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Nonlinear Ground Response Analysis: Recent Experiments and Future Directions

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Birthplace of the Internet

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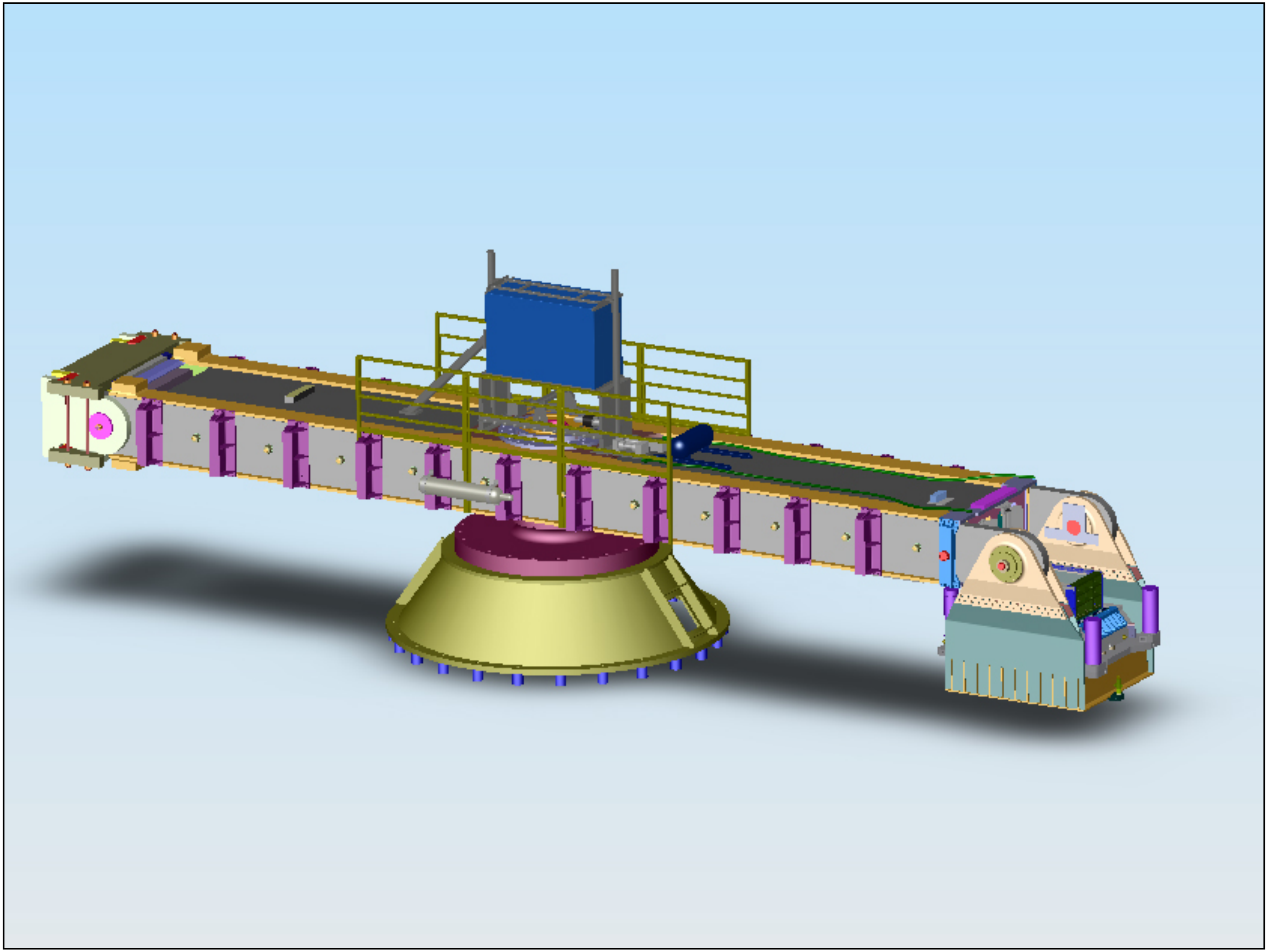
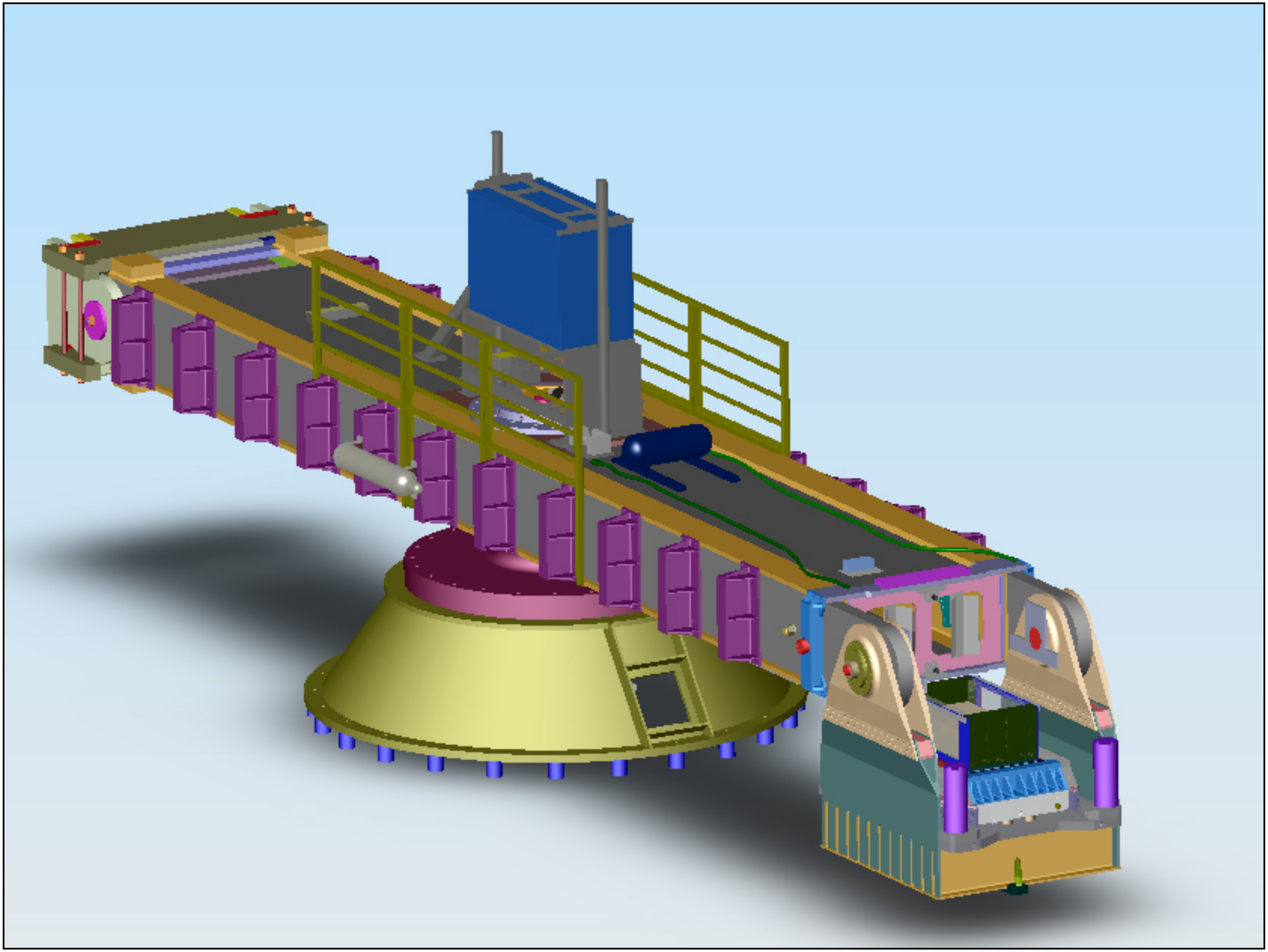
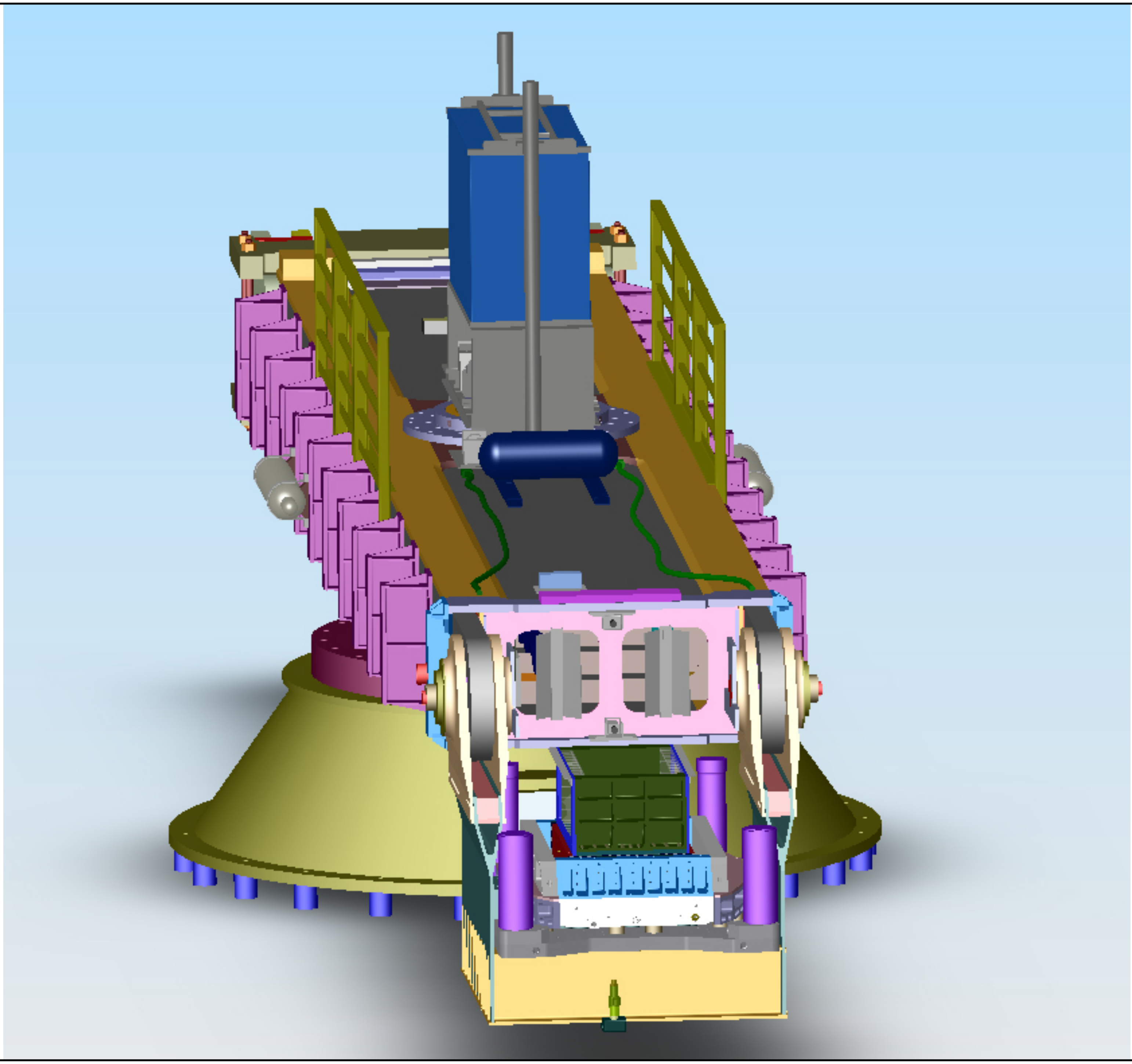
Motivation

