SEISMIC DISPLACEMENTS IN THE ASO CALDERA DEPRESSION ZONE, 2016 M7 KUMAMOTO, JAPAN EARTHQUAKE


Tuesday, June 26 – Friday, June 29: Talk 1646
Outline:

- GEER Reconnaissance of the Kumamoto Earthquake
- Evidence of landslide at Aso Crater
- Ground motions and forward directivity-pulses of fault-proximal records in Aso Caldera
- Analysis of seismic displacement under multidirectional earthquake shaking
- Conclusions
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<td>Team</td>
<td>Robert Kayen Shideh Dashti</td>
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<td>Collaborators</td>
<td>The Japanese Society of Civil Engineering (JSC), The Japanese Geotechnical Society (JGS), Japan Water Works Association, Kumamoto City Waterworks and Sewage Bureau</td>
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Kumamoto Earthquakes
4-14-2016, M6.0, 6.2
4-16-2016, M7.0
Extreme shaking at East Kumamoto/Mashiki town
PGA>1g, PGV>100 cm/s

40 km Surface Rupture zone terminates on flank of Aso Caldera (Lin, et al. 2016)

(Tsuji, 2017)
Surface fissures and SAR-Interferogram of landslide zone (Nakano, et al. 2016)
Sediment properties:

Deformation zone is directly associated with lakebed deposits of Pleistocene Lake Aso (Nakano, et al. 2016). Fine-grained clay and silt particles derived from ash/weathered rock and pumice.
Surface Evidence of ground displacement: Extensional zone upslope termed “Depression Zone”
Initial hypothesis’ (1) Normal fault displacement in caldera ring fault, (2) Landslide feature, (3) volumetric collapse of volcanic ash or sensitive soil. (No surface evidence of Liquefaction!)

Downslope (<1.0°) to north
Head Scarp Zone

Interpretation from GEER-Team TLS-LIDAR and SFM 3D model

- 3D model from UAV flights

~50-100 m wide & 1-2 meters of depression. Slopes of 0.1°-1.0° toward the north (toward outer edge of Aso Caldera sediment)
Clear evidence of Compression & landslide slide toe (GEER)

Figure 4. Pictures of the boreholes and drill pipes that deformed during the mainshock on 16 April, 2016. (a,b) Images taken inside the casing pipe show the bending of the borehole at ~50 m. The diameter of the borehole casing is 150 mm. The yellow dashed lines in panels (a and b) indicate the same depth within the casing. Lower panels show a schematic image of the observed borehole. (c) The drill pipe installed within well C was bent during the 16 April earthquake; un-deformed drilling pipes (left) and the deformed pipes (right). Each pipe is 6 m long and 88.9 mm in diameter. The locations of the wells are displayed in Fig. 2c.
At 50m depth the soil profile indicate pumice and fines derived from ash, from soil borings for hot spring area reported by Tsuji, et al. 2017.

(Surface features and borehole evidence are counter to normal faulting hypothesis.)
Ground Motions: Kumamoto Earthquake, 4/14 M6.2, 4/16 M7.0 (Red/Blue): PGA vs PGV
On-fault axis forward directivity pulse: KMM004 (Asozan)

Off-fault axis, normal record: KMM007 (Takamori)

\[ \text{PGAEW} = 0.32 \text{g} \quad \text{PGAEW} = 0.43 \text{g} \]

\[ \text{PGANS} = 0.26 \text{g} \quad \text{PGANS} = 0.27 \text{g} \]

\[ \text{PGVEW} = 42 \text{ cm/s} \quad \text{PGV}_{\text{EW}} = 40 \text{ cm/s} \]

\[ \text{PGV}_{\text{EW}} = 73 \text{ cm/s} \quad \text{PGV}_{\text{EW}} = 83 \text{ cm/s} \]

\[ \text{PGA}_{\text{NS}} = 0.26 \text{g} \quad \text{PGA}_{\text{NS}} = 0.27 \text{g} \]
Multi-directional compliant seismic displacement model

- Earthquake record rotated into Strike and Dip Components
- Displacements can occur when the combined strike and dip induced stresses exceed the soil yield surface
- Soil yielding is defined in NSP terms.
- The **combined strike and dip-directed stress vector is a better representation of total shear stress on the failure plane**. Traditional Newmark analysis neglect strike motions and underestimates basal shear stresses.

