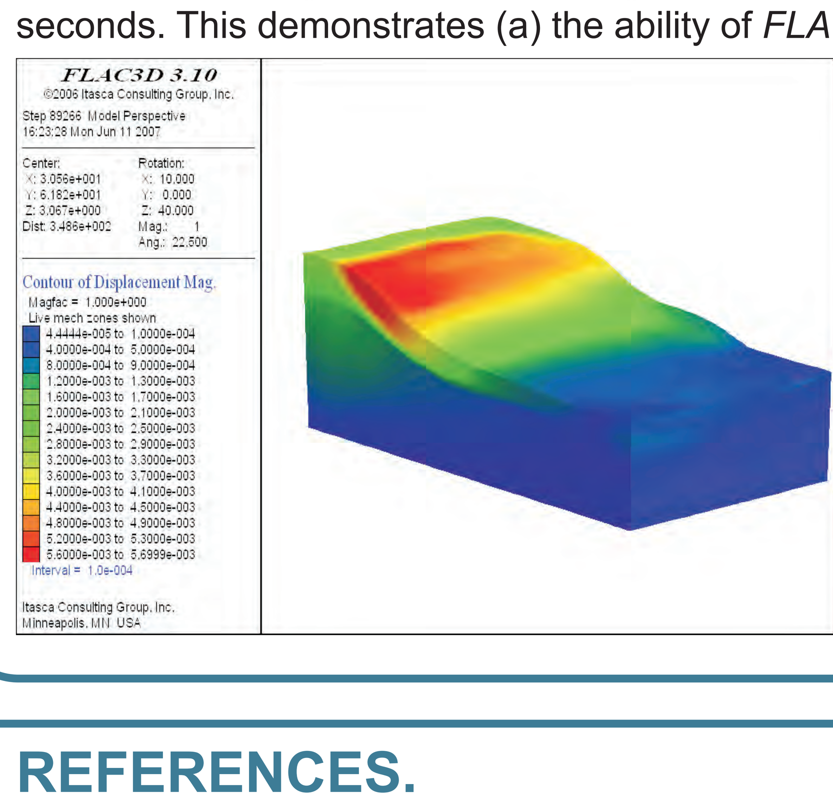

Figure 4. $FLAC^{3D}$ model constructed and analysed as part of seismic and slope stability risk assessment undertaken by STATS Limited.

5. DISCUSSION.

At a simulated pore fluid pressure of 20 MPa, the destabilising effect observed within the models was not sufficient to initiate collapse, even in the most mechanically unsound model, geometry (e). Although, Factor of Safety values approaching unity were recorded (Fig. 3b), suggesting that model geometry (e) was very close to failure. Even though failure did not occur an important observation is the volume of the edifice that is destabilised, regardless of the model geometry. Large reductions in stability were observed in all the models at significant distances from the pressure source. This indicates that deep-sourced internally elevated pore fluid pressures are an efficient mechanism of remotely destabilising large regions of a volcanic edifice. It is therefore proposed that the role of internal pore fluid (gas) pressure, which potentially act at every "active" volcano, is one of general *destabilisation* rather than a full-scale triggering of a collapse event, and that this destabilising effect will leave an edifice susepitable to even small endogenic or exogenic triggers e.g. a seismic event. It is also possible that if an edifice is weak enough then this destabilising effect may be enough to trigger collapse.

The ability to now render fully three-dimensional models in 3D*Shop* using real world topography (See Fig 4.) brings an unprecedented level of realism to the numerical modelling. This, in combination with detailed field and geophysical mapping of the physical properties of an edifice, or indeed any critical slope, has the potential to drastically improve hazard prediction and mitigation from such catastrophic events.

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