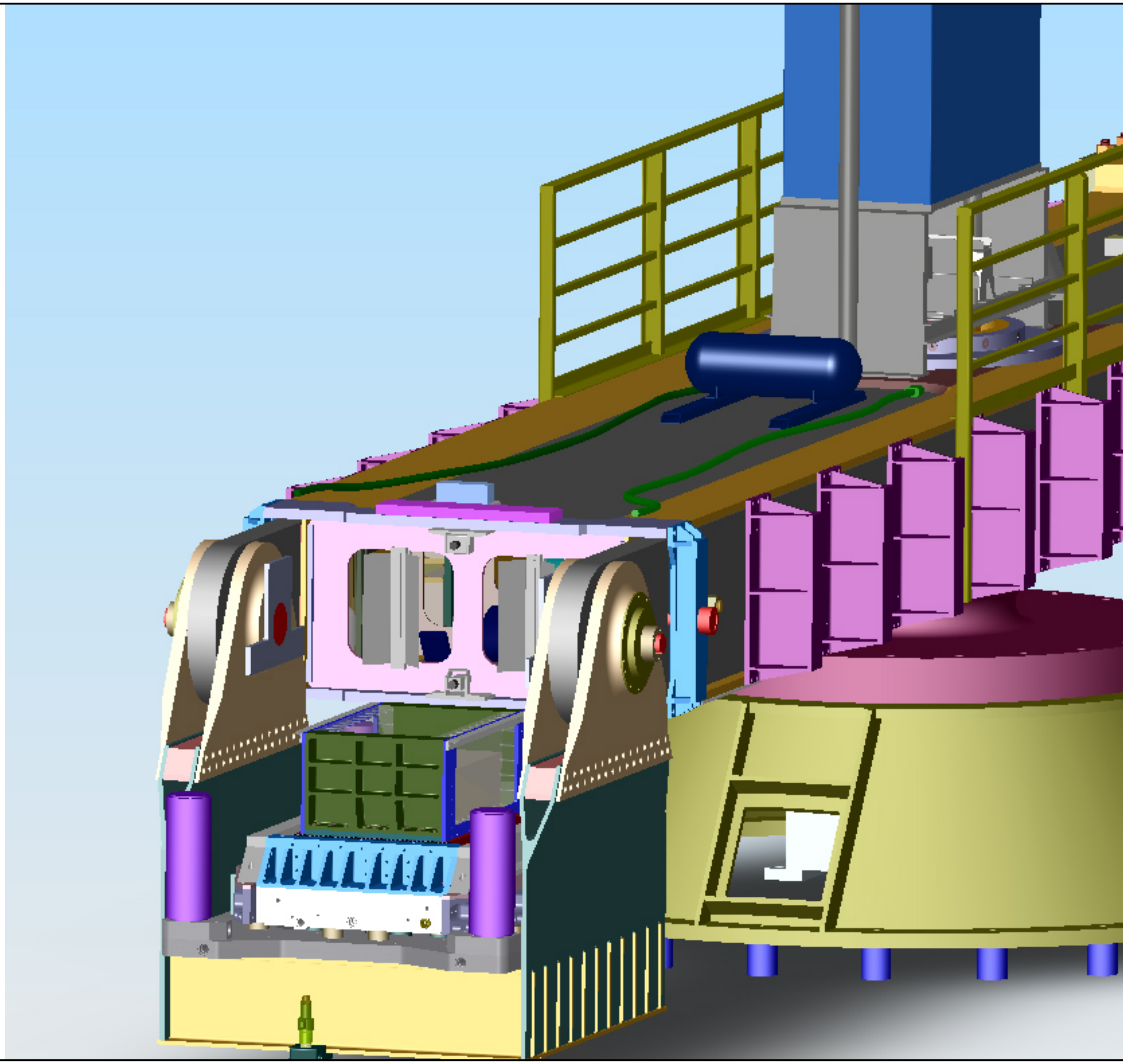
- Nonlinear ground response analysis is generally considered superior to equivalent linear analysis when ground strains become large (i.e., > 1%).
- Experimental or field observations of large-strain site response are sparse.
- Therefore, nonlinear ground response analysis methods are not adequately validated in the range where they are considered to provide the most benefit.

