Low Gravity, High Stakes

Engineering Shake-Resistant Lunar Infrastructure

SOM

Space Resources Roundtable

SKIDMORE, OWINGS & MERRILL

Regolith as Construction Material

Integration of Robotic Construction

Moonquakes

Foundation Systems

Lunar Building Standards

Regolith as Construction Material

Integration of Robotic Construction

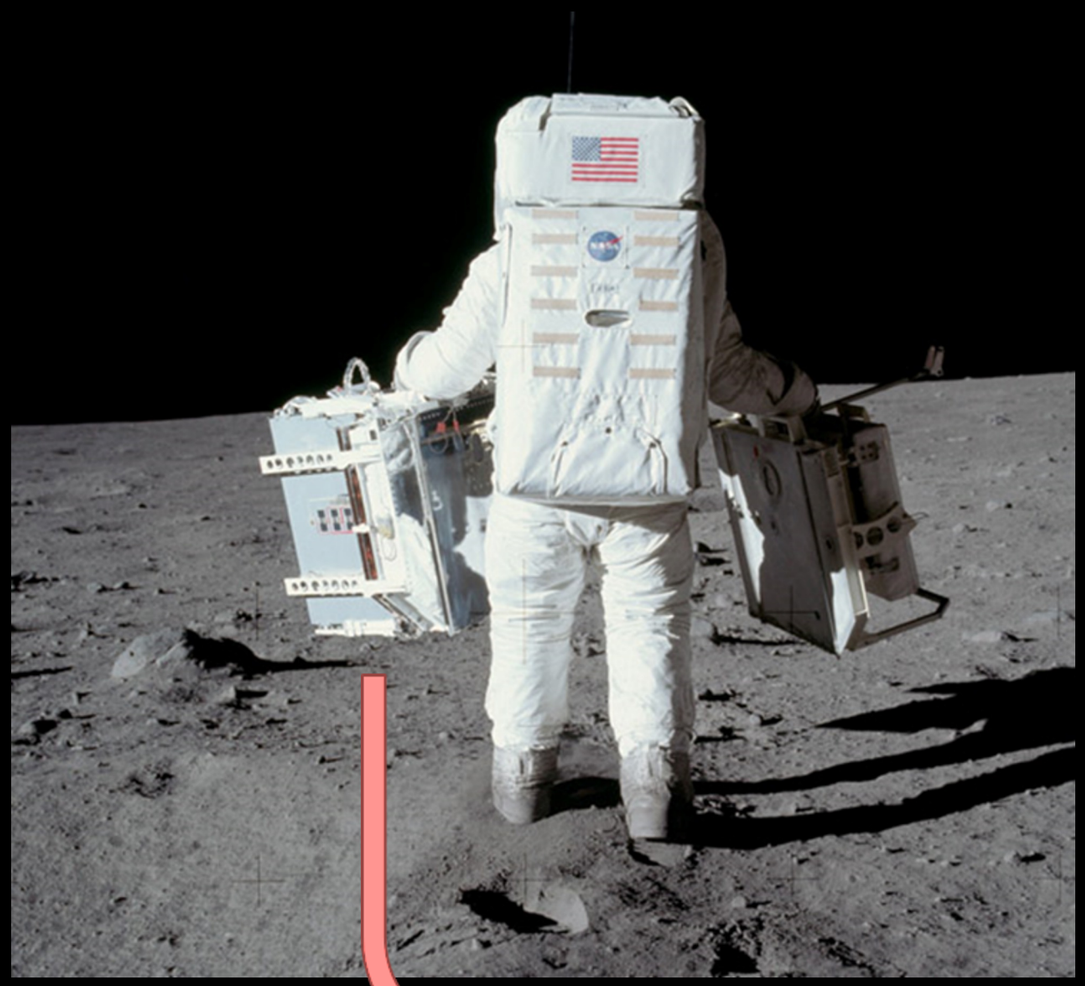
Moonquakes

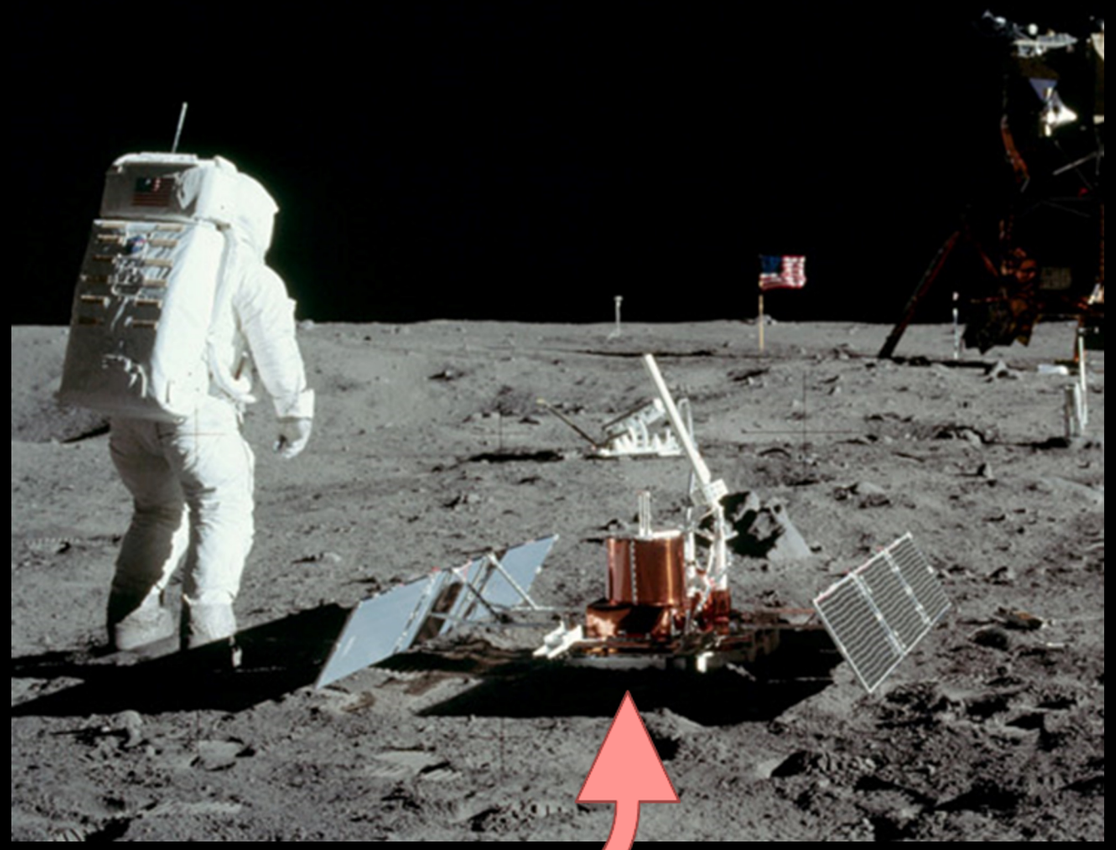
Foundation Systems

Lunar Building Standards

Moonquake had me like

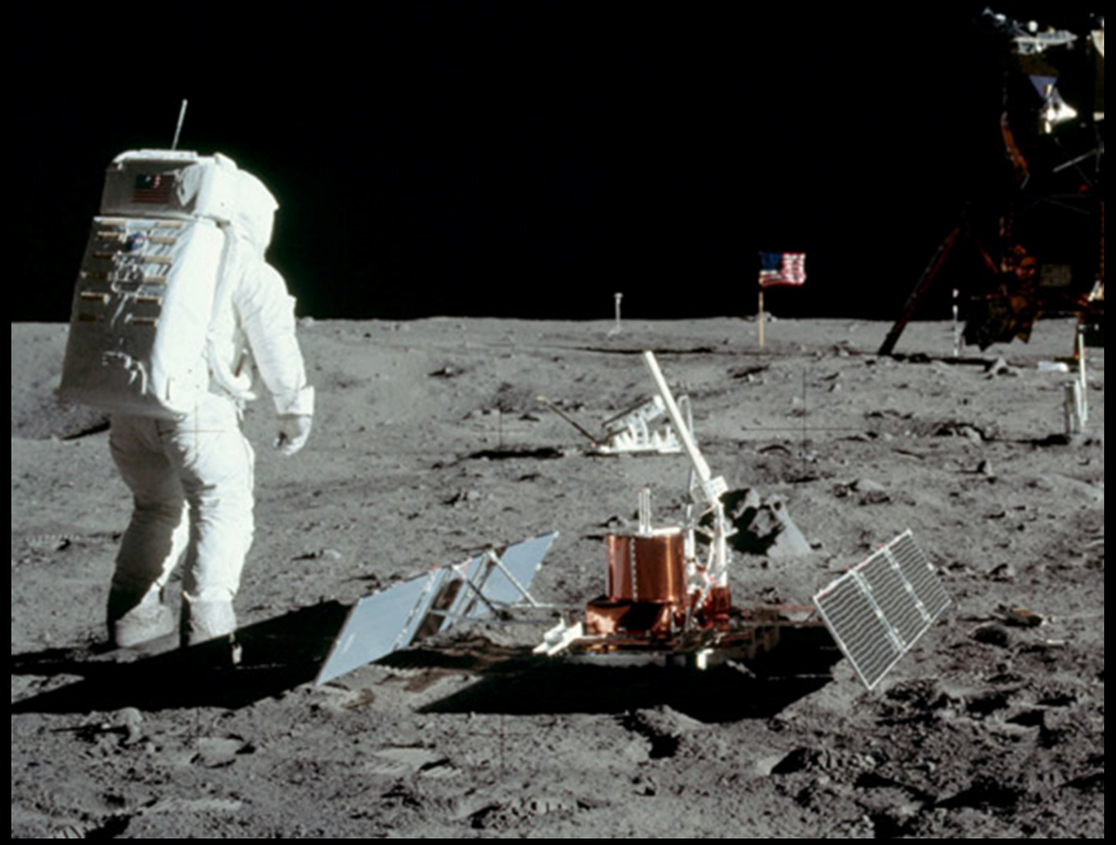
State of Moonquake Knowledge





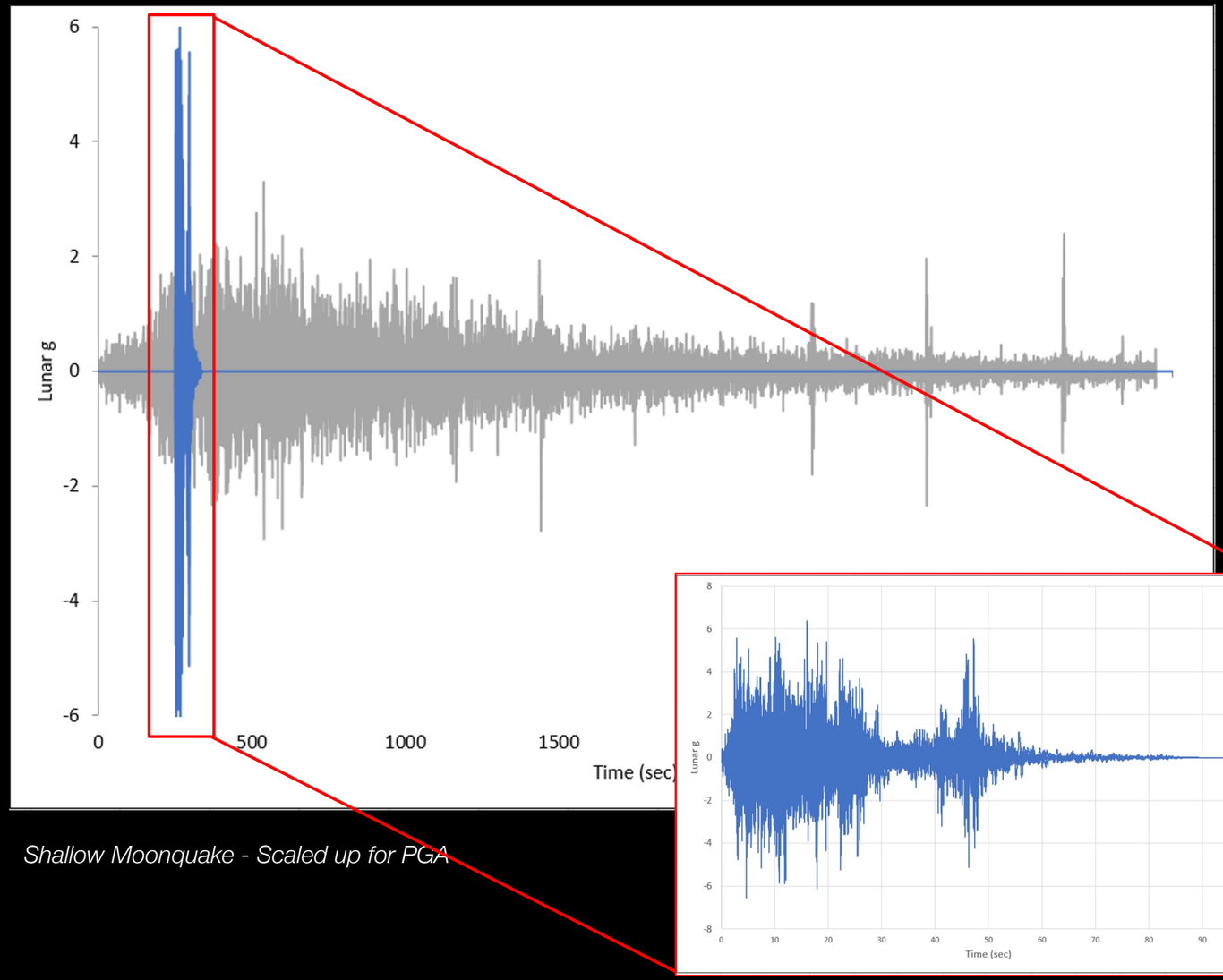
State of Moonquake Knowledge

- **Deep Moonquake**
- **Thermal Moonquake**
