Nonlinear Soil Modeling for Seismic NPP Applications

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Outline

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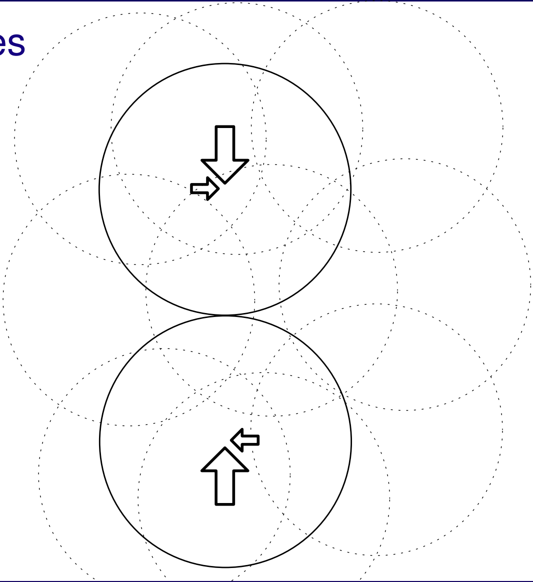
The Problem

- Seismic response of Nuclear Power Plants
- Soil modeling in particular
- Linear elastic
- Equivalent Linear Elastic (current state of practice/art)
- 3D elastic-plastic modeling
- Combine frictional (elastic-plastic, displacement proportional) and viscous (velocity proportional) energy dissipation in one model.

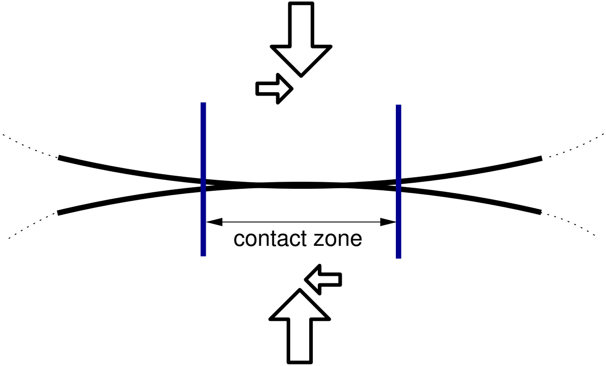
Granular Materials

- Pressure sensitive materials (particles)
- Usually assumed to be linear elastic (at least in the NPP field (?!))
- Can be (rigorously) shown that as they can never be linear elastic (with normal and/or shear contact forces.
- R. D. Mindlin and H. Deresiewicz. Elastic spheres in contact under varying oblique forces. ASME Journal of Applied Mechanics, 53(APM-14):327-344, September 1953.
- Izhak Etsion. Revisiting the Cattaneo-Mindlin concept of interfacial slip in tangentially loaded compliant bodies. Journal of Tribology, 132(2):020801, 2010.