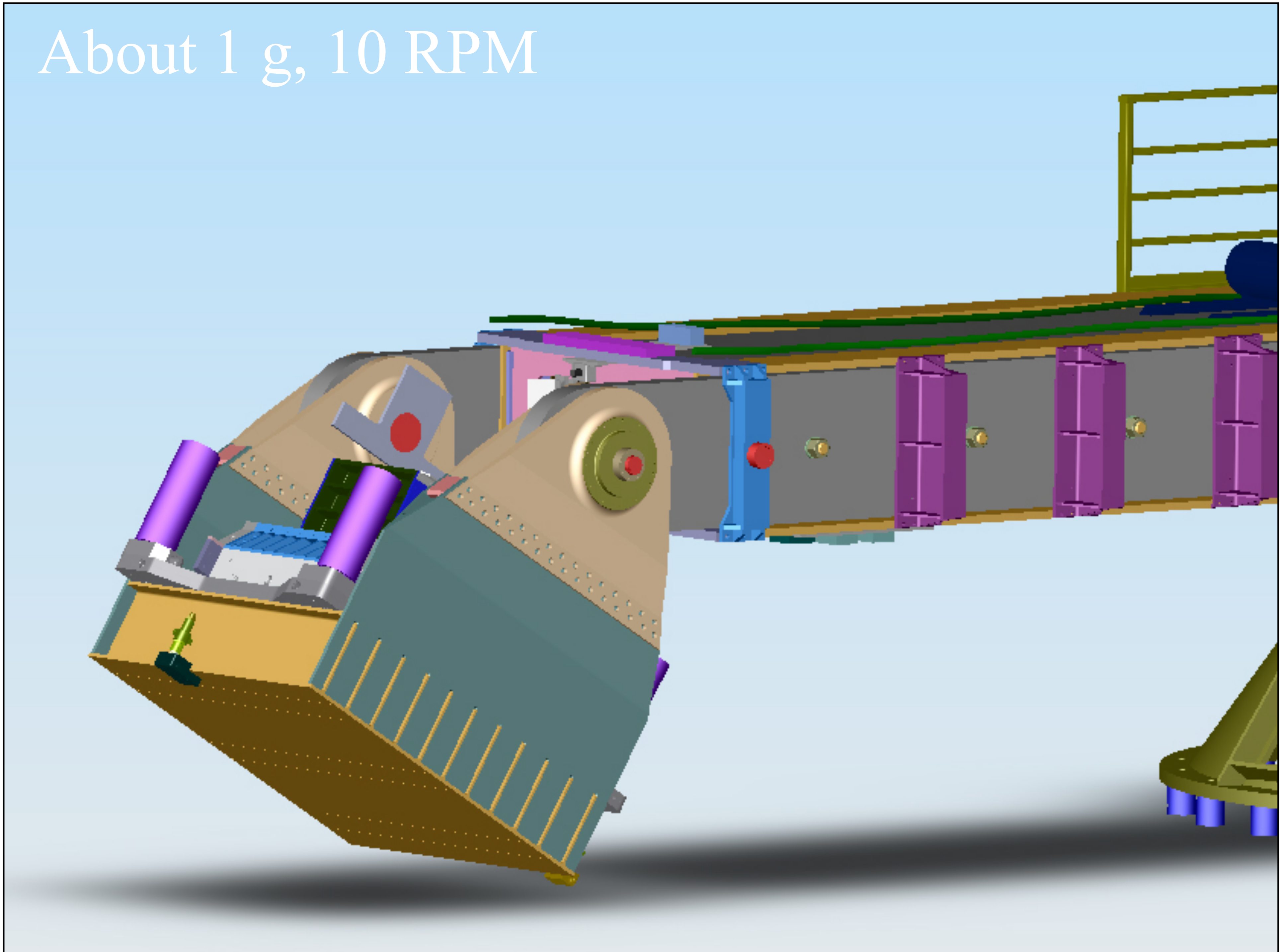

9-m radius
COFFING



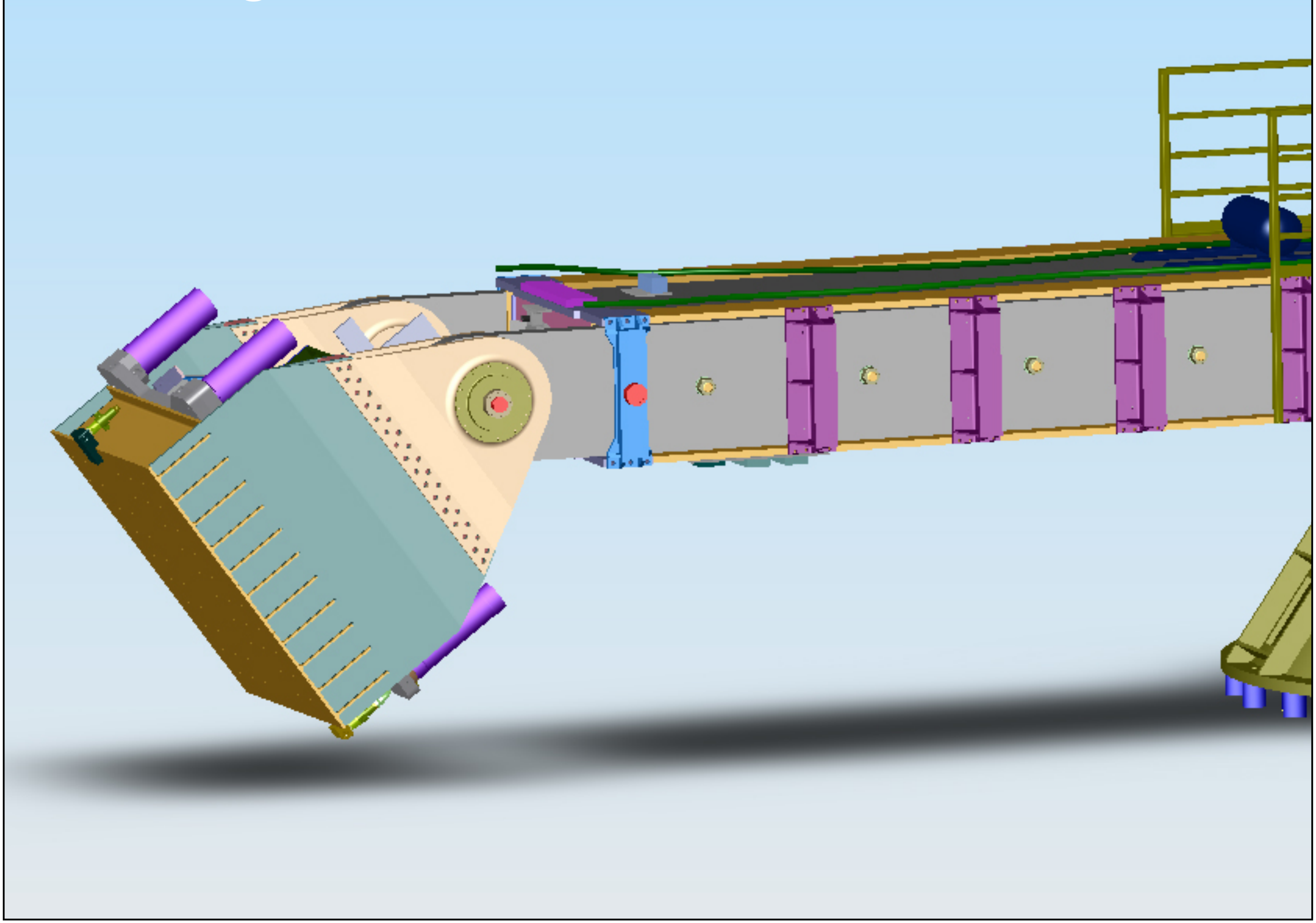


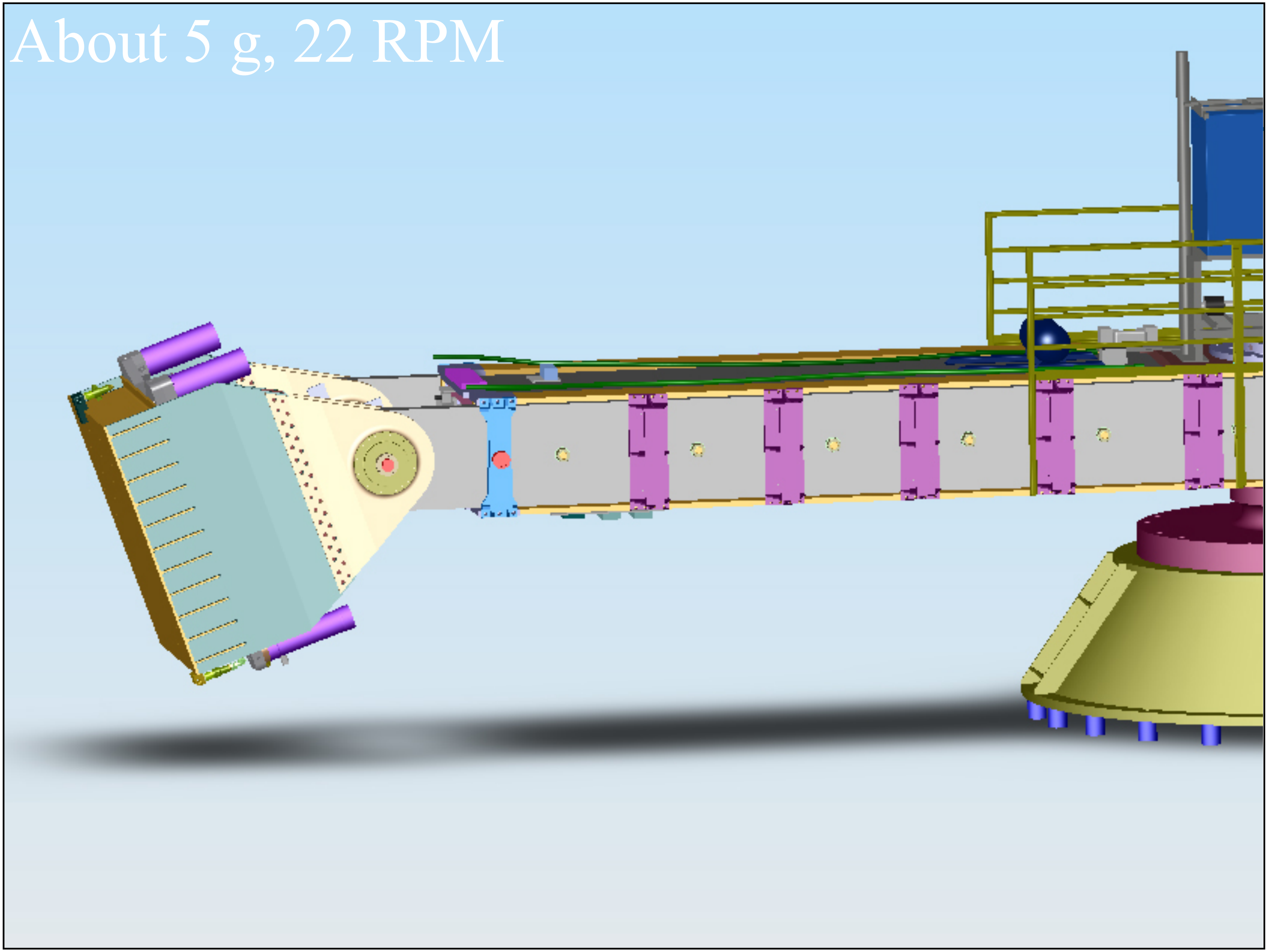




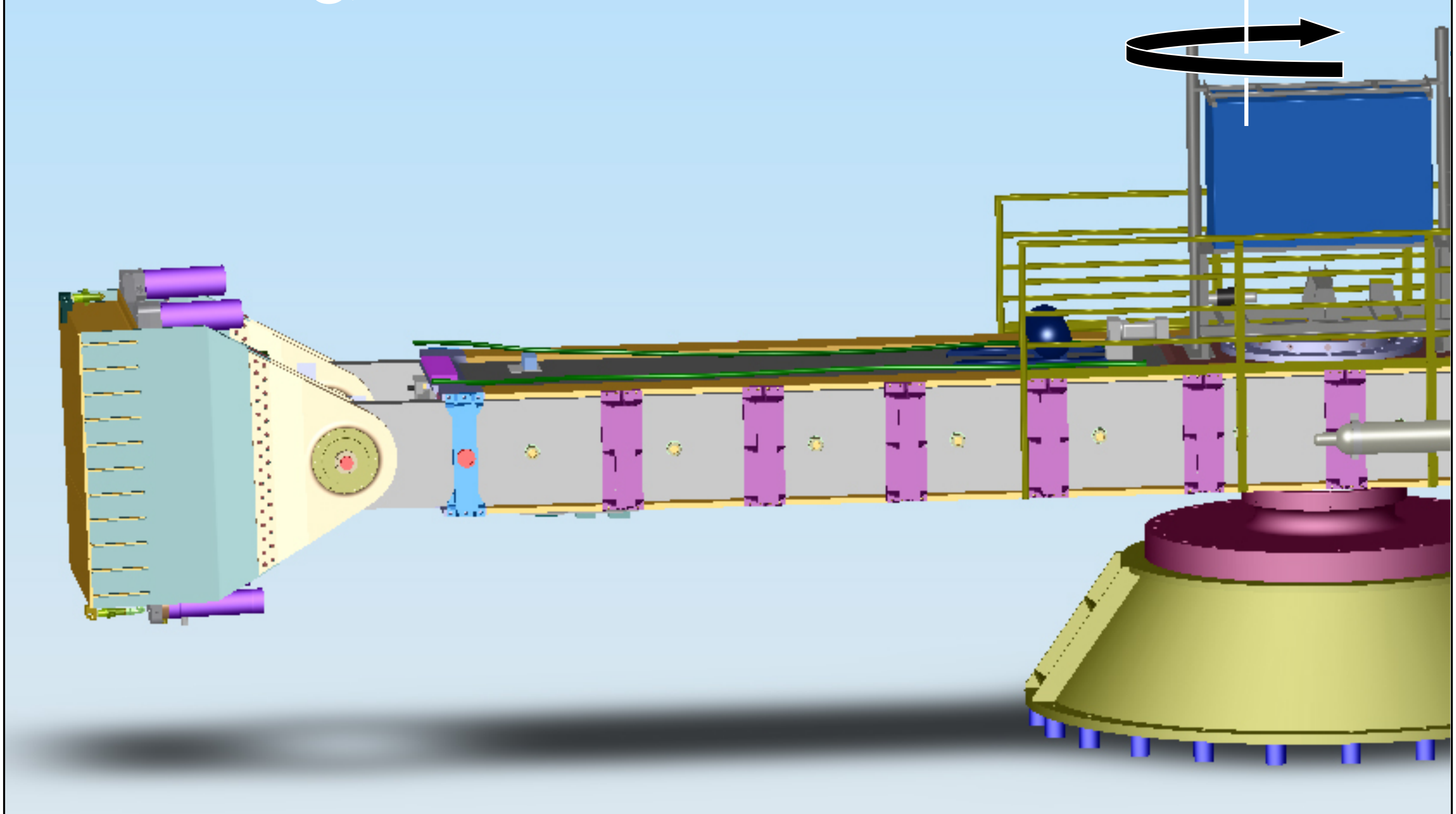

About 1 g, 10 RPM