- **Meteorite Impact Moonquake**
- **Shallow Moonquake**



State of Moonquake Knowledge

- Resemble Intraplate Earthquakes
- High-Frequency Energy Content
- Extended Duration
- Impulsive P- and S-Wave Arrivals
- Reduced Attenuation
- Wider Energy Spread



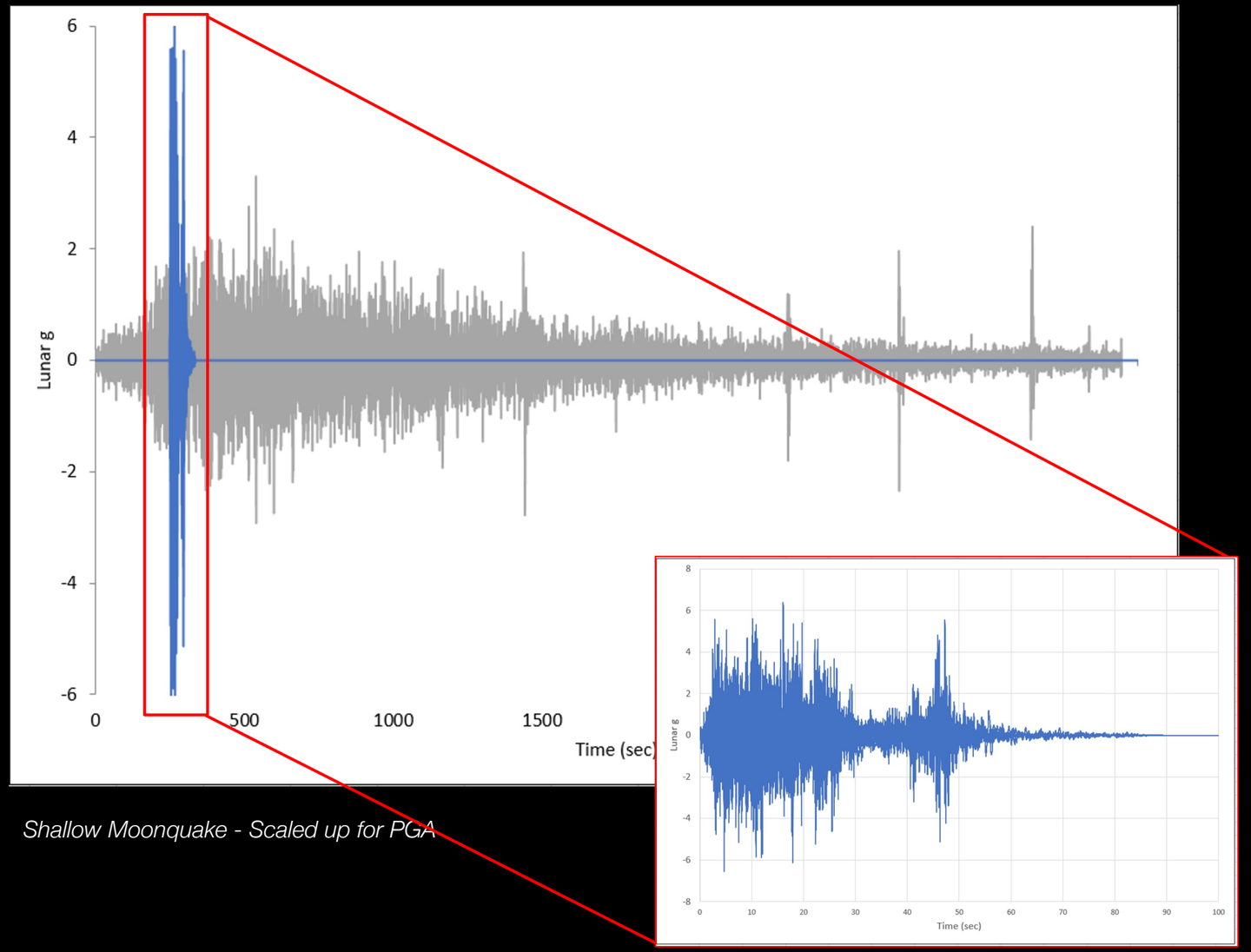
Shallow Moonquake - Scaled up for PGA

State of Moonquake Knowledge

Shallow Moonquake Seismic Wave Properties

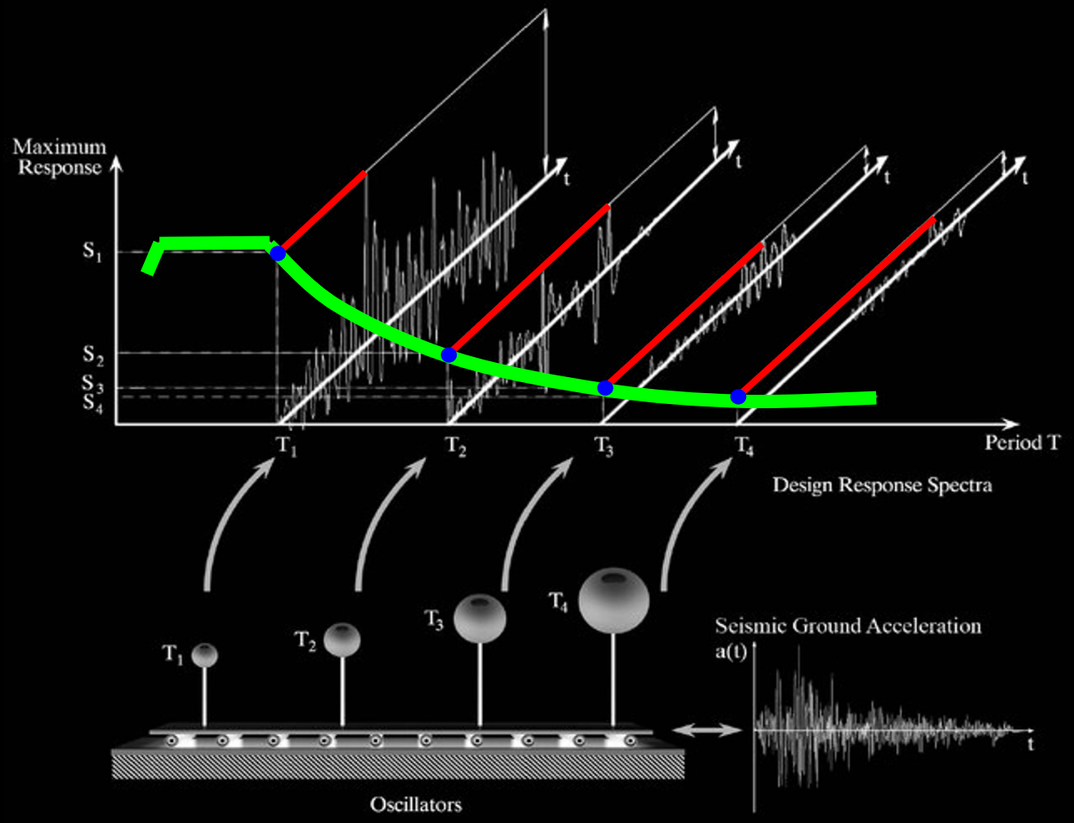
?≋?

Earthquake Seismic Wave Properties

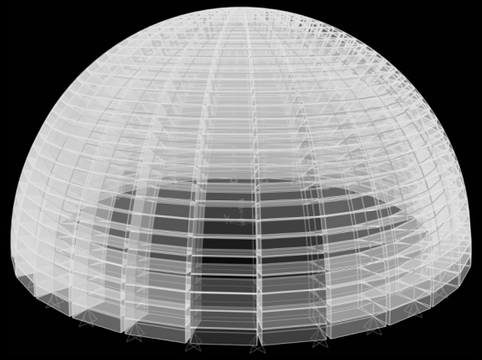


Shallow Moonquake - Scaled up for PGA

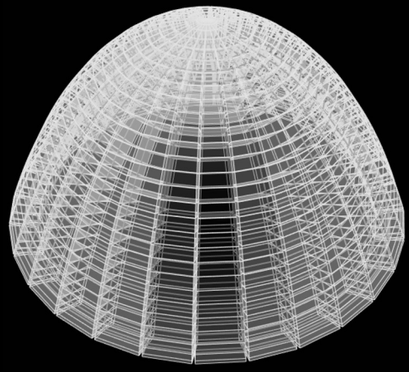
Moonquake Ground Motion Model



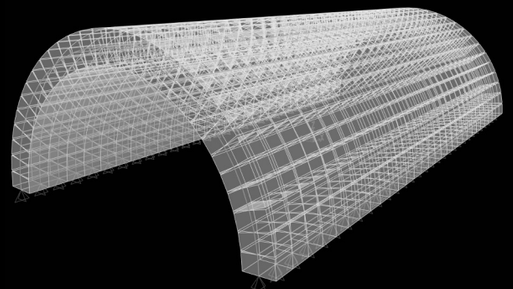
Vrochidou et al. (2014)