Two Spheres

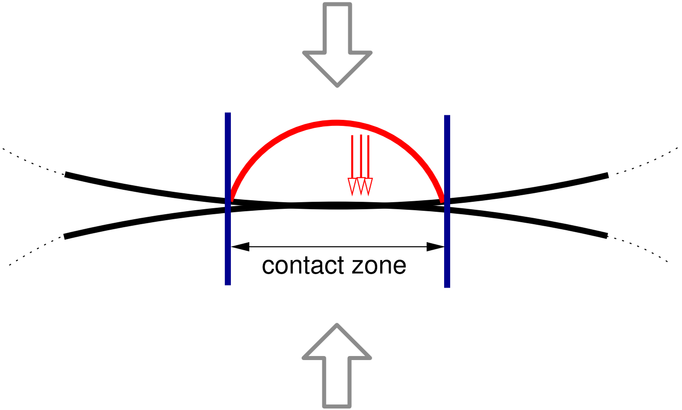


Contact Zone



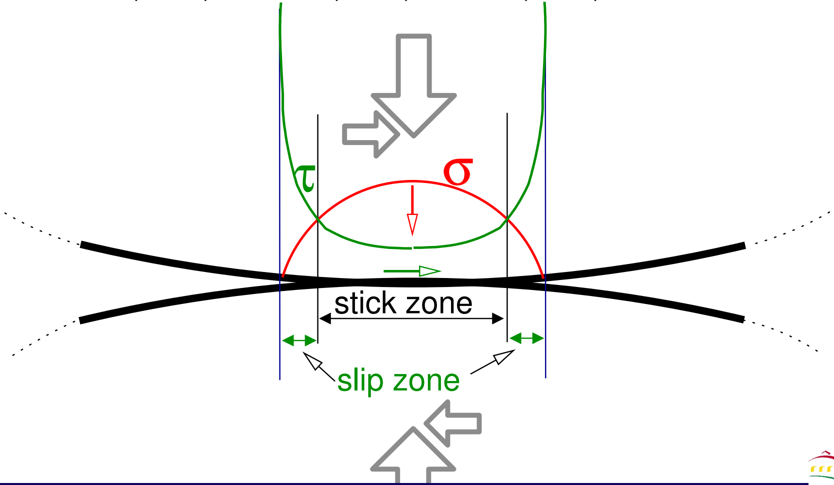
Normal Stresses

Hertz (1882)



Normal and Shear Stresses

Cattaneo (1938), Mindlin (1949), Etsion (2010)



Granular Materials (Summary)

- Particulate materials are never linear elastic

Outline

von Mises perfectly plastic model

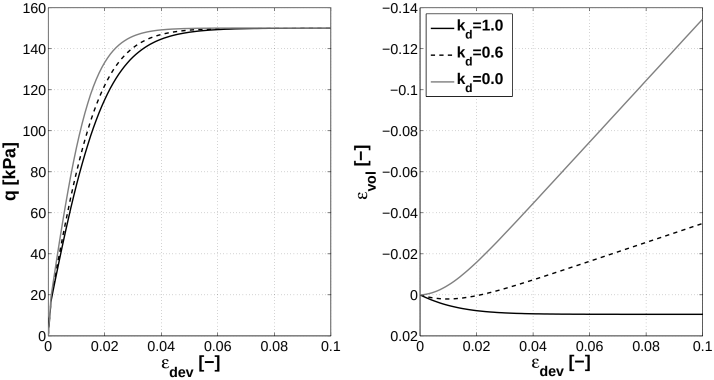
- $f = \sqrt{\frac{3}{2} s_{ij} s_{ij}} - \sigma_0 = 0$
- undrained shear strength s_u ($s_u = \sigma_0 / \sqrt{3}$)

Drucker-Prager kinematic hardening model

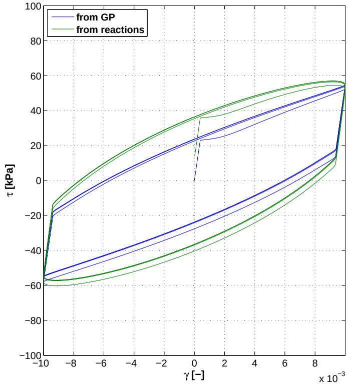
- $f = \sqrt{\left(s_{ij} - p\alpha_{ij}\right)\left(s_{ij} - p\alpha_{ij}\right)} - \sqrt{\frac{2}{3}}kp = 0$
- $\epsilon_{ij}^{p} = \dot{\lambda} m_{ij},\ m_{ij} = \left(\frac{\partial f}{\partial \sigma_{ij}}\right)^{dev} - \frac{1}{3} D \delta_{ij},$

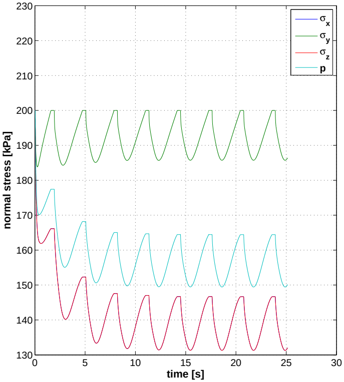
  dilatancy coefficient $D = \xi \left(\sqrt{\frac{2}{3}} k_d - \sqrt{r_{mn} r_{mn}}\right)$
- $\dot{\alpha}_{ij} = \frac{2}{3} h_a \left(\epsilon_{ij}^{p}\right)^{dev} - c_r \alpha_{ij} \sqrt{\frac{2}{3} \left(\epsilon_{rs}^{p}\right)^{dev} \left(\epsilon_{rs}^{p}\right)^{dev}}$