About 2 g, 14 RPM

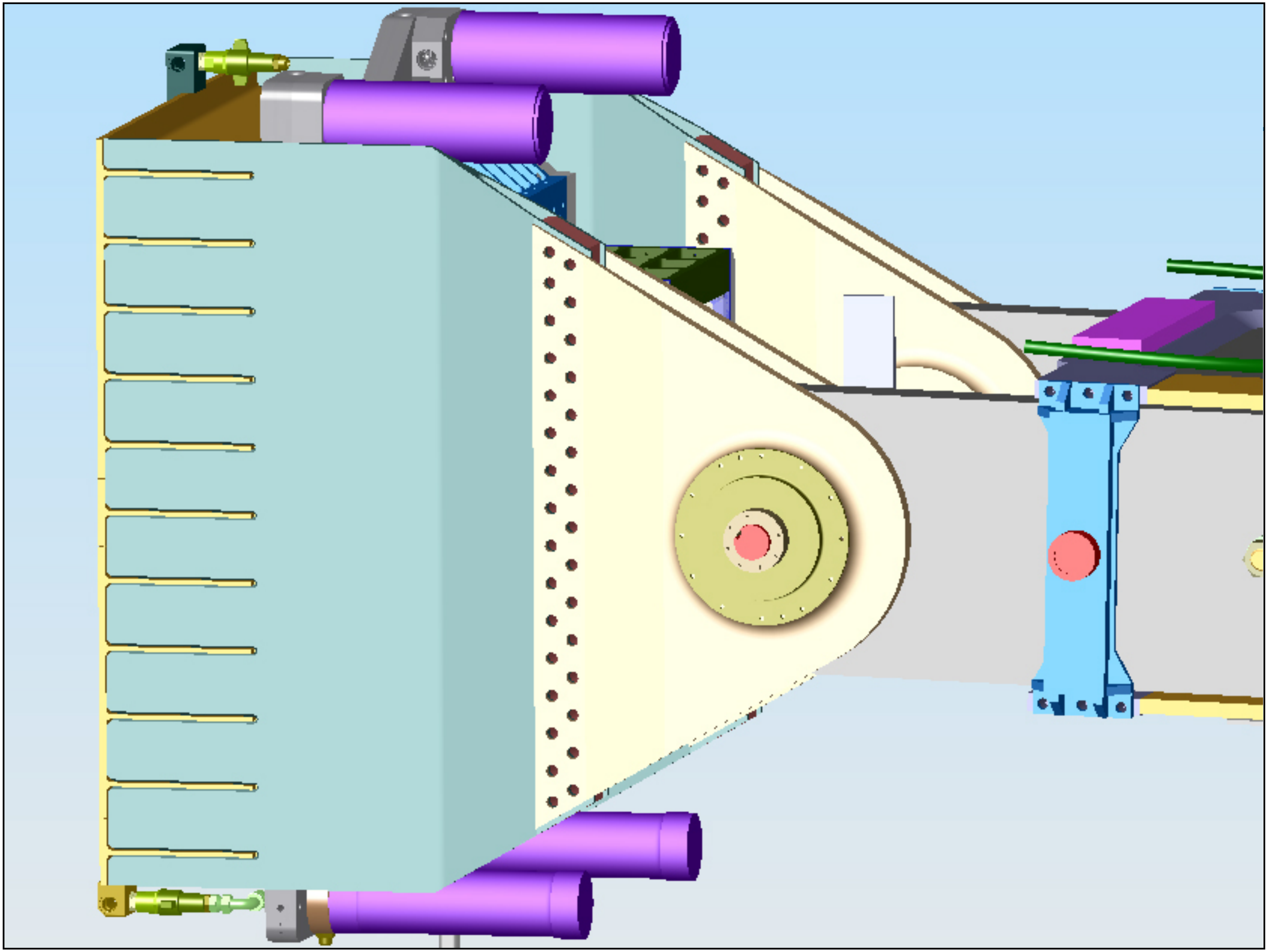


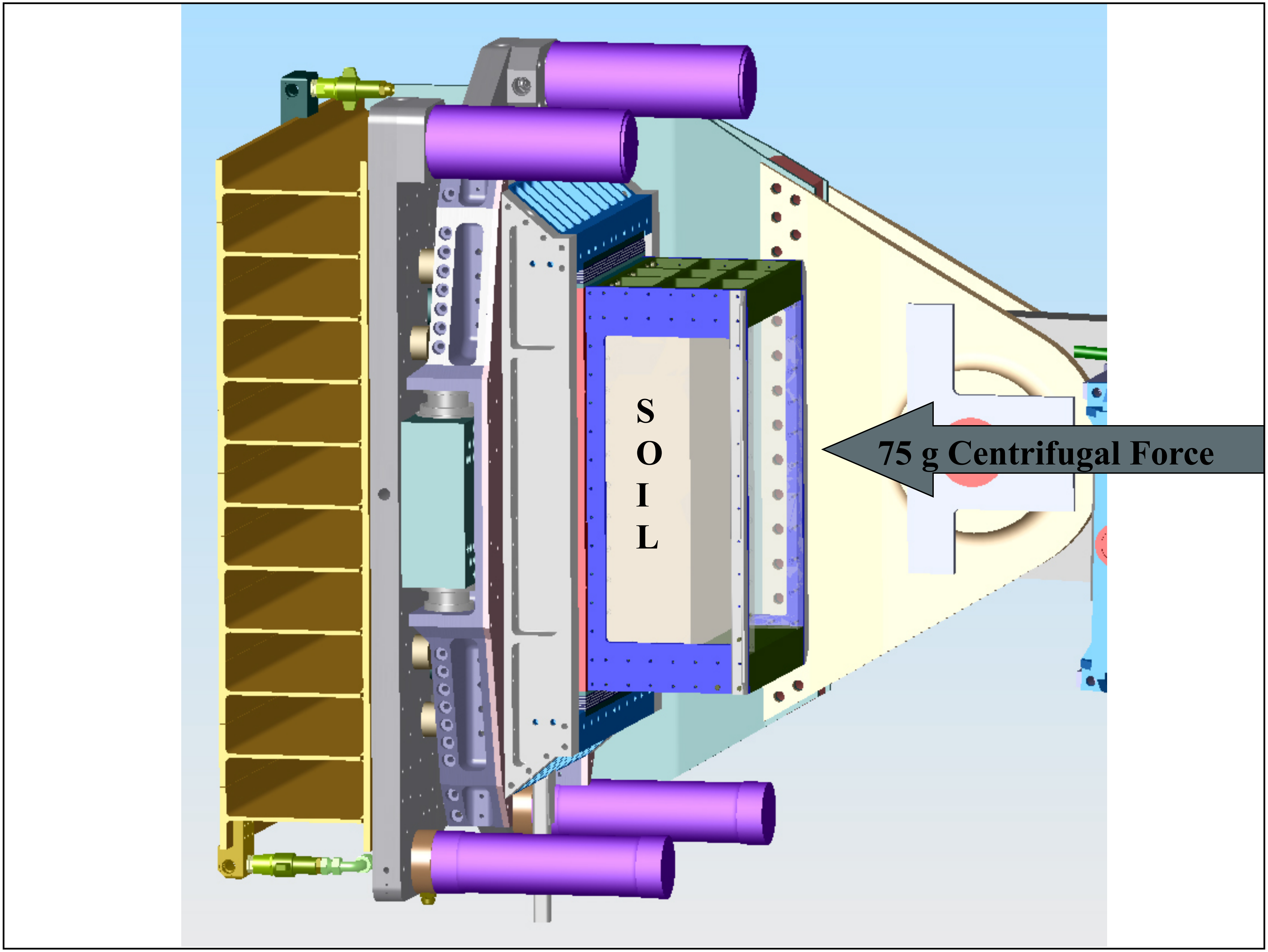

About 5 g, 22 RPM

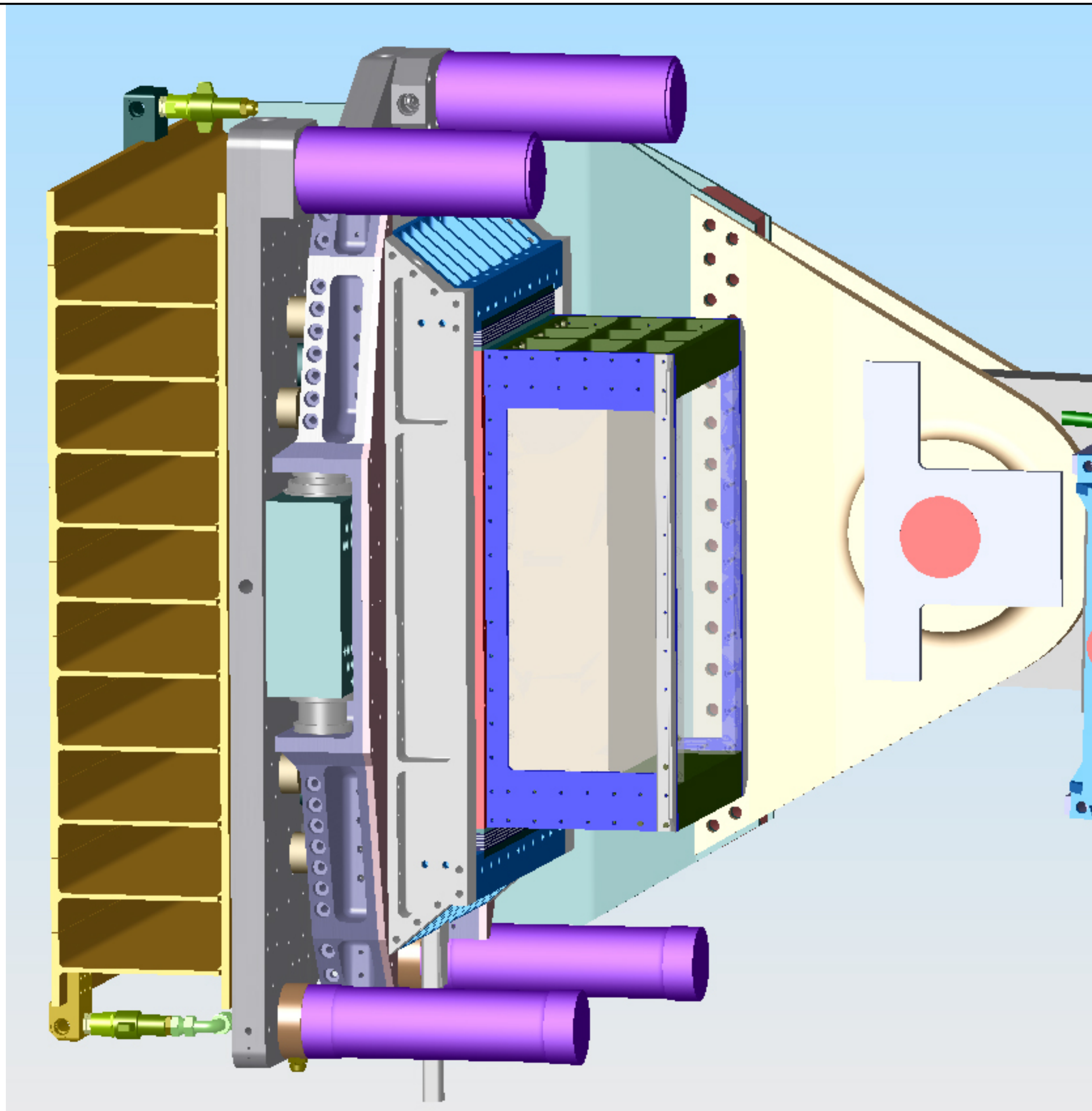
About 60 g, 77 RPM