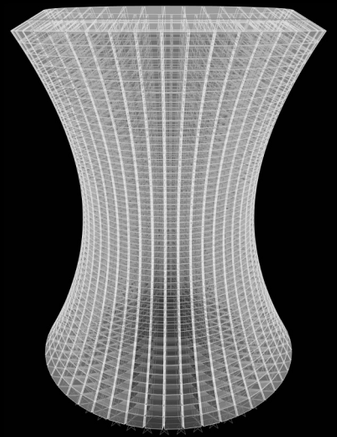
Cylindrical Dome



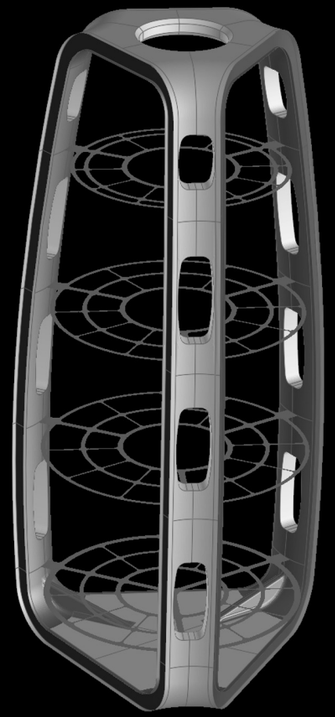
Catenary Dome



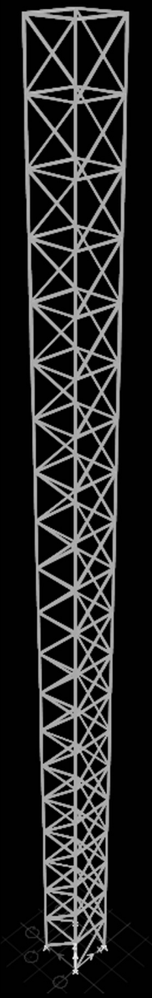
Half Cylinder



Pressurized Hyperboloid
(Marx-X House)



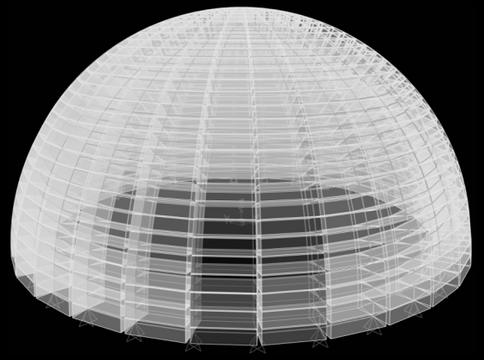
Prefabricated Habitat
(Moon Village - SOM)



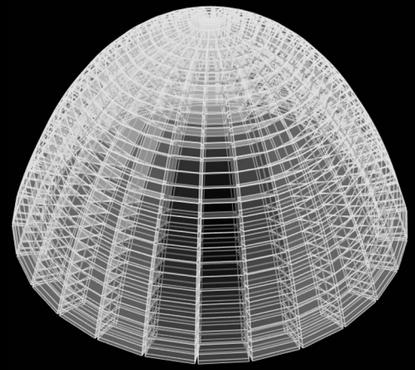
Tall Lunar Tower
(NASA Polar Project)

Moonquake Ground Motion Model

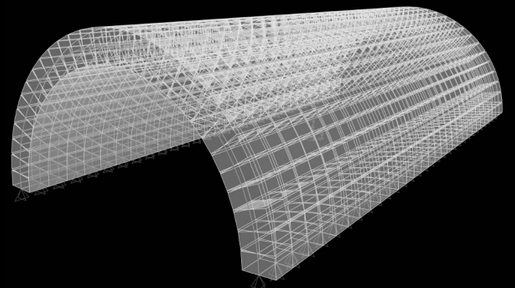
Structural System	Frequency Range (Hz)	Period Range (s)
Unpressurized Cylindrical Dome	5 Hz - 140 Hz	0.20 - 7.14E-3
Unpressurized Catenary Dome	6 Hz - 145 Hz	0.17 - 6.90E-3
Unpressurized Half Cylinder	1 Hz - 80 Hz	1.00 - 0.01
Pressurized Hyperboloid	11 Hz - 59 Hz	0.09 - 0.02
Prefabricated Habitat (Moon Village)	3 Hz - 14 Hz	0.33 - 0.07
Tall Lunar Tower	0.1 Hz - 80 Hz	10 - 0.01



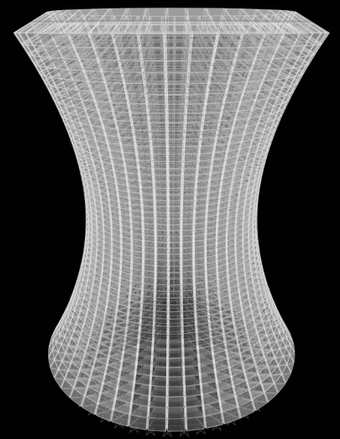
Cylindrical Dome



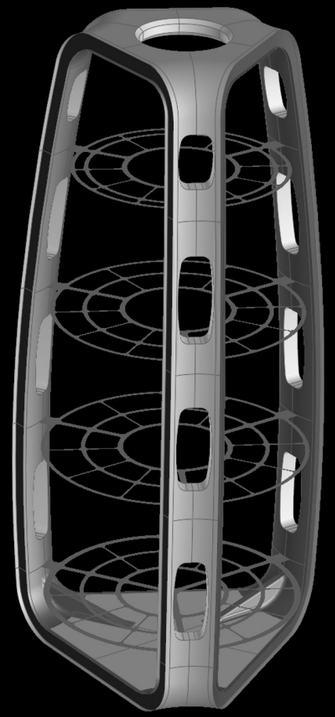
Catenary Dome



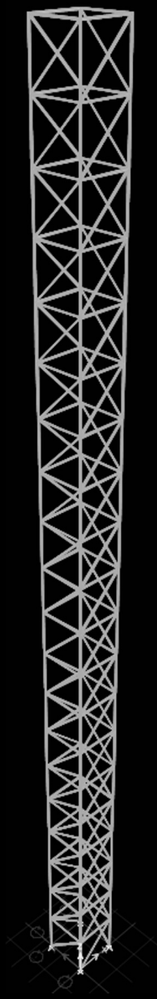
Half Cylinder



Pressurized Hyperboloid
(Marx-X House)



Prefabricated Habitat
(Moon Village - SOM)



Tall Lunar Tower
(NASA Polar Project)

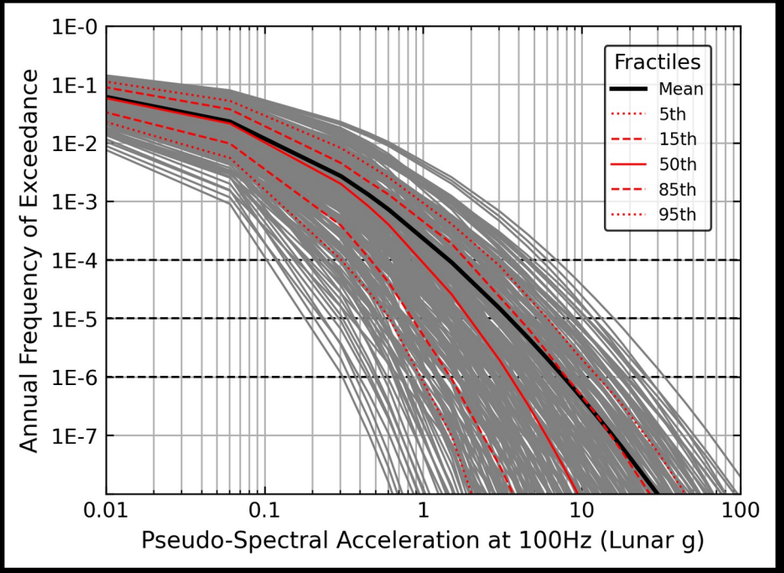
Moonquake Ground Motion Model

Two Main Model Input Parameters:

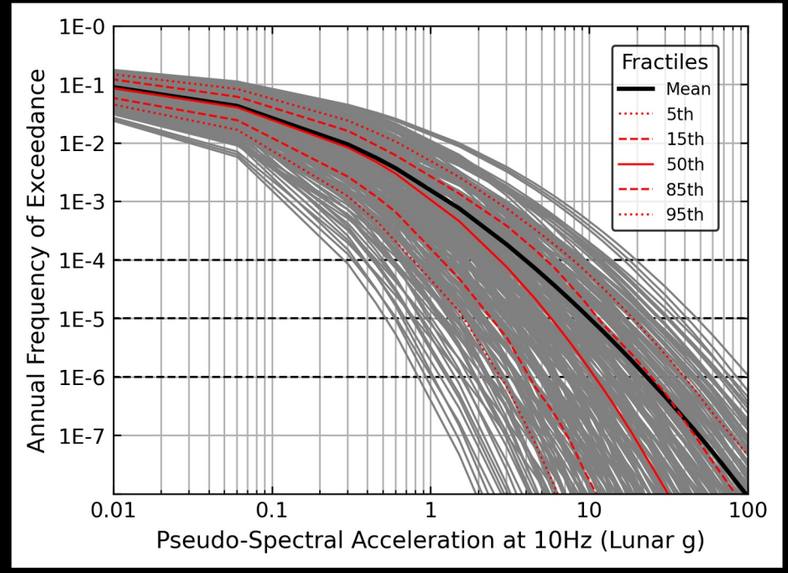
- *Moment Magnitude (M)*
- *Site-to-Source Rupture Distance (R_{rup})*

Preliminary PSHA Parameters:

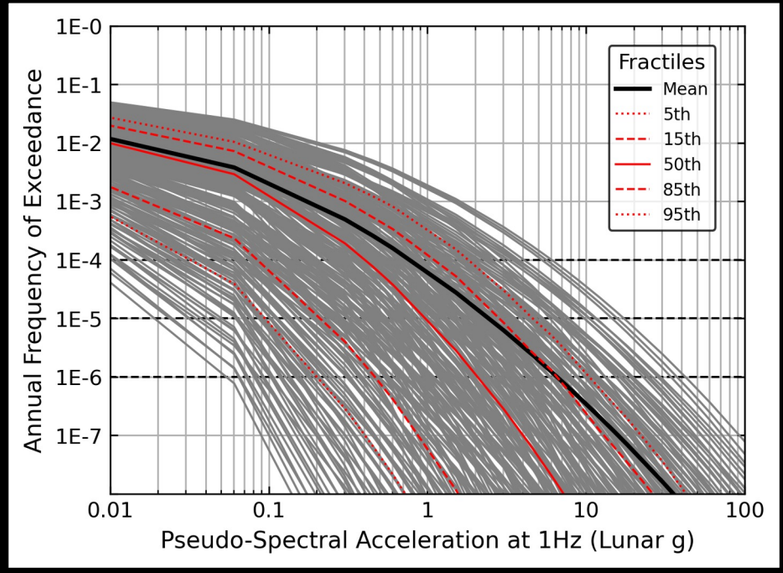
- *Single Recurrence Curve = 28 Events*
- *Observation Period = 6 years*
- *Max Moment Magnitude = 5.0 - 7.0*
- *Depth of Top of Rupture (Z_{TOP}) = Varied*



Mean Hazard Curve and Fractiles at 100Hz



Mean Hazard Curve and Fractiles at 10 Hz



Mean Hazard Curve and Fractiles at 1 Hz

Moonquake Ground Motion Model

Probability of Exceedance (PoE)

What is the probability that the ground motion will exceed certain level?

$$P(n \geq 1|T) = 1 - e^{-\lambda T}$$

Return Period (RP)

How frequent would we expect this level of shaking to occur?

$$Return\ Period = \frac{1}{\lambda}$$

λ - Mean Annual Rate of Exceedance
T - Time Period of Structure

Moonquake Ground Motion Model

Probability of Exceedance (PoE)

What is the probability that the ground motion will exceed certain level?

$$P(n \geq 1|T) = 1 - e^{-\lambda T}$$

Return Period (RP)

How frequent would we expect this level of shaking to occur?

$$Return\ Period = \frac{1}{\lambda}$$

Example:

- Return Period = 475-year
- Time Period of Structure = 50 years

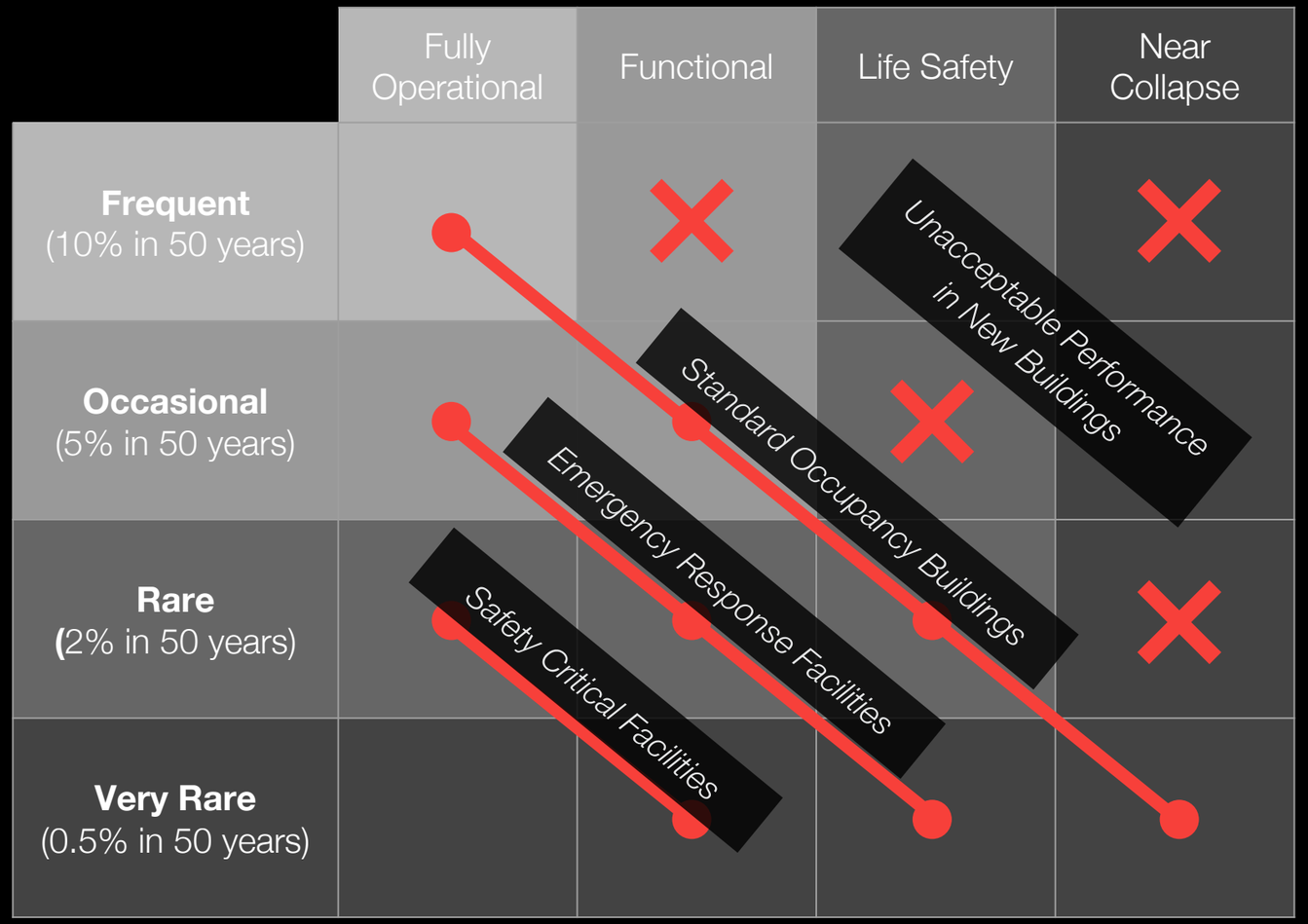
$$475\ years = \frac{1}{\lambda} \longrightarrow \lambda = \frac{1}{475\ years} \longrightarrow P(n \geq 1|T) = 1 - e^{-\left(\frac{1}{475\ years}\right)(50\ years)} \approx 10\%$$

Moonquake Ground Motion Model

Service Life = 50 years

Four Return Periods:

- 475-year | 10% PoE
- 975-year | 5% PoE
- 2,475-year | 2% PoE
- 10,000-year | 0.5% PoE



Moonquake Ground Motion Model

Service Life = 50 years

Four Return Periods:

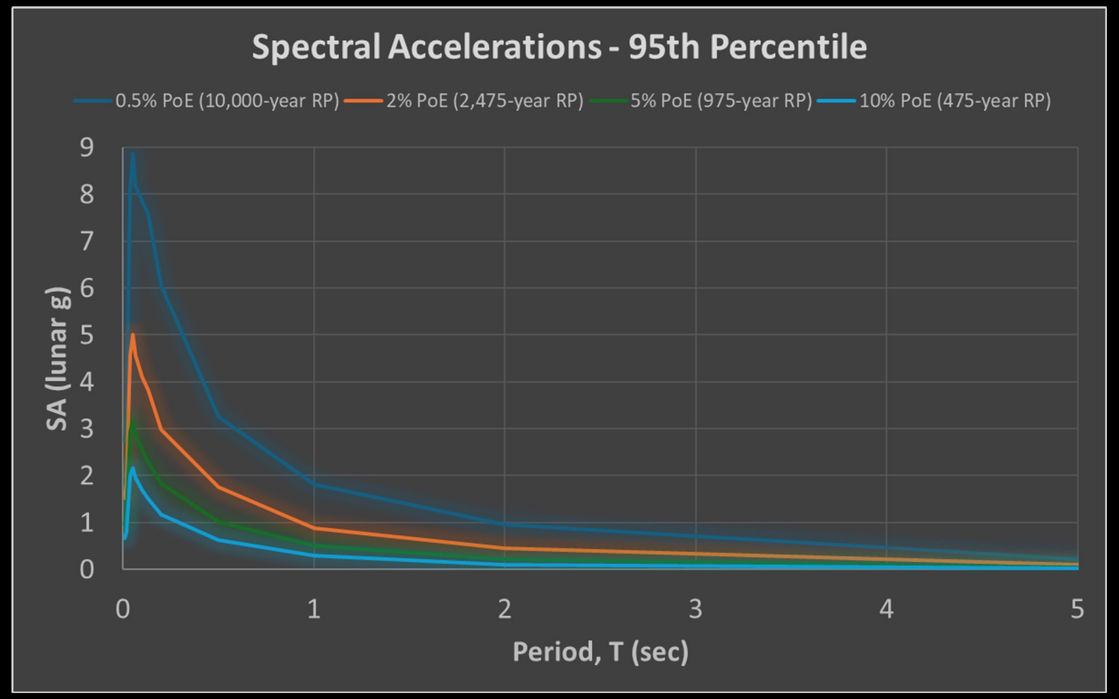
- 475-year | 10% PoE
- 975-year | 5% PoE
- 2,475-year | 2% PoE ← High-Importance Terrestrial Buildings (i.e., hospitals)
- 10,000-year | 0.5% PoE ← Nuclear Facilities

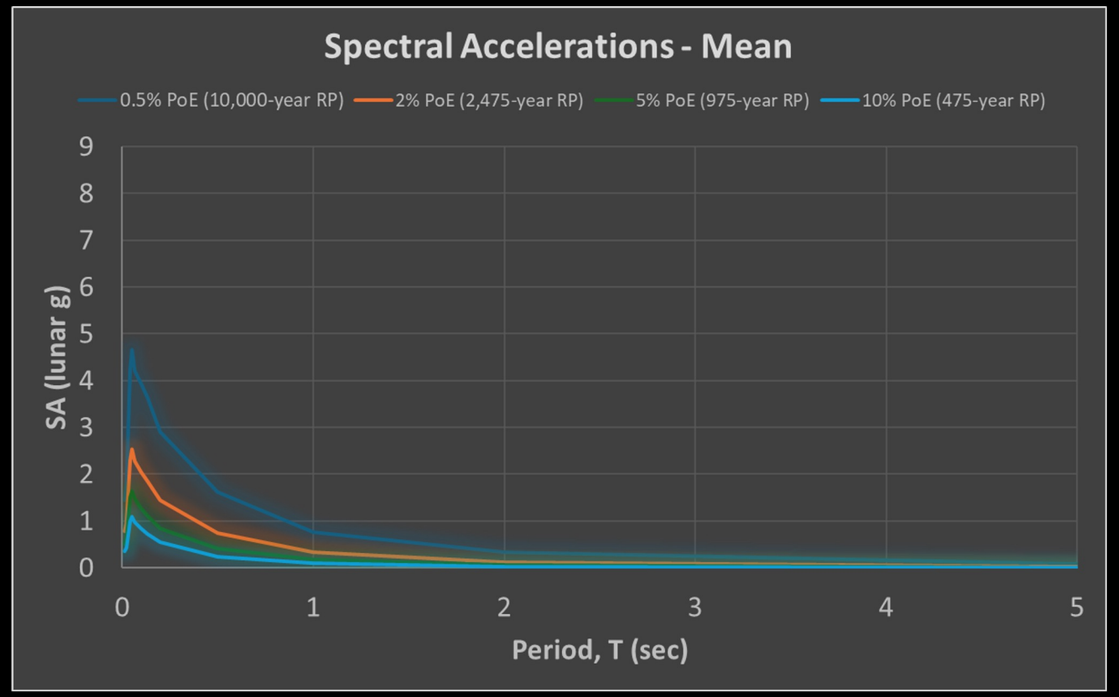
Moonquake Ground Motion Model

Service Life = 50 years

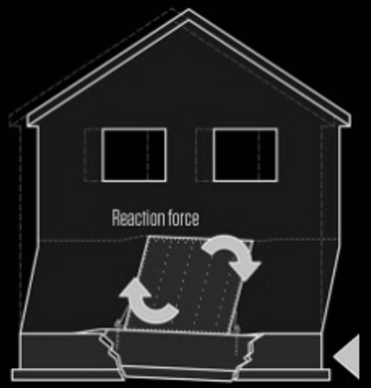
Four Return Periods:

- 475-year | 10% PoE
- 975-year | 5% PoE
- 2,475-year | 2% PoE
- 10,000-year | 0.5% PoE



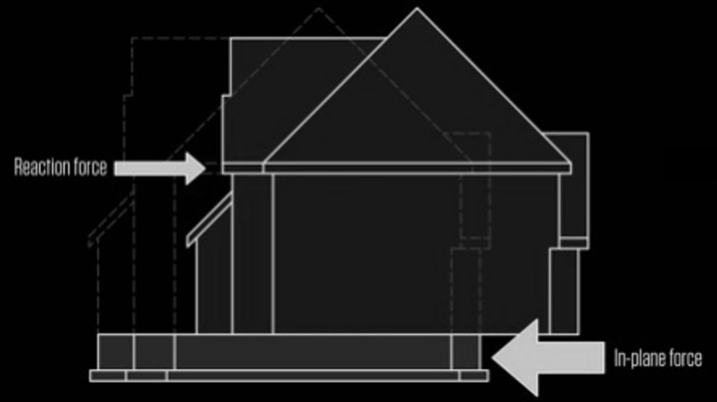


Effects of Seismic Force



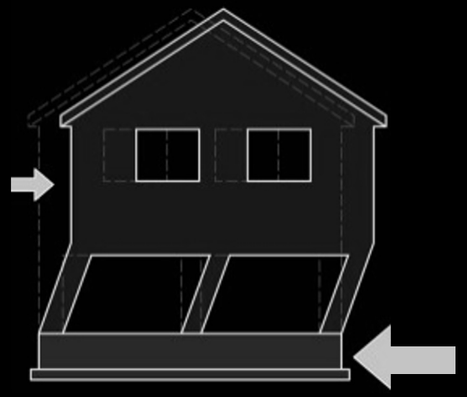
Overturning

Toppling from uplift.



