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Observations and finite element modeling of the Aso Caldera depression zone resulting from the 2016 Kumamoto Earthquake

Observations et modélisation des éléments finis de la zone de dépression de l'Aso Caldera résultant du séisme de Kumamoto de 2016

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ABSTRACT: The Geotechnical Extreme Events Reconnaissance (GEER) Association, funded by the United States National Science Foundation (US NSF), conducted a reconnaissance of the Kumamoto region following the April 16th M_w 7.0 earthquake in Japan. One of the major case histories identified as a part of the GEER reconnaissance was a large depression zone that developed in the western portion of the Aso Caldera. Vertical surface displacements of up to several meters occurred in a zone of the caldera approximately 30-m to 110-m wide and 10-km long. This paper presents preliminary finite element models investigating whether the observed ground deformation is consistent with potential displacement along a fault.

1 INTRODUCTION

The Geotechnical Extreme Events Reconnaissance (GEER) Association, funded by the United States National Science Foundation (US NSF), conducted a reconnaissance of the Aso Caldera depression zone May 12th and 13th, 2016 following the April 16th M_w 7.0 Kumamoto Earthquake in Japan.

Detailed three-dimensional surveys of the deformed ground surface and affected structures were created over several kilometers of the depression zone by GEER using terrestrial LiDAR and Structure from Motion (SfM) from UAV video. Details on these measurement methods are available in Kayen et al. (2016). Vertical surface displacements of 0.5 m to 2.5 m (average of 0.5 m to 1.25 m) were measured in a zone 30-m to 110-m wide (average 50-m to 65-m wide) within the Aso Caldera, as shown in Figure 1, for a length of approximately 10 km. A bridge and a number of structures were affected by the ground deformation in this zone. According to local residents, the depression zone formed coseismically with the Kumamoto mainshock (Konagai et al. 2017).

Various earthquake investigation teams were unable to definitively identify the cause of the ground depression in the field. Various theories, such as ash-layer compaction, liquefaction, lateral spreading, and surface fault rupture, were considered (e.g., Konagai et al. 2016). Although the depression zone extends out roughly linearly from the northern end of the Futagawa Fault, and one trench study in 2015 found evidence of previous normal faulting at the depression zone from two thousand years ago (Konagai et al. 2017), no part of the depression zone was included in regional fault maps. Recent finite-fault studies (e.g., Yagi et al. 2016) have found no evidence of seismogenic rupture inside of the Aso Caldera, with seismogenic (strike-slip) rupture on the causative Futagawa Fault terminating at the approximate edge of the caldera. Lin et al. (2016) found that the seismogenic strike-slip fault may have been blocked by the hot temperature of the Aso magma chamber, which may have induced an upward pressure that resulted in the formation of an extension zone in the caldera. InSAR analyses

estimated the western portion of the caldera moved downwards by about 0.5 m and north-northwest by about 2.0 m (Himematsu and Furuya 2016) or 1.0 m north-northwest (Tsuji et al. 2017). Deformation of well casings adjacent to the depression zone indicated the presence of slip along a roughly flat plane 50 m below the ground surface (Tsuji et al. 2017).

The potential mechanism investigated in this paper for the formation of the Aso Caldera depression zone is fault movement resulting from the potential extensional stresses induced in the caldera by interaction between the Futagawa Fault and the Aso magma chamber. Calderas have numerous faults owing to their complex history of caldera collapse and resurgence and likely from pre-existing extensional structures and regional faults (e.g., Acocella et al. 2004, Geyer and Marti 2014). This paper presents preliminary finite element modeling results of whether the observed depression zone is consistent with potential displacement along an extensional fault.



Figure 1. The depression zone as viewed by GEER from a local bridge.

2 FINITE ELEMENT MODEL

A preliminary 2D finite element model was developed of the depression zone to analyze the expected surface deformations resulting from potential surface fault rupture. The numerical

modeling methodology general follows that presented in Oettle and Bray (2017).

General soil conditions in the Aso Caldera were based on publically available borings that recorded 20 m to 70 m of very soft lacustrine clay, reaching a void ratio of 5 to 7, over bedrock (Kayen et al. 2016). Therefore the NGI-ADP constitutive model (Grimstad et al. 2012) was selected for the lacustrine clay due to its advanced consideration of divergent stress paths present in normal faulting and for its well-defined failure strain, which is important for modeling surface fault rupture (Bray et al. 1994, Oettle and Bray 2017). Detailed laboratory testing of the clay was not available for the depression zone, so general soft clay model parameters were selected. The key selected parameters are unit weight 13 kN/m^3 , G_w/S_u^A 500, γ_f^C 0.5%, γ_f^E 3.0%, γ_f^{DSS} 2.0%, s_u^A ref 35 kPa, s_u^P/s_u^A 0.4, s_u^{DSS}/s_u^A 0.7, and K_0 0.5. The thickness of the lacustrine clay was assumed to be 32 m for this model, which was a typical depth to bedrock recorded in the available boring logs.

It was hypothesized that a normal fault could potentially cause the development of the depression zone through thick, soft soil deposits. Therefore a normal fault was implemented at the bottom of the finite element model (i.e., at the top of bedrock) as a displacement boundary condition. The fault dip was assumed to be zero based on well deformations reported in Tsuji et al. (2017). Horizontal movement was assumed to be 1 m to 2 m based on reported InSAR measurements.

3 RESULTS

The finite element results were remarkably consistent with the observed depression zone. The resulting width of the trough caused by fault rupture was approximately 60 m, consistent with the typical width of the Aso depression zone of 50 m to 65 m. The peak vertical downward movement in the approximate center of the soil graben was about 0.5 m to 1.0 m (for an assumed causative horizontal movement of 1 m to 2 m), also consistent with typical measured movements in the Aso depression zone of 0.5 m to 1.25 m. Results from the finite element model are provided in Figure 2.

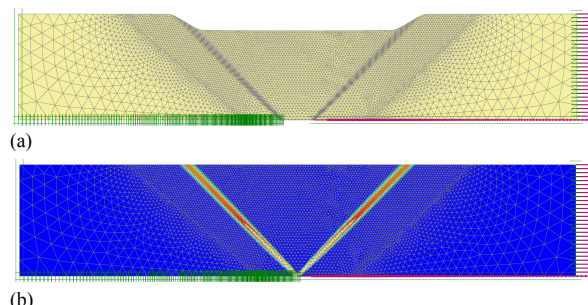


Figure 2. Finite element model results of faulting in the Aso Caldera (for a horizontal movement of 2 m) as a potential mechanism for the development of the depression zone. (a) A deformed mesh exaggerated by a factor of 5, and (b) a contour plot of shear strain.

4 CONCLUSIONS

This finite element study showed that the depression zone observed in the Aso Caldera can be well explained by a single, flat or low-angle normal fault in the bedrock underlying the deep, soft lacustrine deposits of the caldera. Ground surface deformation resulting from normal faulting through thick sediments is known to be complex, including expression of a secondary antithetic fault (Bray et al. 1994), as observed in these modeling results. It is these soil mechanics that likely caused the depression zone to form.

The underlying fault movement may have occurred on one of the numerous faults expected in the caldera, possibly as a result of an extensional stress regime induced by the Futagawa Fault interaction with the magma chamber (Lin et al. 2016). However, unlike the Lin et al. (2016) model, we feel it is unlikely that two separate faults ~60 m apart extended parallel 5 km down into the caldera rock. More likely, the depression zone is only present in the lacustrine deposits, with a single flat or low-angle normal fault in the bedrock, movement along which was likely non-seismogenic based on finite-fault studies.

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