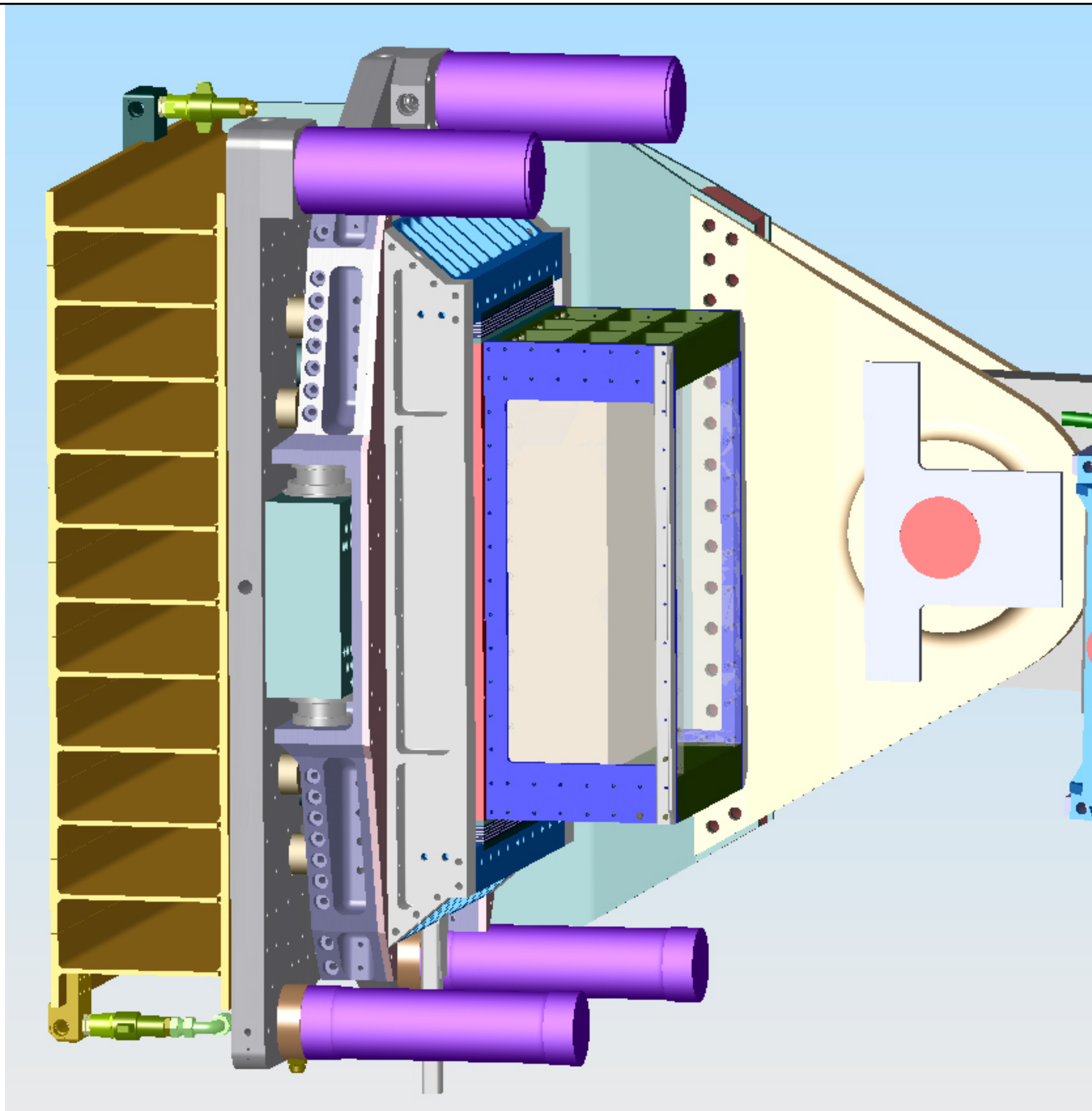


The centrifugal acceleration increases the vertical stress profile in the model such that the vertical stress in a 0.5m thick soil layer approximates a 30m thick prototype profile.