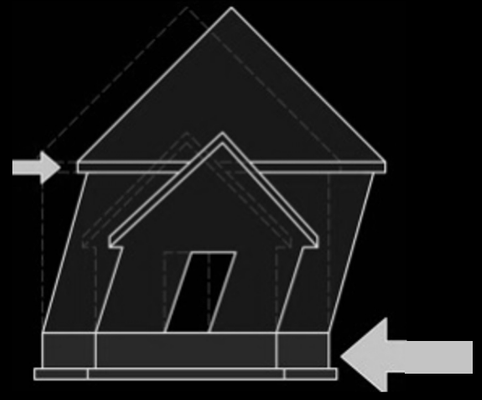
Sliding

Lateral movement at base.



Soft-Story Failure

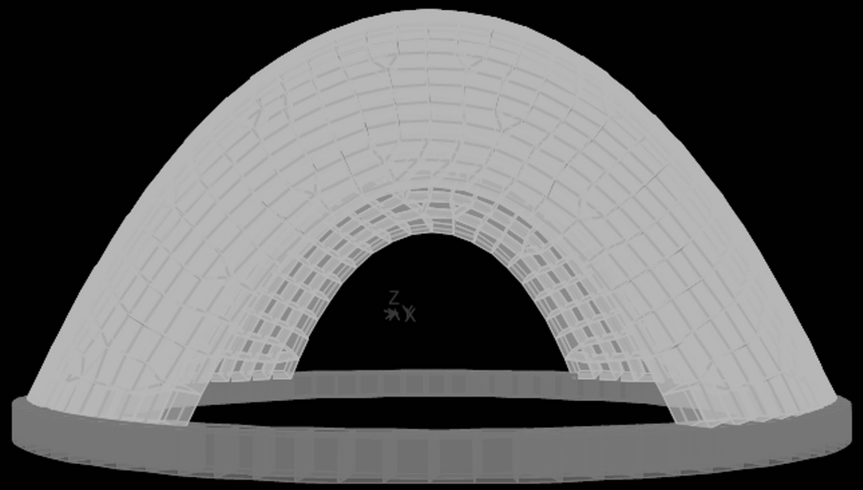
Weak lower level collapse



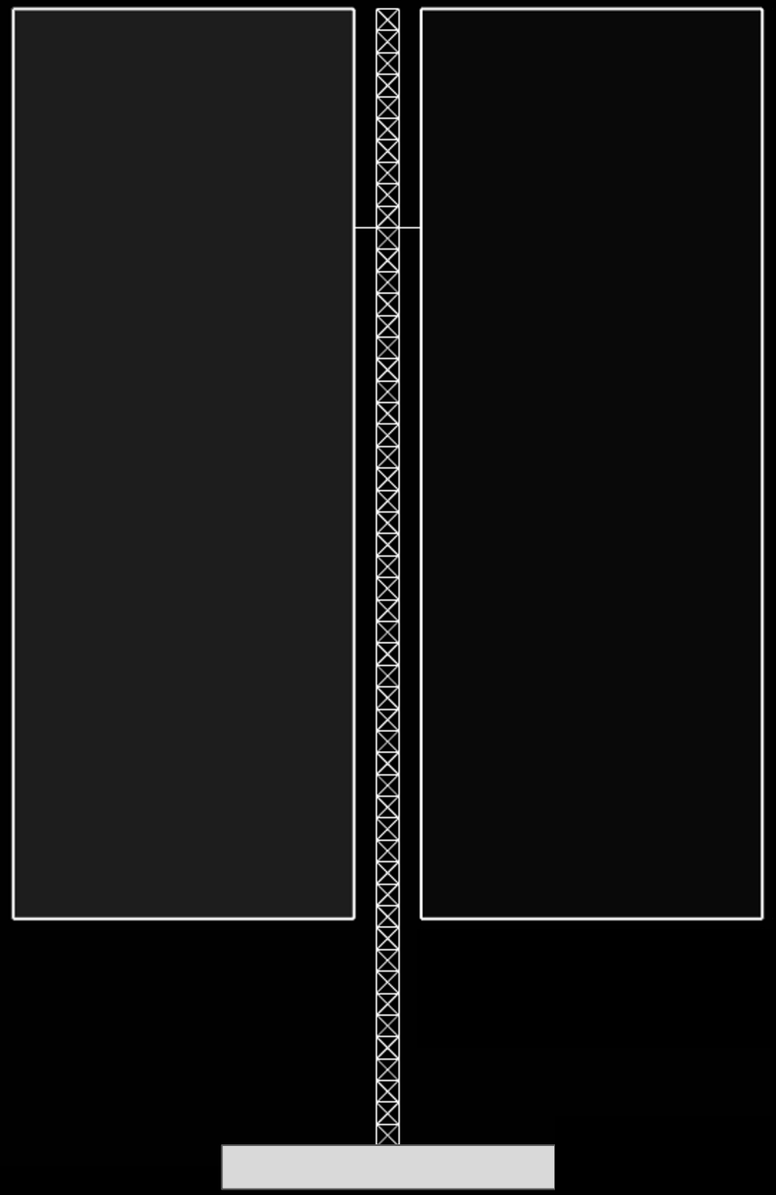
Racking

Distorted vertical frame.

Structural Analysis



Unpressurized Catenary Dome



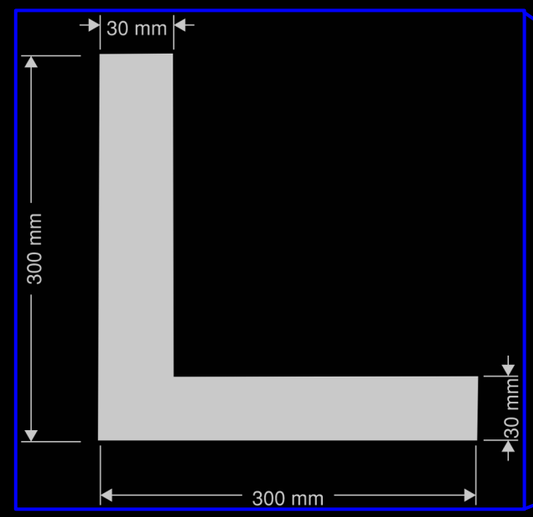
Tall Lunar Tower

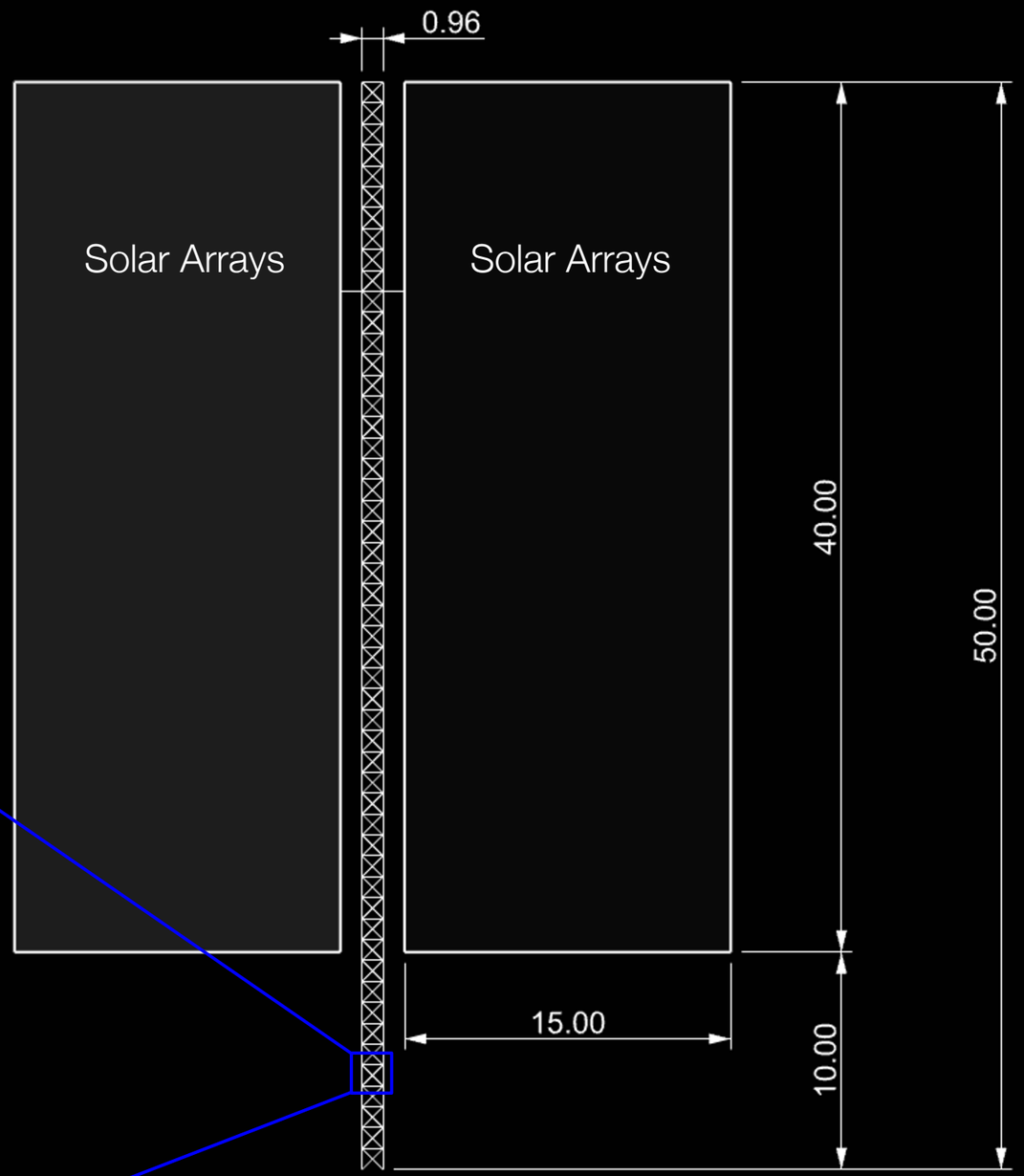
Structural Analysis

Tall Lunar Tower

Structural Design Parameters

TLT Total Height (H) =	50 m
Width of Solar Panel (b_B) =	40 m
Height of Solar Panel (c_B) =	30 m
Standoff Height (a) =	10 m
Total Solar Panel Load =	2.78 kN