Drucker-Prager kinematic hardening model

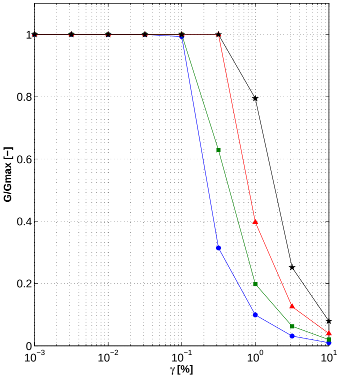


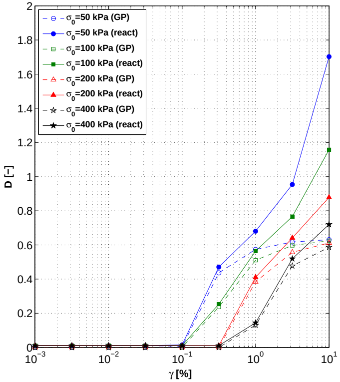
Drucker-Prager Kinematic Hardening Model with Viscosity



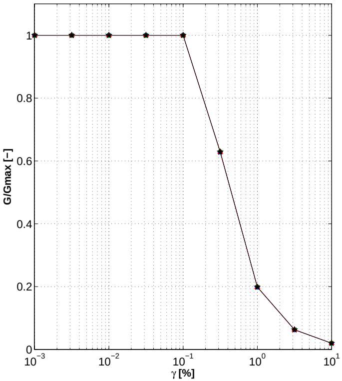


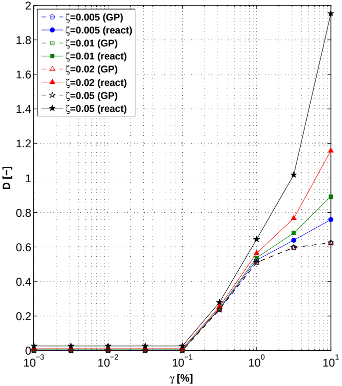
DK - Variation in Yield Stress



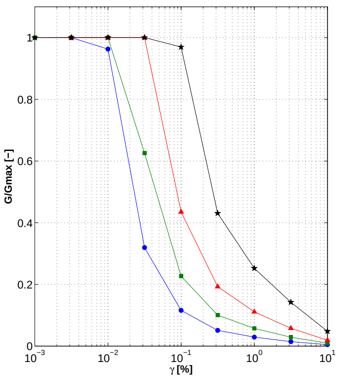


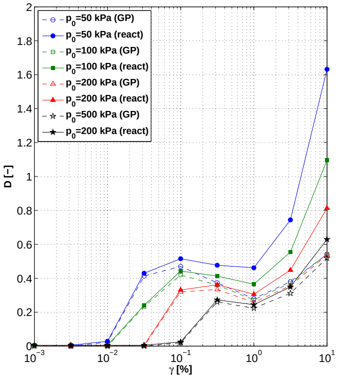
DK - Variation in Damping Coefficient



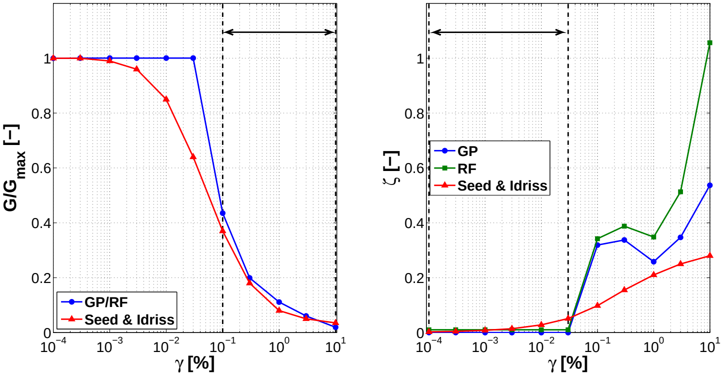


DK - Variation in Initial Confinement





Comparison with G/G_{max} and Damping Curves



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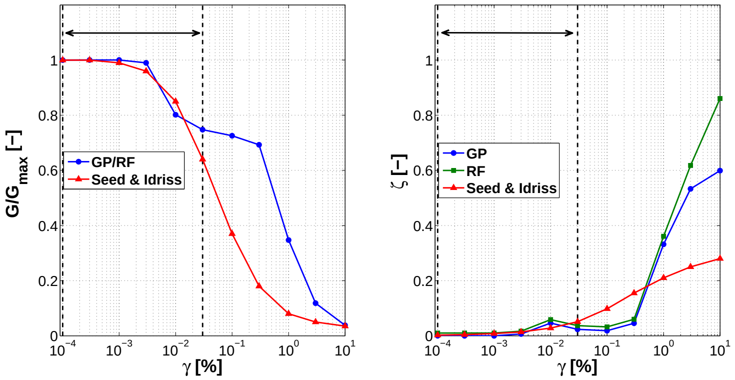
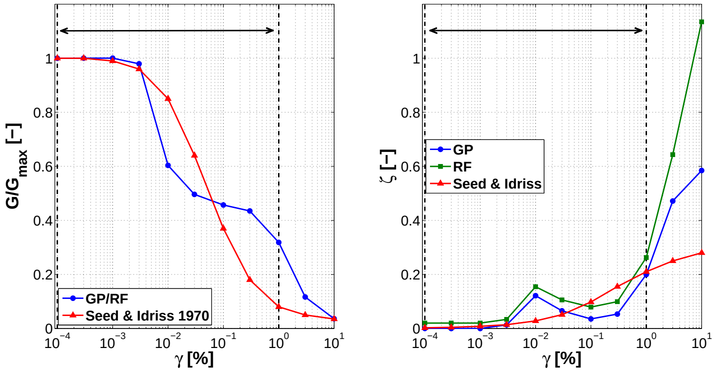


Comparison with G/G_{max} and Damping Curves



PJ Model: Assumptions

- Split stress into frictional and viscous components
  $\sigma_{ij} = \sigma_{ij}^{f} + \sigma_{ij}^{v}$
- Remove the elastic region (limit analysis)
- Rotating kinematic hardening

PJ Model: Elasticity

$$d\sigma_{ij} = D^{e}_{ijhk}\left(d\epsilon_{hk} - d\epsilon^{p}_{hk}\right)$$

$$ds_{ij} = 2G_{max}\left(de_{hk} - de^{p}_{hk}\right)$$

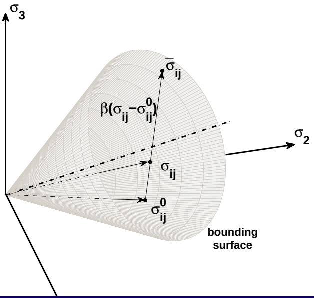