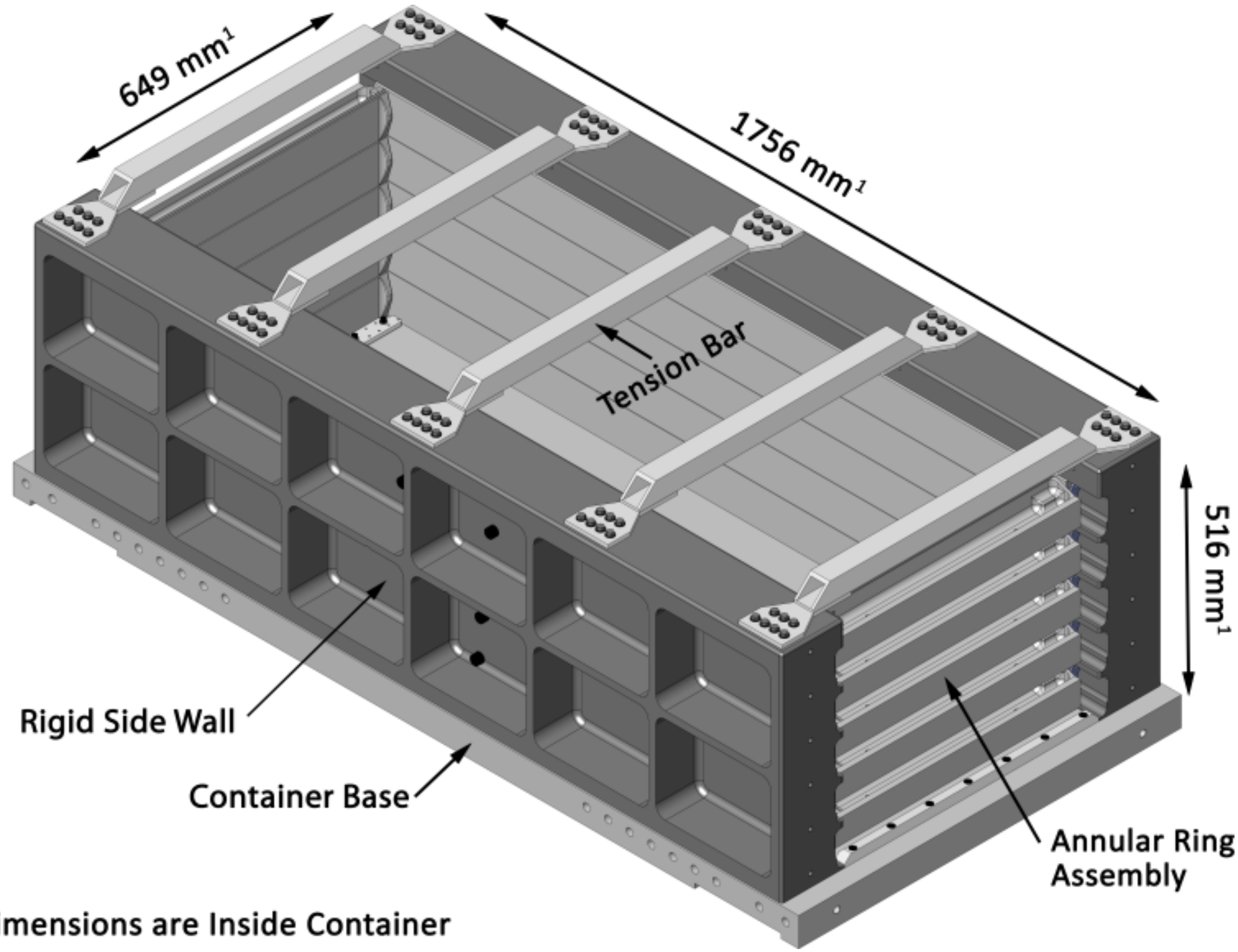



S O I L
75 g Centrifugal Force



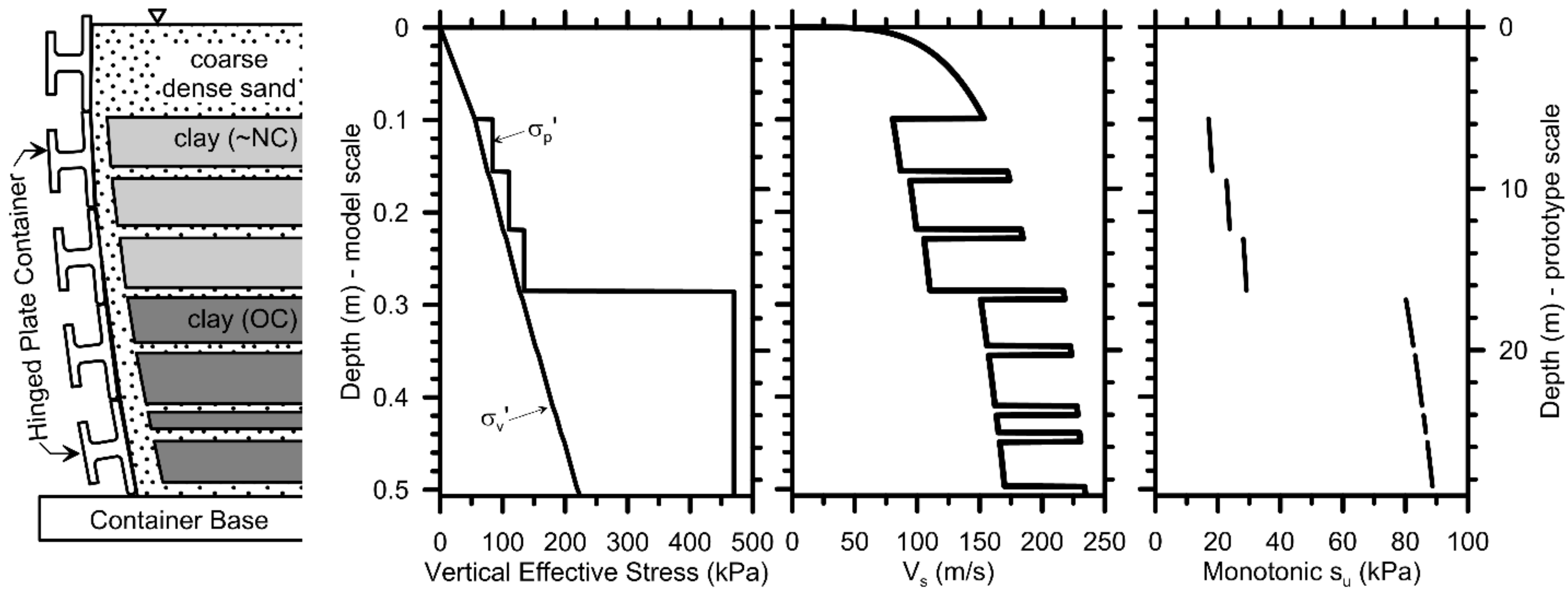


UCLA Hinged Plate Container

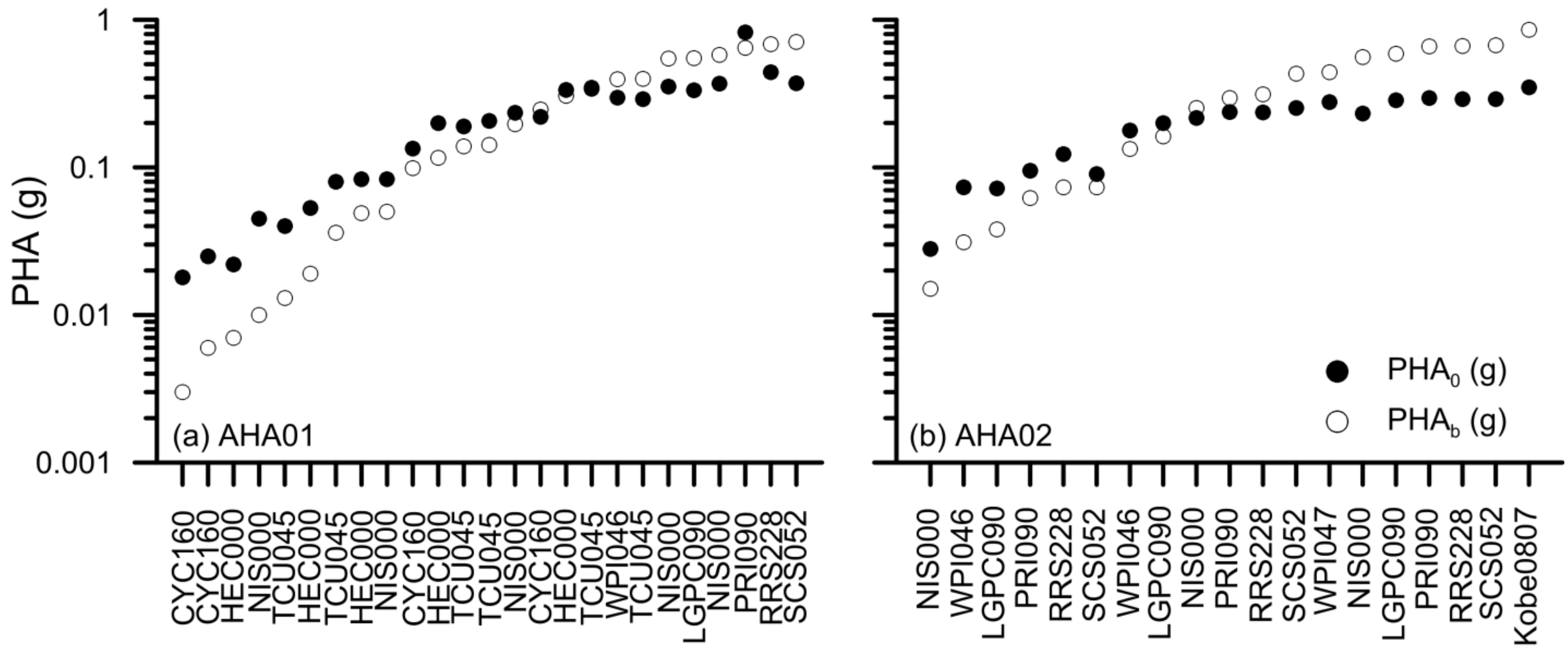


[1]Dimensions are Inside Container

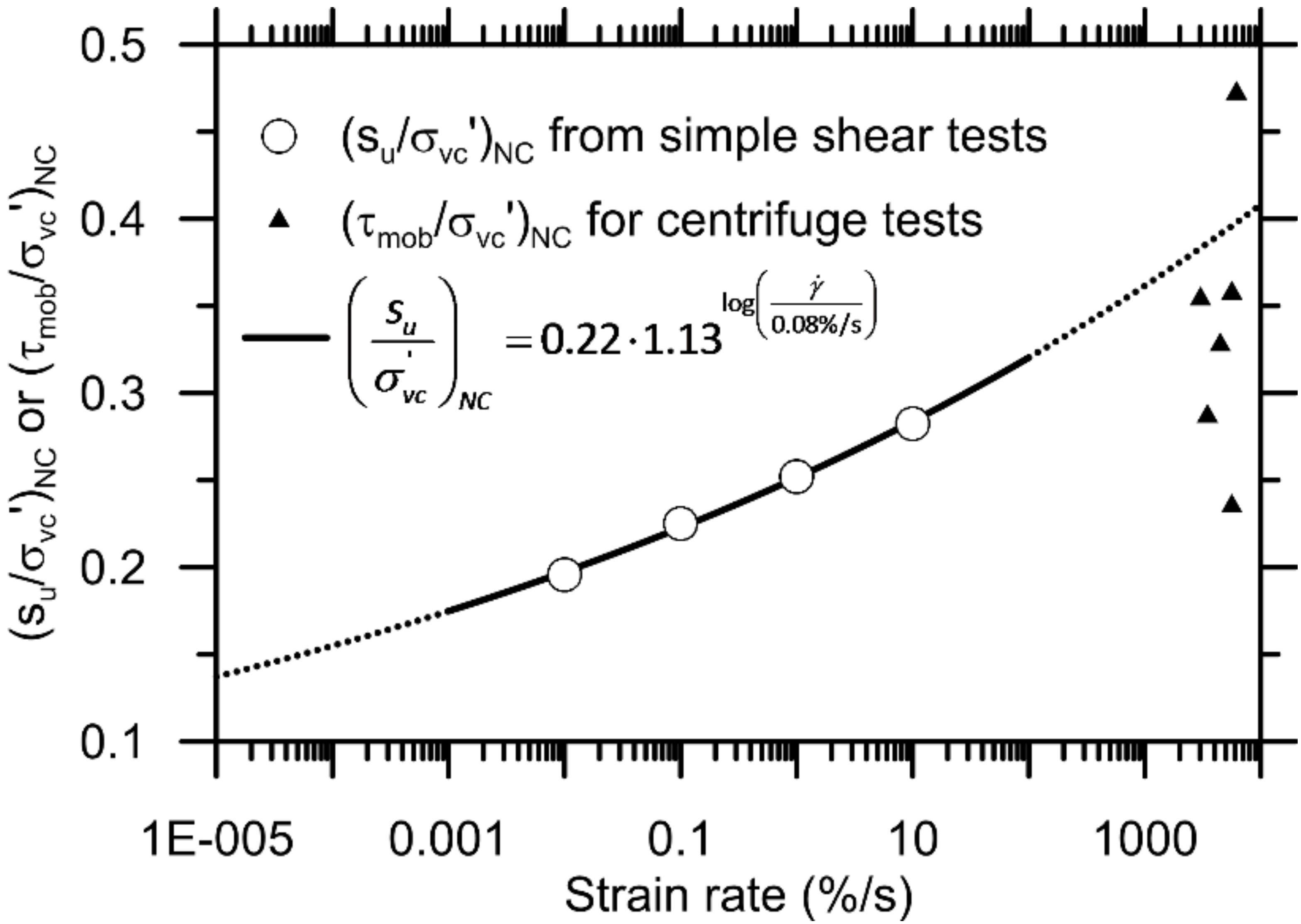
Soil Profile



Site Amplification



UCLA Influence of Strain Rate on Shear Strength



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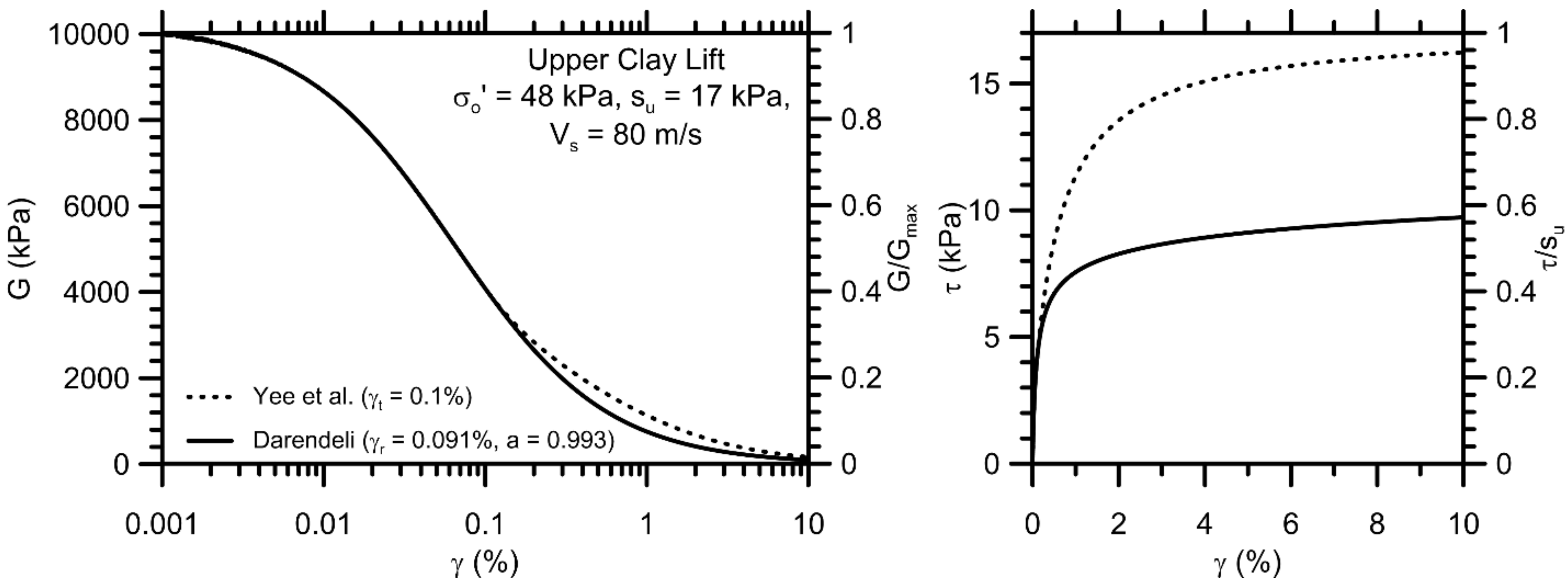
Site Response Simulations