Structural Analysis

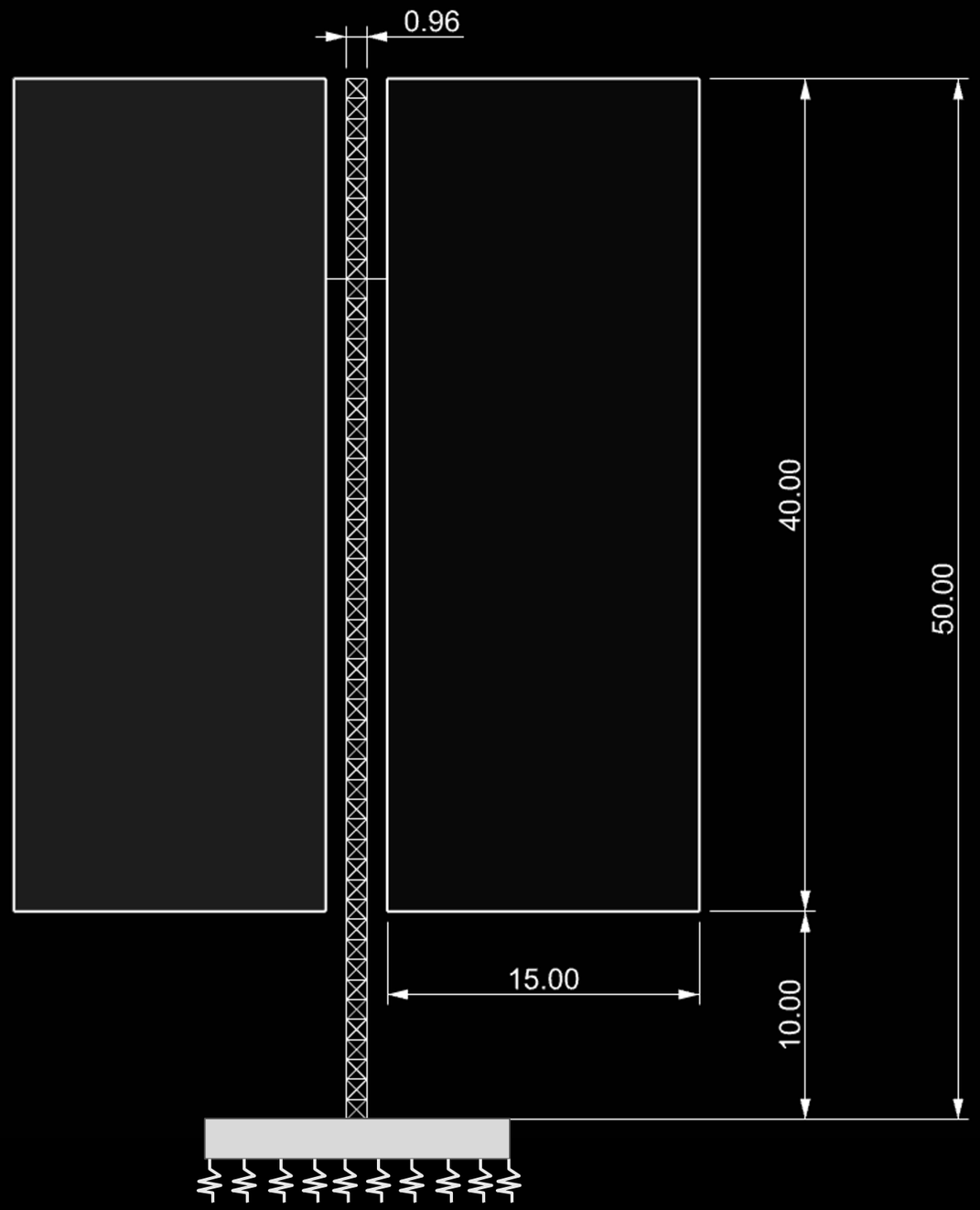
Tall Lunar Tower

Structural Design Parameters

TLT Total Height (H) = 50 m
Width of Solar Panel (b_B) = 40 m
Height of Solar Panel (c_B) = 30 m
Standoff Height (a) = 10 m
Total Solar Panel Load = 2.78 kN

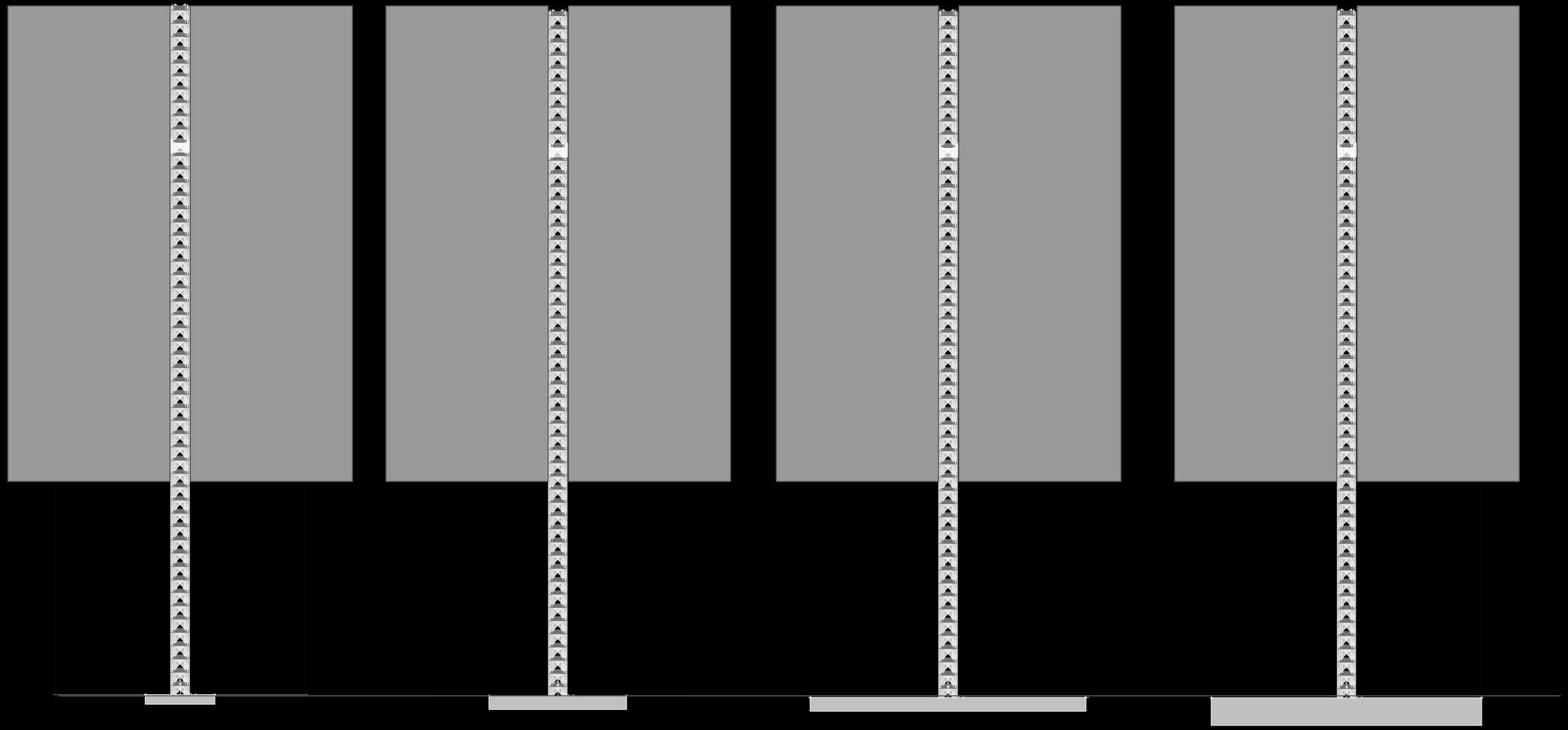
Foundation Properties

Foundation Type: Mat Foundation
Material: Sintered Regolith
Area Springs: Vertical Subgrade Modulus (Regolith Stiffness)