$$dp = -K\left(d\epsilon_{vol} - d\epsilon^{p}_{vol}\right)$$

where $p = -\sigma_{kk}/3$, $\epsilon_{vol} = \epsilon_{kk}$, $s_{ij} = \sigma^{dev}_{ij}$, $e_{ij} = \epsilon^{dev}_{ij}$, $G_{max} = E/2\left(1+\nu\right)$ and $K = E/3\left(1-2\nu\right)$

PJ Model: DP Yield and Bounding Surface

$$f_y = \frac{3}{2}\left(s_{ij} - p\alpha_{ij}\right)\left(s_{ij} - p\alpha_{ij}\right) - k^2 p^2 = 0$$

$$f_B = \frac{3}{2} s_{ij} s_{ij} - M^2 p^2 = 0$$



PJ Model: Plastic Flow and Translation Rule

Borrowed from Manzari and Dafalias (1997)

$$d\epsilon^{p}_{hk} = d\lambda \left(n^{dev}_{ij} - \frac{1}{3} D \delta_{ij} \right)$$

$$D = \xi \left(\alpha^{d}_{ij} - \alpha_{ij} \right) n^{dev}_{ij} = \xi \left(\sqrt{\frac{2}{3}} k_d n^{dev}_{ij} - \alpha_{ij} \right) n^{dev}_{ij}$$

$$d\alpha_{ij} = \| d\alpha_{ij} \| n^{dev}_{ij}$$

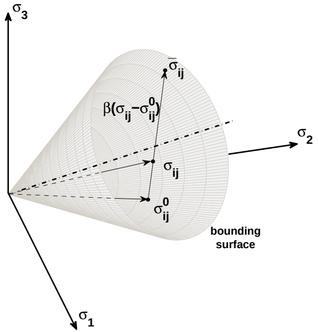
PJ Model: Vanishing Elastic Region

$$\lim_{k\to 0} f_y = 0 \Rightarrow \lim_{k\to 0} s_{ij} = p\alpha_{ij} \Rightarrow ds_{ij} = d\alpha_{ij}p + \alpha_{ij}dp$$

$$n_{ij}^{dev} = \frac{ds_{ij} - \alpha_{ij}dp}{\|ds_{ij} - \alpha_{ij}dp\|}$$

$$\|d\alpha_{ij}\| = \frac{1}{pN^{dev}} \frac{\partial f}{\partial \sigma_{ij}} d\sigma_{ij}$$