- Simulations performed in DeepSoil and OpenSees (PIMY and PDMY material models).
- Simulations performed using nonlinear and equivalent linear methods.
- Shear strength varied as follows: (1) extrapolation of modulus reduction equations (generally valid only up to 0.3% strain), (2) modulus reduction curve adjusted to match monotonic shear strength, and (3) modulus reduction curve adjusted to match rate-corrected shear strength.

UCLA Adjusting Tail of Modulus Reduction Curve



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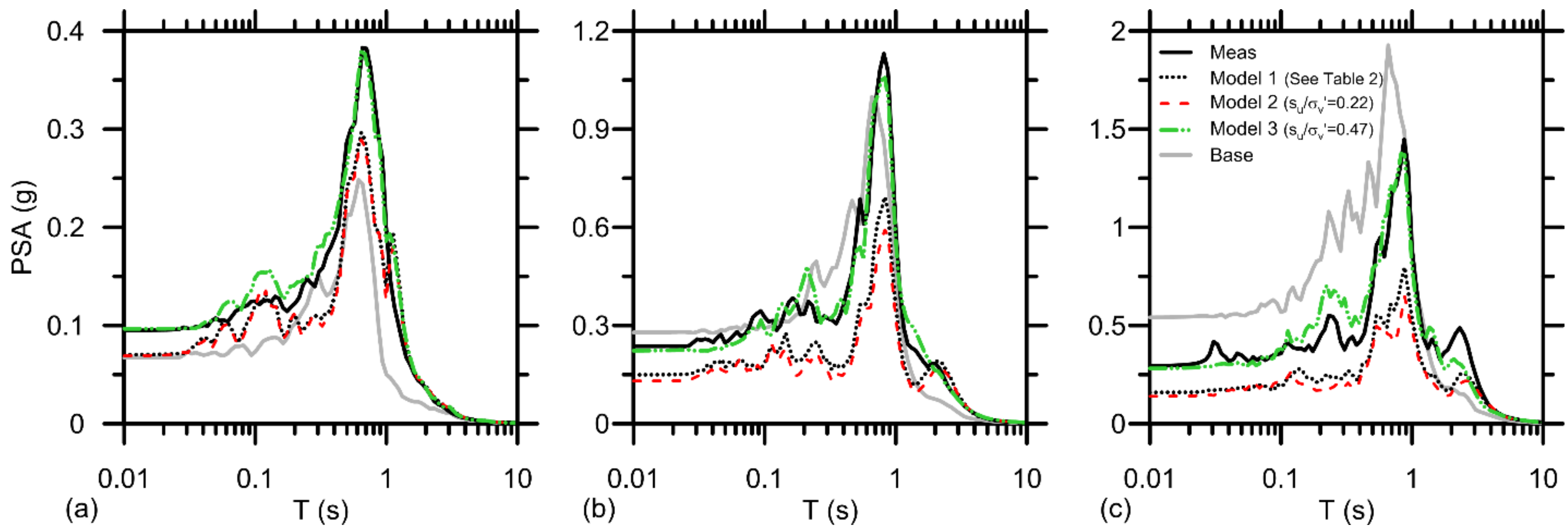
Influence of Shear Strength

Nonlinear Modeling using DeepSoil



Black Solid Line: Measured surface response spectrum

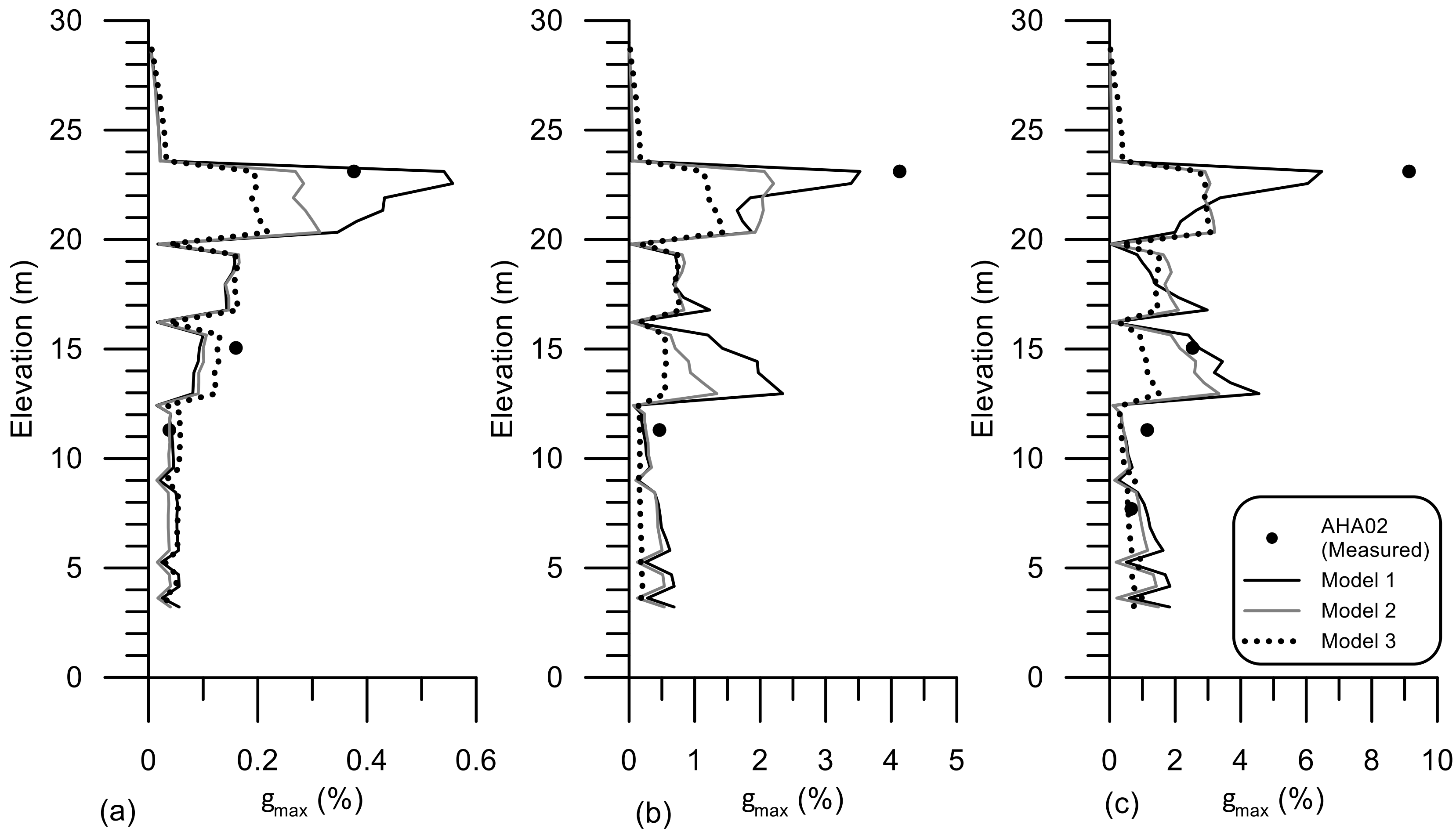
Grey Line: Measured base response spectrum

