Nonlinear body waves in the shallow subsurface, implications of flow-law rheologies

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Behavior of soil in strong shaking

- Traditional approach
- Pseudo-elastic
- Masing rules
- Testable non-intuitive features
  - Stress stays constant at constant strain
  - Strain stays constant at constant stress
Flow flow rheology

- Strain RATE depends nonlinearly on STRESS
- Plastic, rate and state friction, and nonlinear viscosity are well known.
- Widely used in Earth science – Plate pushing
- Stress is
  - Shear modulus *
    (total strain – anelastic strain)
Flow flow rheology

- Strain RATE depends nonlinearly on STRESS
- Damage rate:
  - Change in shear modulus with time is proportional to anelastic strain rate
  - Healing occurs
- Stress is
  - Shear modulus \(*\)
  (total strain – anelastic strain)
  Model result
Friction: scaling

- Ratio of dynamic stress to lithostatic stress (Coulomb stress ratio) is dynamic acceleration in g’s.
- S wave acceleration in g’s clips at effective coefficient of friction.
- Observed

- Strong P waves
- Downward dynamic acceleration of 1 g produces vertical tension on horizontal planes.
- Weakens planes for shear stress.
- Should suppress S-waves
- Observed
Viscous mud (predicted and observed)

• Nonlinear shear failure begins at low dynamic shear stress.
• Anelastic strain rate increases gradually with dynamic stress.
• Normal traction may not matter much.
• Detect with decrease of soil resonant frequency from anelastic damage.
• Large dynamic accelerations are not strongly suppressed.
• Tensional P-waves may not suppress S waves.
Kumamoto earthquakes

- KMMH16
- Thin natural volcanic soil
- Complicated reverberating layer
- Co-located surface and borehole station
Kumamoto earthquakes

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- Thin natural volcanic soil
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- Transfer function from small events
- Reverberation frequency decreases and then recovers
Transfer function prediction-Mainshock
Strong Kumamoto foreshock

- Strong S waves arrived during strong tensional P waves
- Viscous not frictional
- P wave overtakes S wave
Net effects

• Direct diminution of energy by nonlinear attenuation.
• Damage decreases resonant frequency and strengthens resonance.
• Incoming signal is somewhat stronger at lower resonant frequency.
• It takes time for elastic moduli to recover after shaking.
• Horizontal: Tohoku FKSH10
Nonlinear interaction of seismic waves

- Natural experiments
- S and P waves (this talk)
- Reverberating S waves arrive before fault tip.
- Nonlinearly weaken soil above tip.
- Distributed zone of shallow damage
Practical implications

- We do not advocate jettisoning of established engineering practice.
- Still flow-law rheologies including friction and nonlinear viscous flow provide testable predictions.
- 1-D calculations easy
- 3-D calculations feasible but burdensome.

KMMH16 for the Kumamoto mainshock