$$\|d\alpha_{ij}\| = \sqrt{\frac{2}{3}} \frac{dq}{p}$$



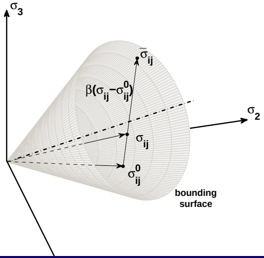
PJ Model: Hardening Modulus and Plastic Multiplier

$$\|d\alpha_{ij}\| = \frac{2}{3}\frac{Hd\lambda}{p}$$

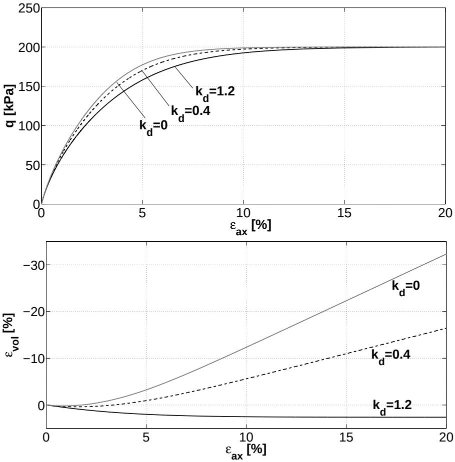
$$d\lambda = \frac{2G_{max}\|de_{ij}\| + Kd\epsilon_{vol}\alpha_{ij}n_{ij}^{dev}}{2G + \frac{2}{3}H - KD\alpha_{ij}n_{ij}^{dev}}$$

PJ Model: Stress Projection, Hardening and Unloading

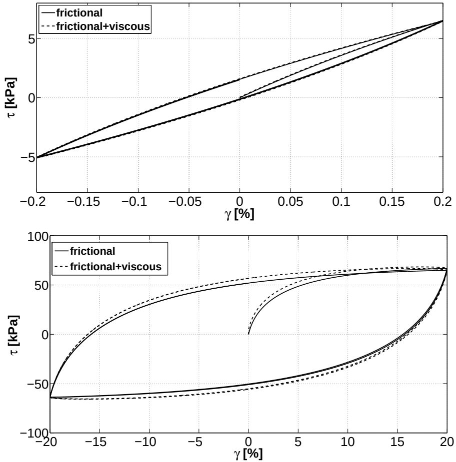
$$d\beta = -(1+\beta)\frac{\bar{s}_{ij}ds_{ij} - \dfrac{2}{3}M^2\bar{p}dp}{\bar{s}_{ij}\left(s_{ij}-s^0_{ij}\right) - \dfrac{2}{3}M^2\bar{p}\left(p-p^0\right)} > 0$$



PJ Model: Triaxial Response



PJ Model: Pure Shear Cyclic



PJ Model: Calibration for G/G_{max} and Damping

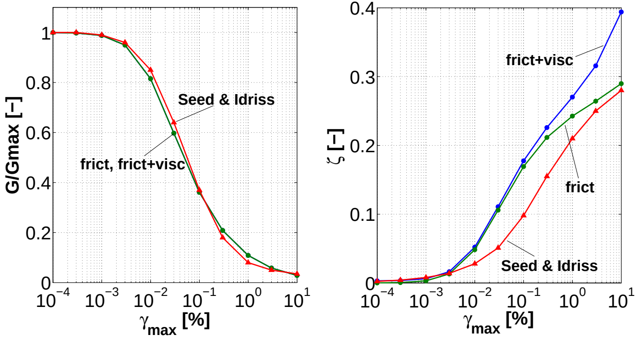


Figure: Comparison between experimental and simulated G/G_{max} and damping curves (p_0=100 kPa, T=2π s, ζ = 0.003, G_{max} = 4 MPa, ν=0.25, M=1.2, k_d=ξ=0, h=G/(112p_0), m=1.38)

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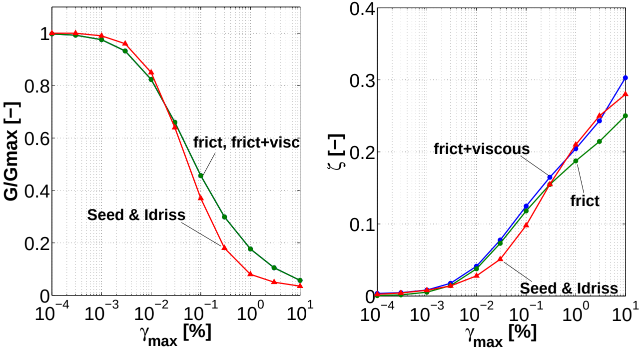