Earthquake stresses are added to static slope gravitational shear stress.
Traditional Newmark Analysis

- Only dip-directed motion considered
- No estimation of excess pore water (no adjustment in effective stress $p'$ or strain-dependent strength, $s'$)

Inclined ground – slope stress ($\gamma' h \sin \alpha$) above the ‘hydrostatic line’

Earthquake-induced stress superimposed on slope stress

Stresses exceeding the soil yield surface drive downslope seismic displacements
Traditional Newmark Analysis

\[ \tau \text{ (down dip slope)} \]

\[ q \]

\[ \tau \text{ (up dip slope)} \]

Multi-Directional Newmark Analysis

\[ p' \]
Traditional Newmark Analysis

τ (down dip slope)

q

τ (up dip slope)

Multi-Directional Newmark Analysis

Slope Stress

Hydrostatic line
Traditional Newmark Analysis

\[ q \]

\[ \tau \text{ (down dip slope)} \]

\[ \tau \text{ (up dip slope)} \]

Multi-Directional Newmark Analysis

- Slope Stress
- Hydrostatic line
Slope Stress

Hydrostatic line

τ (down dip slope)

τ (up dip slope)

Traditional Newmark Analysis

Multi-Directional Newmark Analysis
Traditional Newmark Analysis

Multi-Directional Newmark Analysis

\[ q \]

\[ \tau \text{ (down dip slope)} \]

\[ \tau \text{ (up dip slope)} \]

Slope Stress

Hydrostatic line
Traditional Newmark Analysis

Multi-Directional Newmark Analysis

\( q \)

\( \tau \) (down dip slope)

\( \tau \) (up dip slope)

Slope Stress

Hydrostatic line
Traditional Newmark Analysis

μ (down dip slope)

μ (up dip slope)

Slope Stress

Hydrostatic line
Traditional Newmark Analysis

τ (down dip slope)

q

τ (up dip slope)

Multi-Directional Newmark Analysis

Slope Stress

Hydrostatic line
Traditional Newmark Analysis

Multi-Directional Newmark Analysis

τ (down dip slope)

q

τ (up dip slope)

Slope Stress

Hydrostatic line
Traditional Newmark Analysis

\( \tau \) (down dip slope)

Slope Stress

Hydrostatic line

\( \tau \) (up dip slope)

Multi-Directional Newmark Analysis
Earthquake motions are superimposed on static slope stress

\[ \tau \text{ (down dip)} \]

\[ \tau \text{ (up dip)} \]

\[ \tau \text{ (strike left)} \]

\[ \tau \text{ (strike right)} \]

Multi-Directional Newmark Analysis

Stresses exceeding the soil yield surface drive Strike and Dip-directed seismic displacements

\[ \theta = \tan^{-1} \left[ \frac{\sum \tau_{\text{strike}}}{\sum \tau_{\text{dip}}} \right] \]

Critical State - Associated Flow rule (Wood, 1991) used to control the direction of seismic displacement:

\[ \theta = \tan^{-1} \left[ \frac{\sum \tau_{\text{strike}}}{\sum \tau_{\text{dip}}} \right] \]
Yield Acceleration, $k_y$, in terms of geotechnical Normalized Soil Parameter (NSP) Framework

$\gamma_w =$ water density  
$\gamma =$ soil bulk density  
$h_w =$ water table depth (~2 meters, flooded areas in depression zone)  
$H =$ depth to base of landslide (50 m)  
$S_n=$effective stress normalized strength (~0.3)  
OCR = Overconsolidation ration (assumed to be 1.0)  
$\alpha =$ slope angle in degrees (0.1°-1.0°)

$$k_y = \left[1 - \frac{\gamma_w}{\gamma} \left(1 - \frac{h_w}{H}\right)\right] \frac{A_c A_r S_n (OCR)^{\gamma_o}}{\cos^2 \alpha} - \sin \alpha$$

Traditional simple sliding block frictional definition of yield acceleration, $k_y$

$$k_y = (FS - 1) \times \sin \alpha$$

At Aso, we assumed $S_n=0.3$, OCR=1.0. Boring, typical soil properties!
Aso Ground Motion (KMM004)

A) Computed dip loads and capacity

B) Displacements 1.0°, slope to north (001°)

- Currently: scale record down to estimate 50m.
- Future: need to deconvolve 50m record based in $V_s$

B) Strike displacements (181°)
Combining strike and dip displacements – seismic displacement trajectory

Compliant model uses shear wave velocities from SPAC and SASW surface wave tests collected in 6/17 and 12/17 (~320m/s ave.)
Aso Record w/ forward directivity
Displacement Trajectory: KMM004

Takamori Record, off fault axis
Displacement Trajectory: KMM007
Conclusions

• Liquefaction (Fujiwara, 2016)? Possible, but not Likely.
  • Reducing strength $S_n$ to $S_r$ leads to similar/smaller & reversible displacements on nearly flat slopes.
  • Computed displacements become more East-West directed due to ground motion, NOT Observed in field.
  • Liquefaction at 50m exceeds any observation in global case-history database by 250%. No surface indication.
  • SPAC & SASW velocities $V_{s,50m} \sim 320$ m/s, non-liquefiable material (Kayen et al. 2013; Andrus & Stokoe, 2000).
Conclusions:

- Large ground displacement feature (10km$^2$) observed in former lakebed deposits of Aso Caldera, thickness 50m.

- Ground motions indicate forward directivity along axis of fault rupture.

- Multi-directional seismic sliding-displacement model support field observations of landslide trajectory using normal soil strength estimates ($S_n=0.3$, OCR=1.0)

- Liquefaction not required to achieve 1-2 meters of seismic displacement. No liquefaction field evidence.

- Feature is likely seismic block displacement in lake-bed deposits in ash basal layer deposit located at 50 meters.