Structural Analysis

Tall Lunar Tower



5m x 5m x 0.7m

10m x 10m x 1m

20m x 20m x 1m

20m x 20m x 2m

Structural Analysis

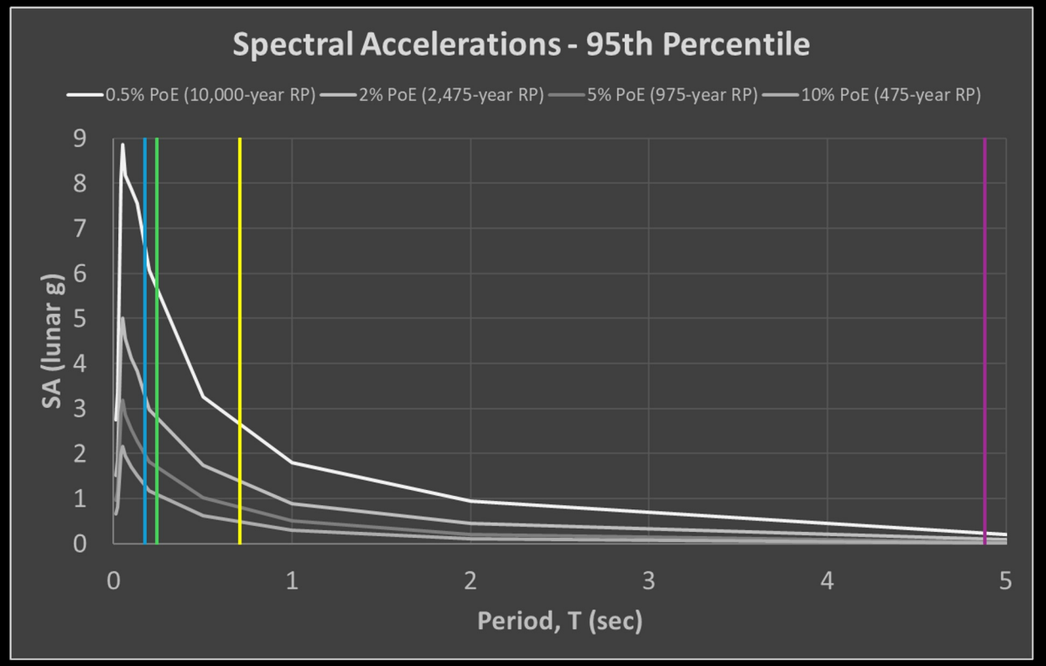
Tall Lunar Tower

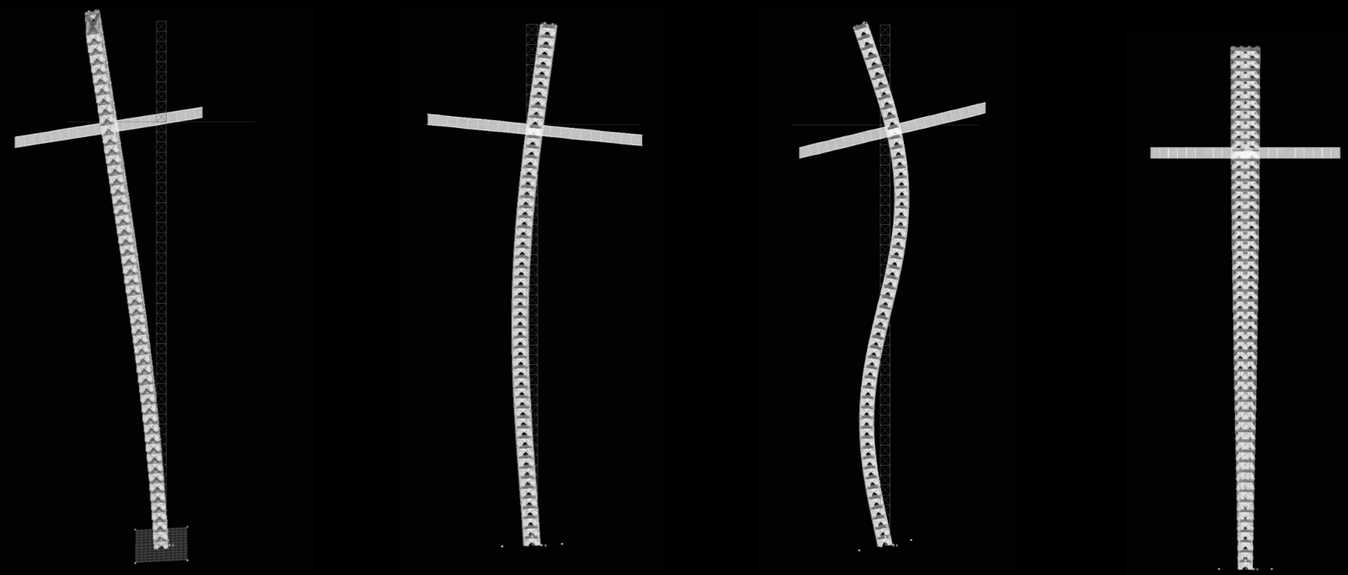
Response Spectrum

Dynamic Analysis

Dynamic Characteristics using Modal Analysis

Geometric Nonlinearity Not Allowed

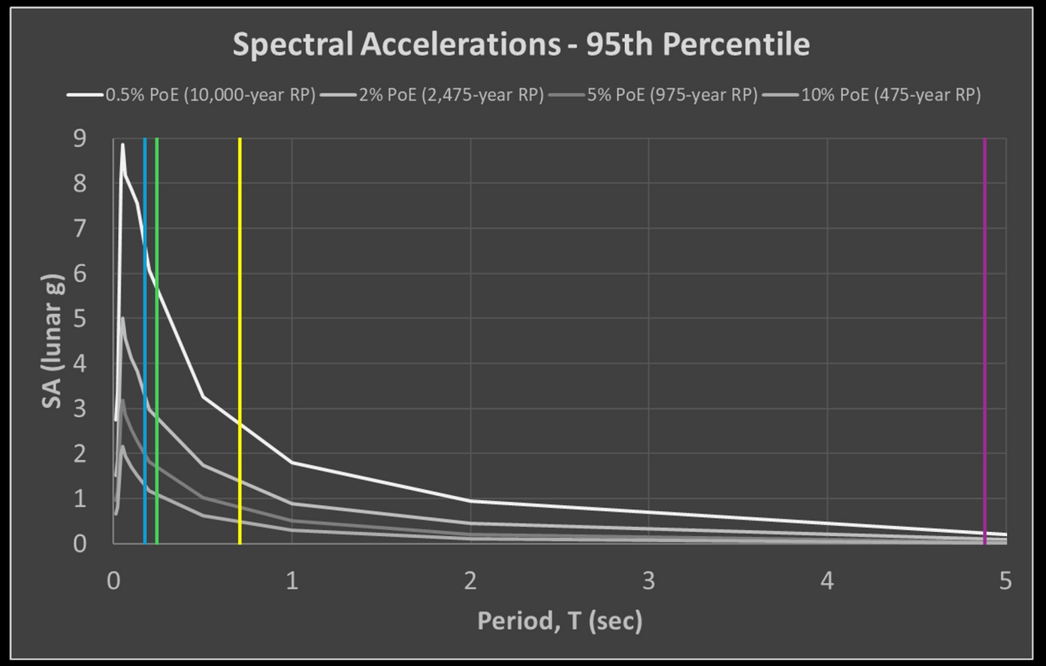




Mode 1/2 *Mode 3/4* *Mode 5/6* *Mode 7*

Structural Analysis

Tall Lunar Tower



Response Spectrum

Dynamic Analysis

Dynamic Characteristics using Modal Analysis

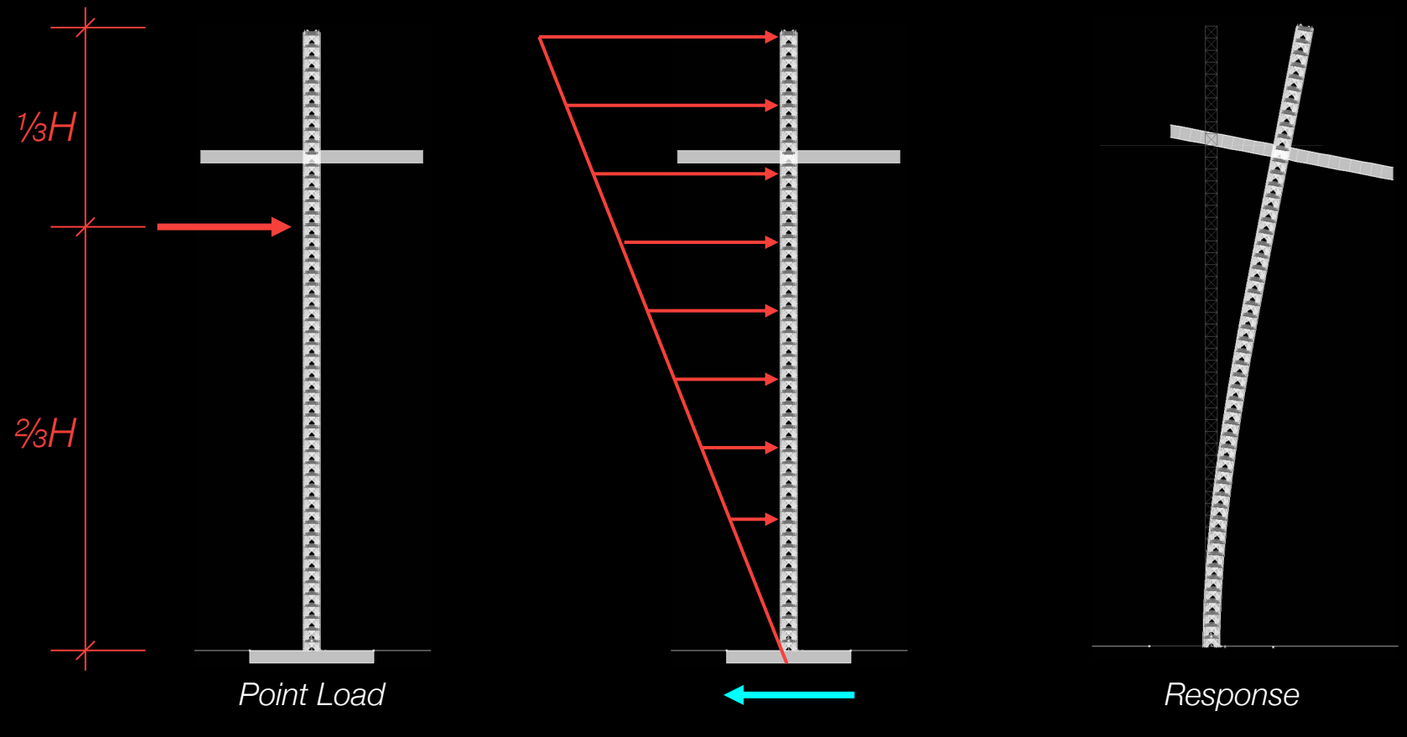
Geometric Nonlinearity Not Allowed

Equivalent Lateral Force (ELF)

Static Analysis

Approximation of Seismic Effect

Geometrical Nonlinearity Allowed



Structural Analysis

Tall Lunar Tower

Response Spectrum

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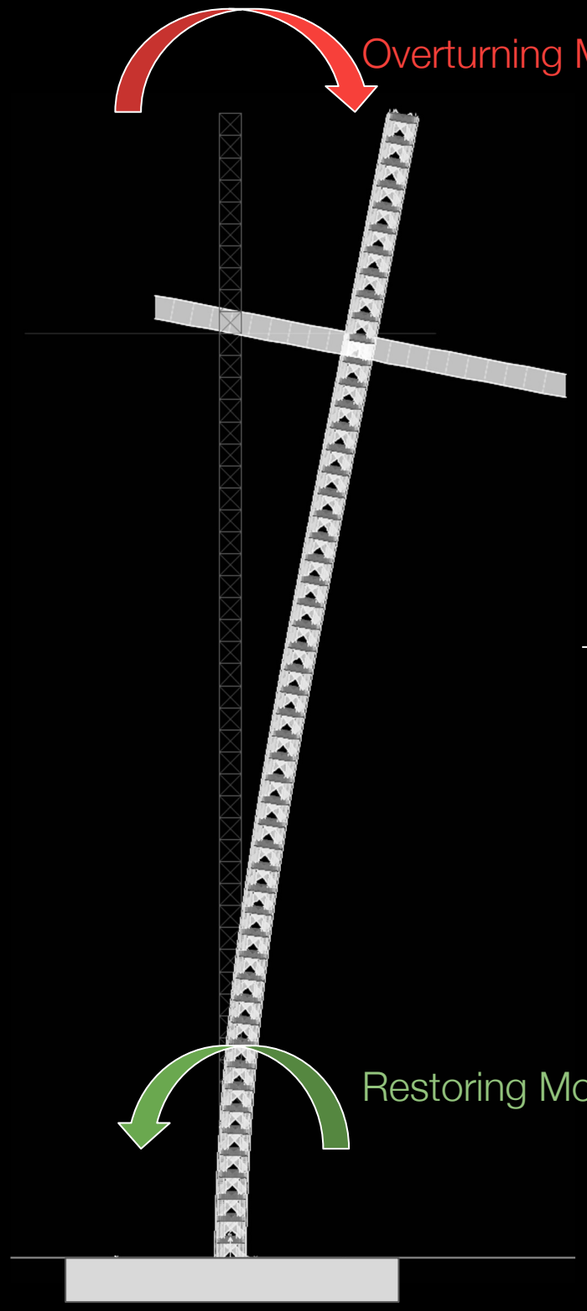


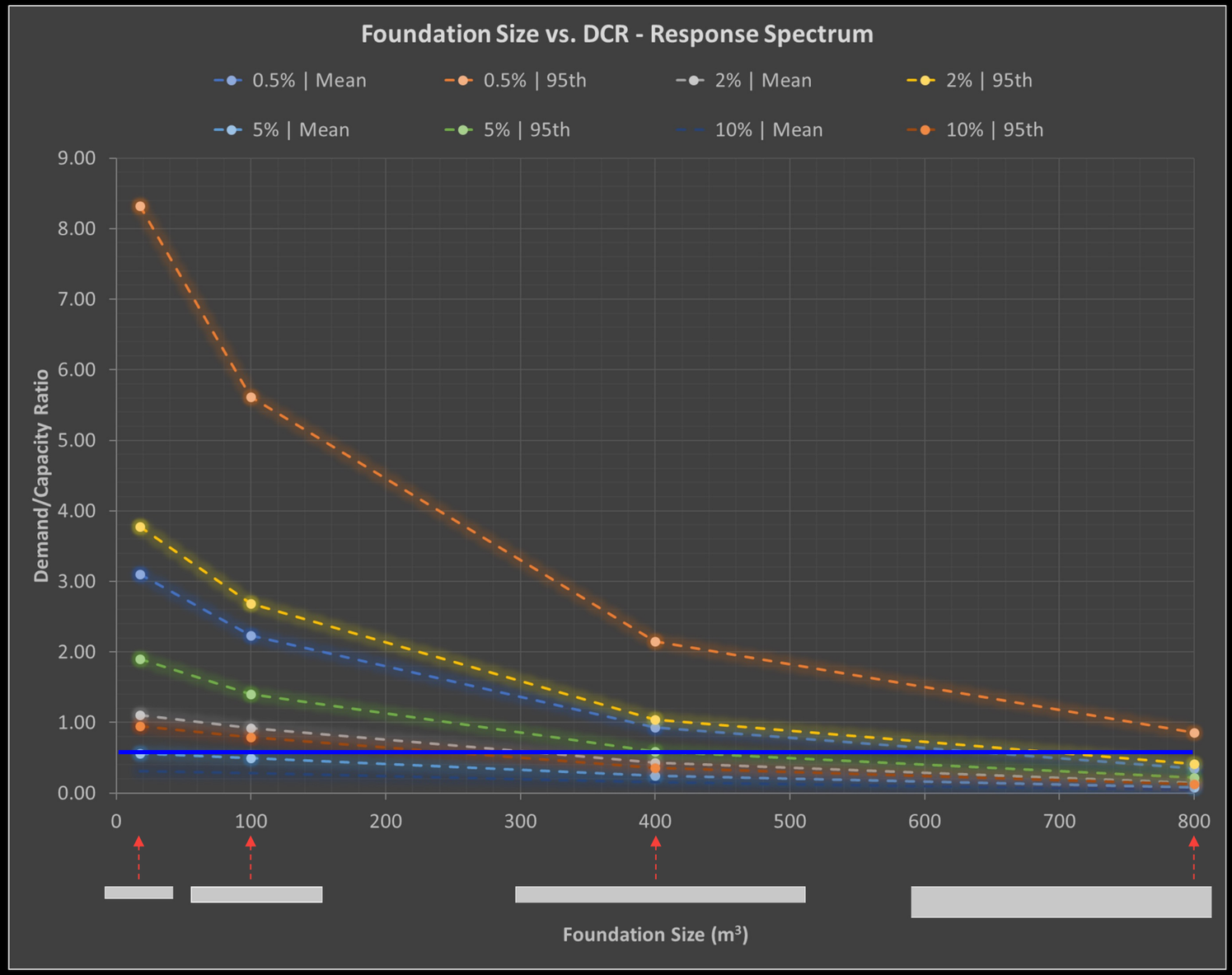
$$\frac{\text{Overturning Force}}{\text{Restoring Force}} = \frac{\text{Demand}}{\text{Capacity}}$$