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PJ Model: Variation in Confining Pressure

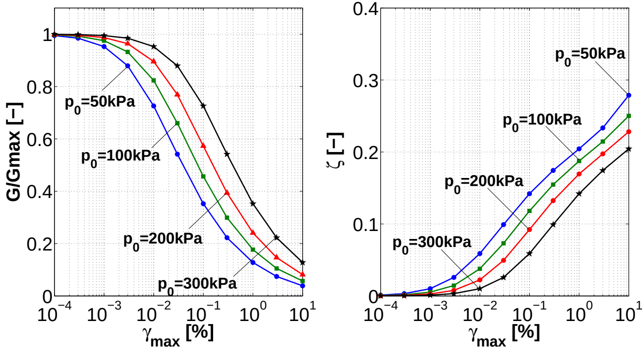

Figure: Simulated G/G_{max} and damping curves at varying confining pressure (T=2π s, G_{max} = 4 MPa, ν=0.25, M=1.2, k_d=ξ=0, h=G/(15p_0), m=1)

PJ Model: Variation in Hardening Parameter *h*

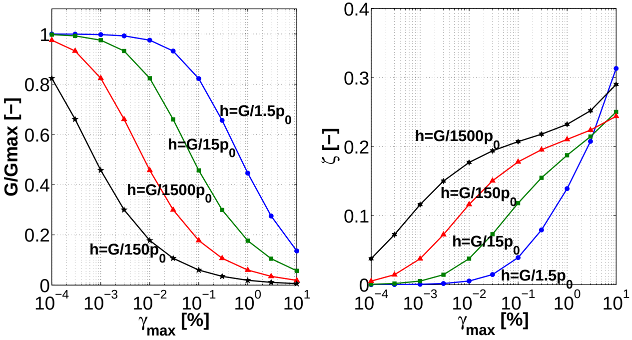

Figure: Simulated G/G_{max} and damping curves at varying h (p_0=100 kPa, T=2π s, G_{max} = 4 MPa, ν=0.25, M=1.2, k_d=ξ=0, m=1)

PJ Model: Variation in Hardening Parameter *m*

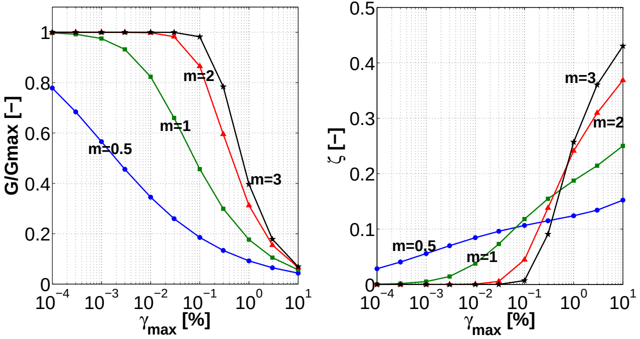

Figure: Simulated G/G_{max} and damping curves at varying m (p_0=100 kPa, T=2π s, G_{max} = 4 MPa, ν=0.25, M=1.2, k_d=ξ=0, h=$G_{max}/(15p_0)$)

PJ Model: Variation in Viscous Damping

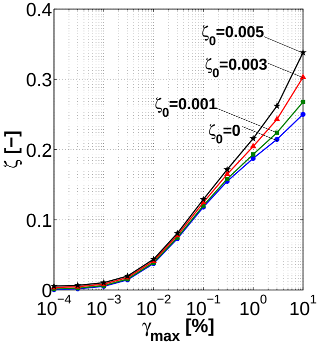

Figure: Damping curves simulated at varying ζ_0 (p_0=100 kPa, T=2π s, G_{max} = 4 MPa, ν=0.25, M=1.2, k_d=ξ=0, h=G_{max}/(15p_0), m=1)

Outline

Summary

- Frictional and Viscous energy dissipation for granular materials
- Classical elastic-plastic models with addition of viscous damping
- Vanishing elastic region elastic-plastic material model
- Important for professional practice since G/G_{max} and damping curves (all just in 1D !) is what is available, and this model calibrates well, and is full 3D model.