Black Dotted Line: Extrapolate Darendeli's equation to large strain

Red Line: Use monotonic undrained shear strength profile

Green Line: Use rate-corrected undrained shear strength profile

Strain Profiles



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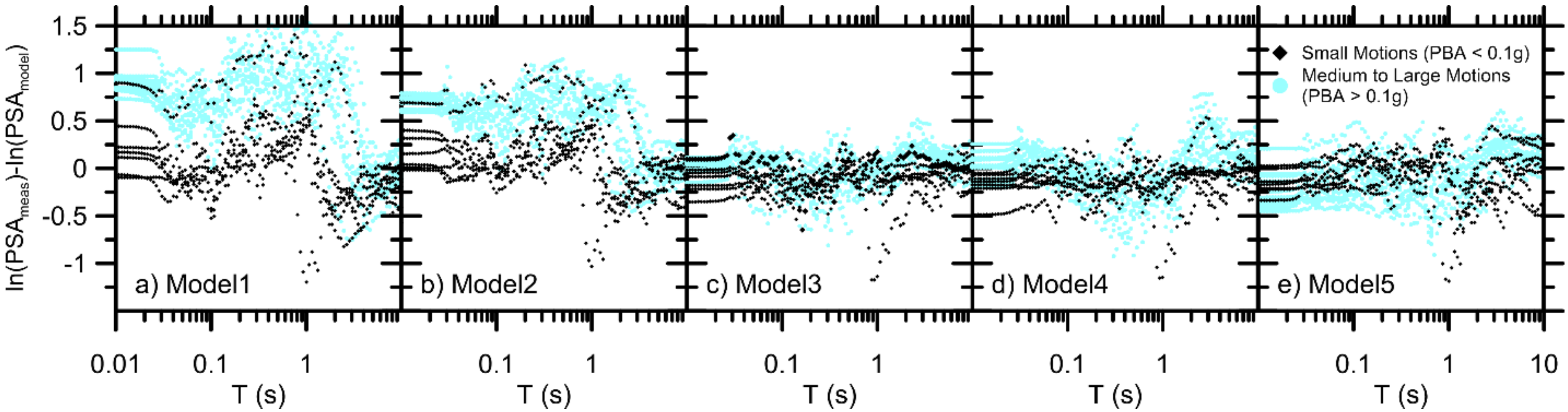
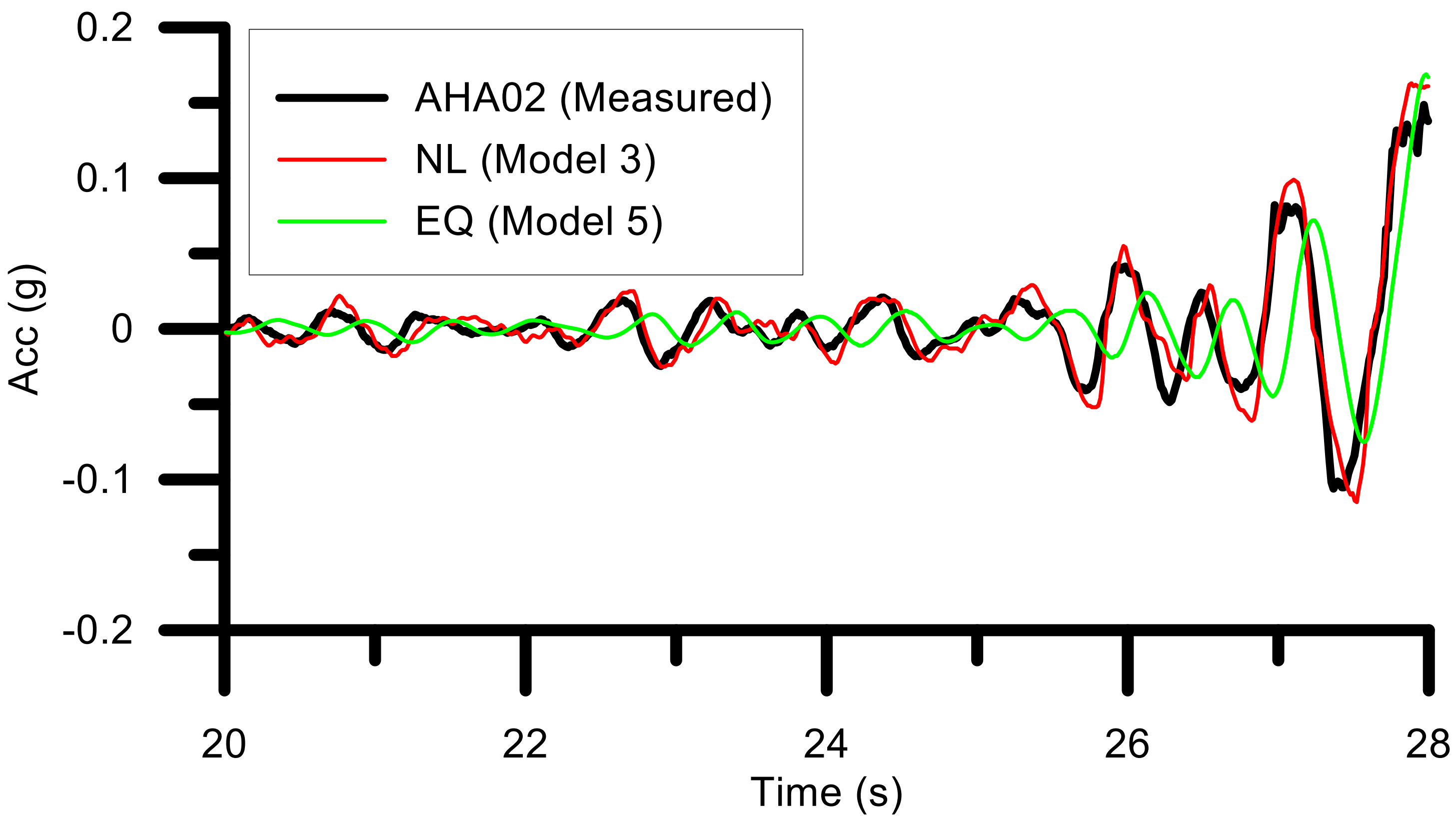
S_a Residuals



Model	Nonlinear (NL) or Equivalent Linear (EQ)	Modeling Platform	$(s_u/s_{vc}')_{NC}$	Yee et al. (2013) Shear Strength Correction?
1	NL	DeepSoil	see note[a]	No
2	NL	DeepSoil	0.22	Yes
3	NL	DeepSoil	0.47	Yes
4	NL	OpenSees	0.47	Yes
5	EQ	DeepSoil	0.47	Yes

[a] Shear strength extrapolated from Darendeli's equation.

Equivalent Linear



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Future Directions

- Nonlinear site response codes have varying ability to match a target modulus reduction and damping curve.
  - DeepSoil: Adjustments to "target" modulus reduction curve needed to achieve desired strength (newest release has fixed this problem). Small-strain damping is frequency independent. Hysteretic damping can reasonably match target.
  - OpenSees (PDMY and PIMY material models): Can match target modulus reduction curve. Typically used with 2-point Rayleigh damping that is frequency dependent. Hysteretic damping uses Masing's rules, which over-damps at high strain.

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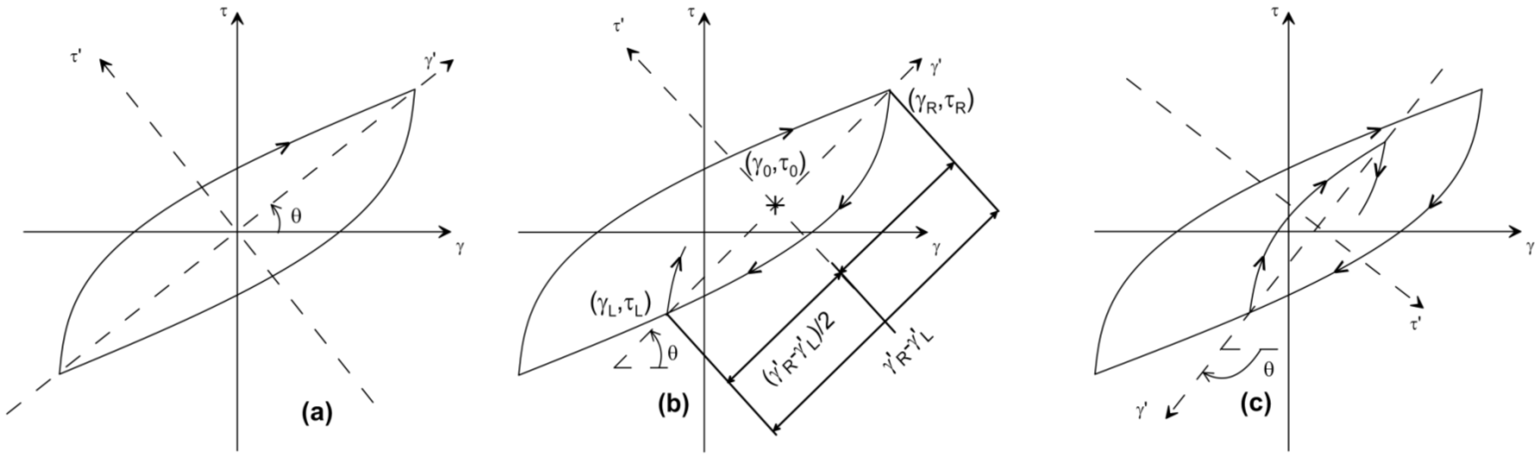
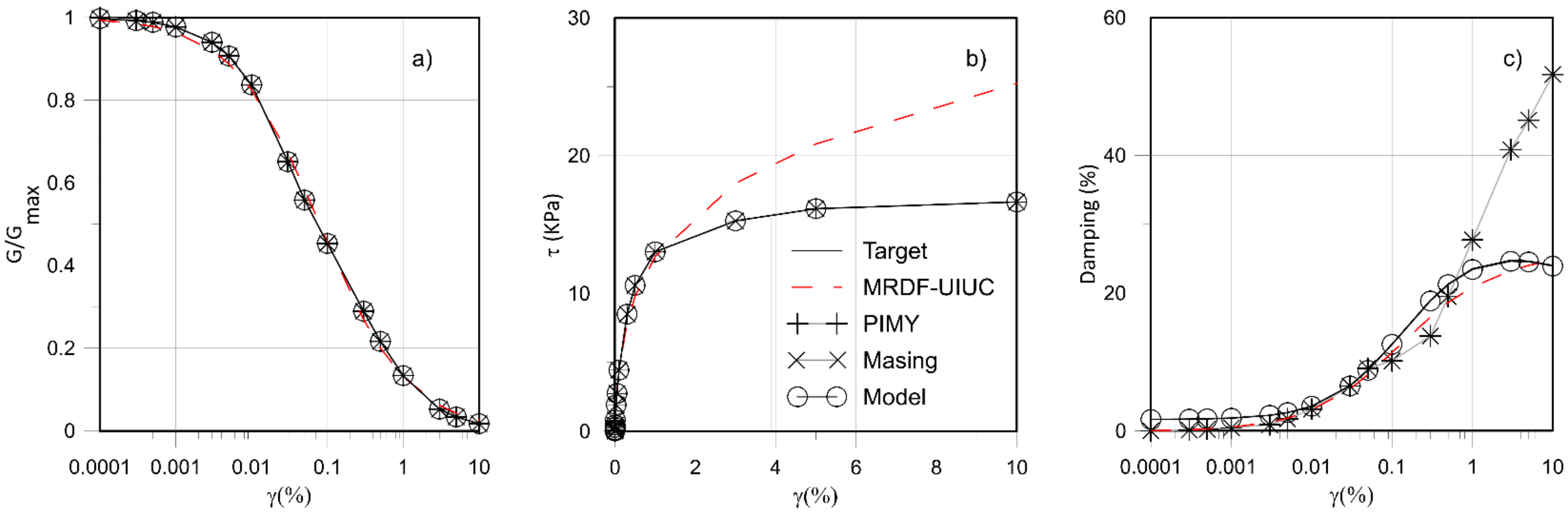
Future Directions

- There is a need for elasto-plastic constitutive models that better handle small-strain behavior by matching target modulus reduction and damping curve, and are accessible to practicing engineers.
- More work is needed to quantify and model strain rate effects.
- Engineers often use shear strength values that are too low, believing this practice to be conservative. The opposite is true for site response analysis.

New Unload-Reload Model





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The End

Thank You!