Structural Analysis

Tall Lunar Tower

Response Spectrum - Results

- Idealized Structure
- Insufficient Lever Arm
- Low Rotational Stiffness
- Increased Oveturning Risk
- Safety Factor ≥ 2.0 (DCR ≤ 0.5)

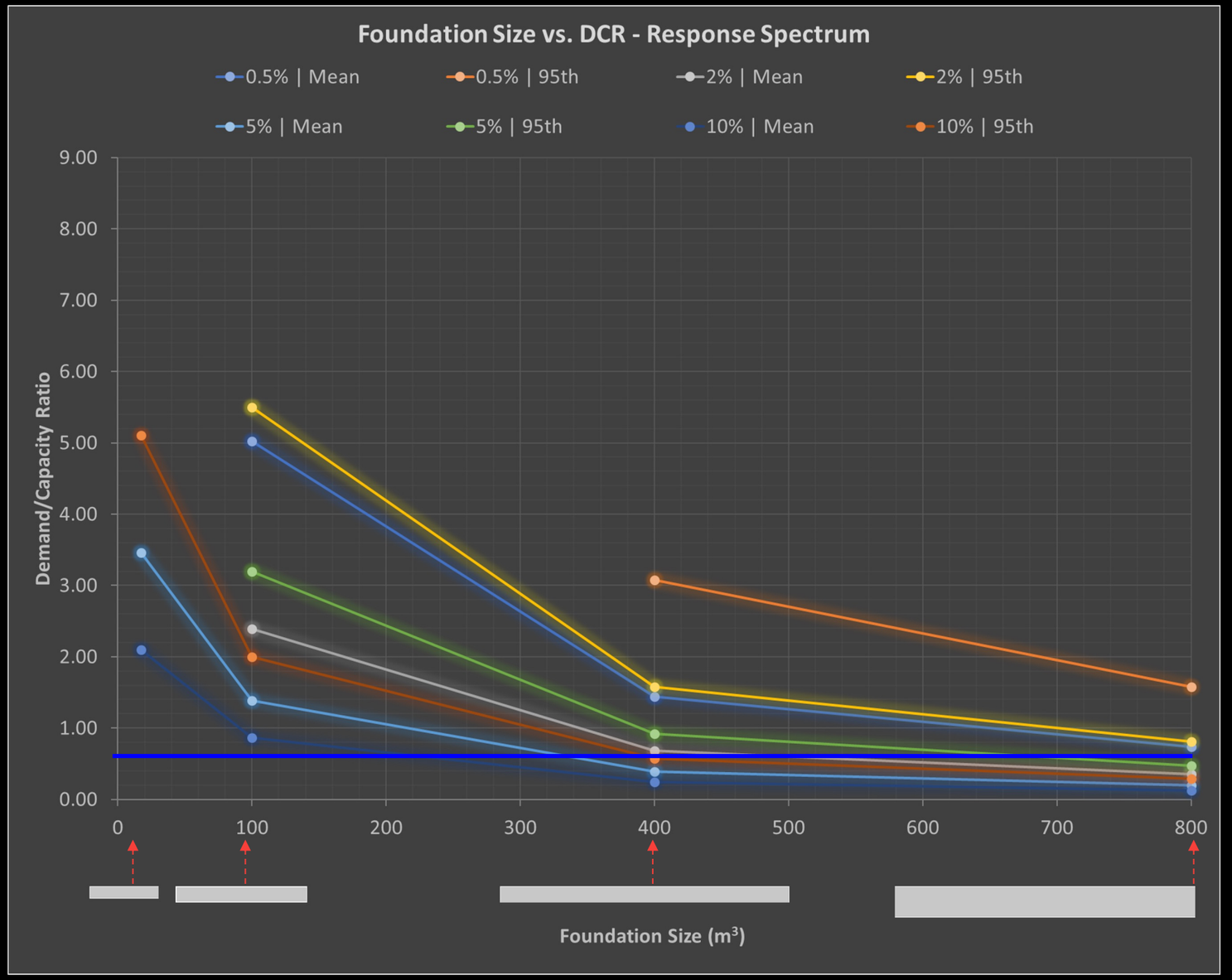


Structural Analysis

Tall Lunar Tower

Equivalent Lateral Force - Results

- Idealized Structure
- Insufficient Lever Arm
- Low Rotational Stiffness
- Increased Oveturning Risk
- Safety Factor ≥ 2.0 (DCR ≤ 0.5)
- Instability due to Geometrical Nonlinearity



Structural Analysis

Catenary Dome

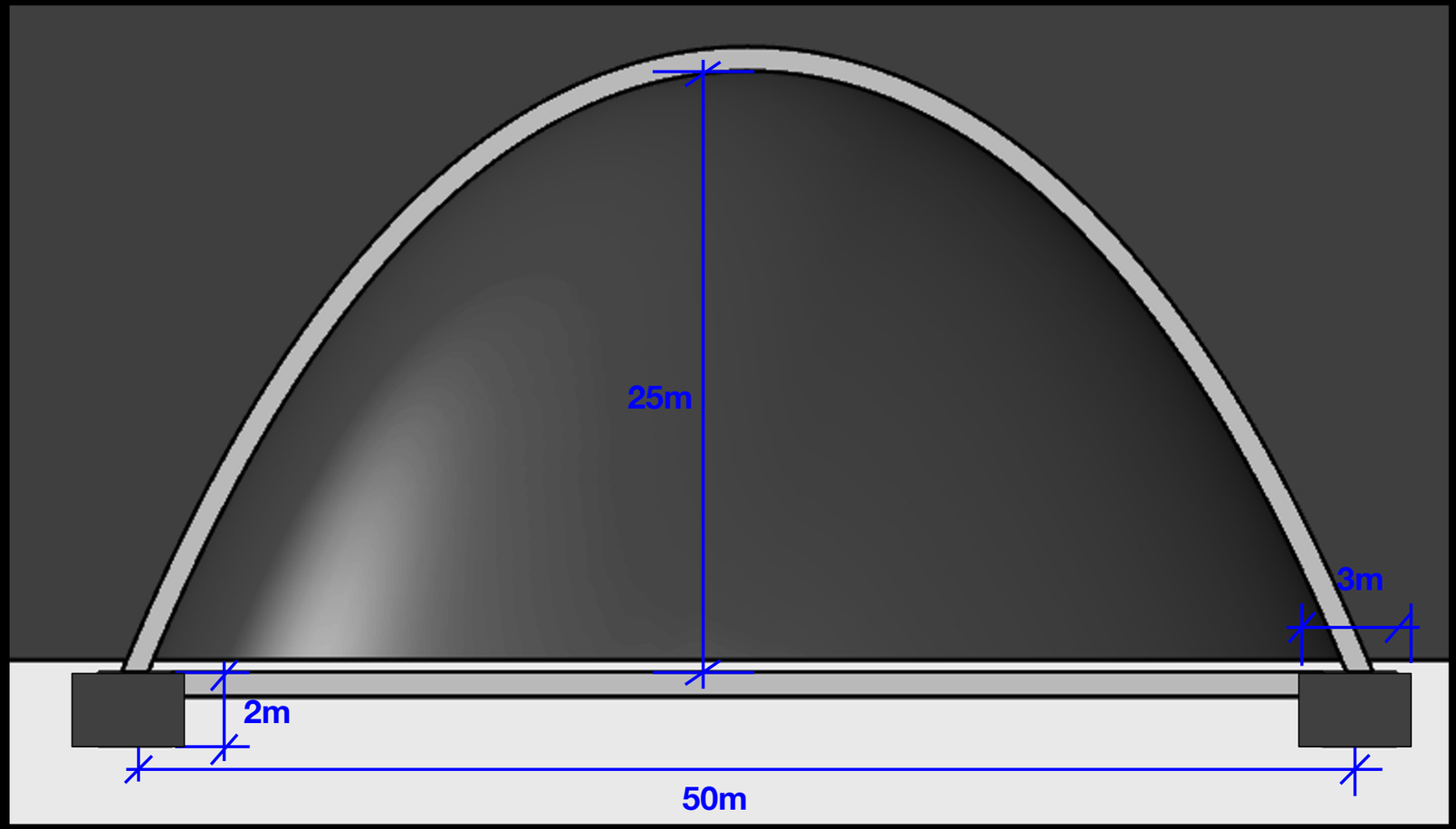
Structural Design Parameters

Dome Height (H_d) =	25m
Dome Central Diameter (D) =	50 m
Dome Shell Thickness (t_d) =	1.5 m
Foundation Height (H_f)=	2 m
Foundation Width (t_f) =	3m

Non-Structural Slab

Thickness = 1m

Spanning between Ring Foundation



Structural Analysis

Catenary Dome

Response Spectrum

Dynamic Analysis

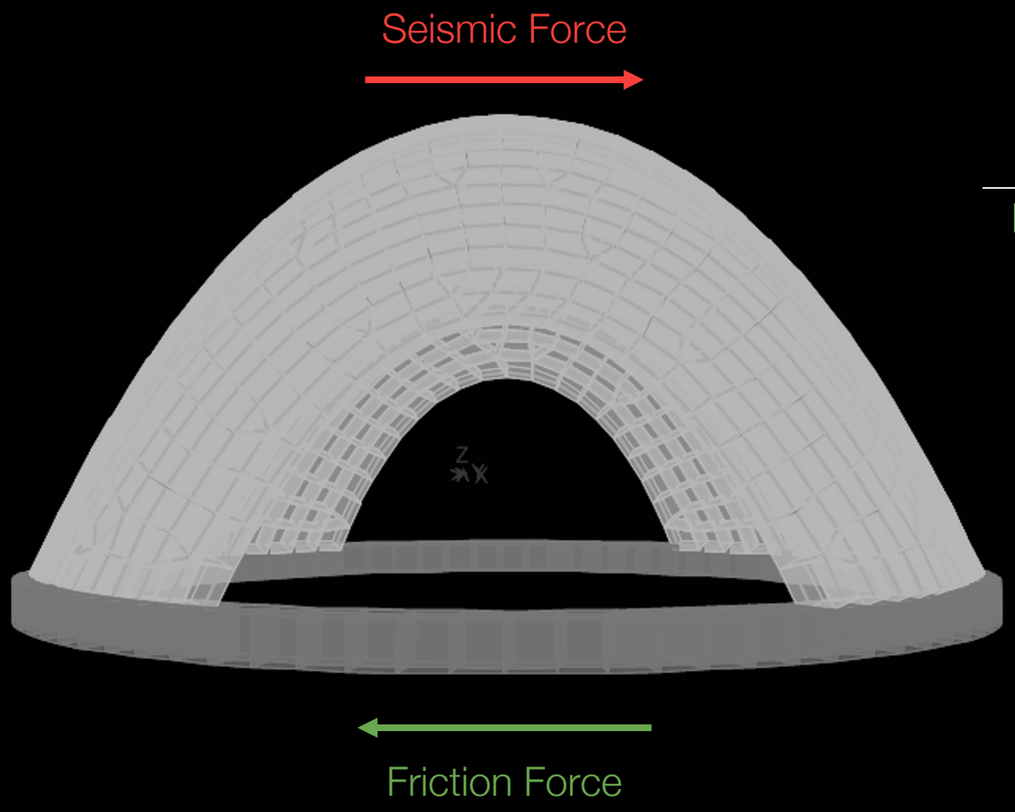
High Frequency/Short Period Structure

Geometrical Nonlinearity not included

Bearing Pressure due to Structural Weight

Structural Sliding

Assumed Regolith Coefficient of Friction = 0.2

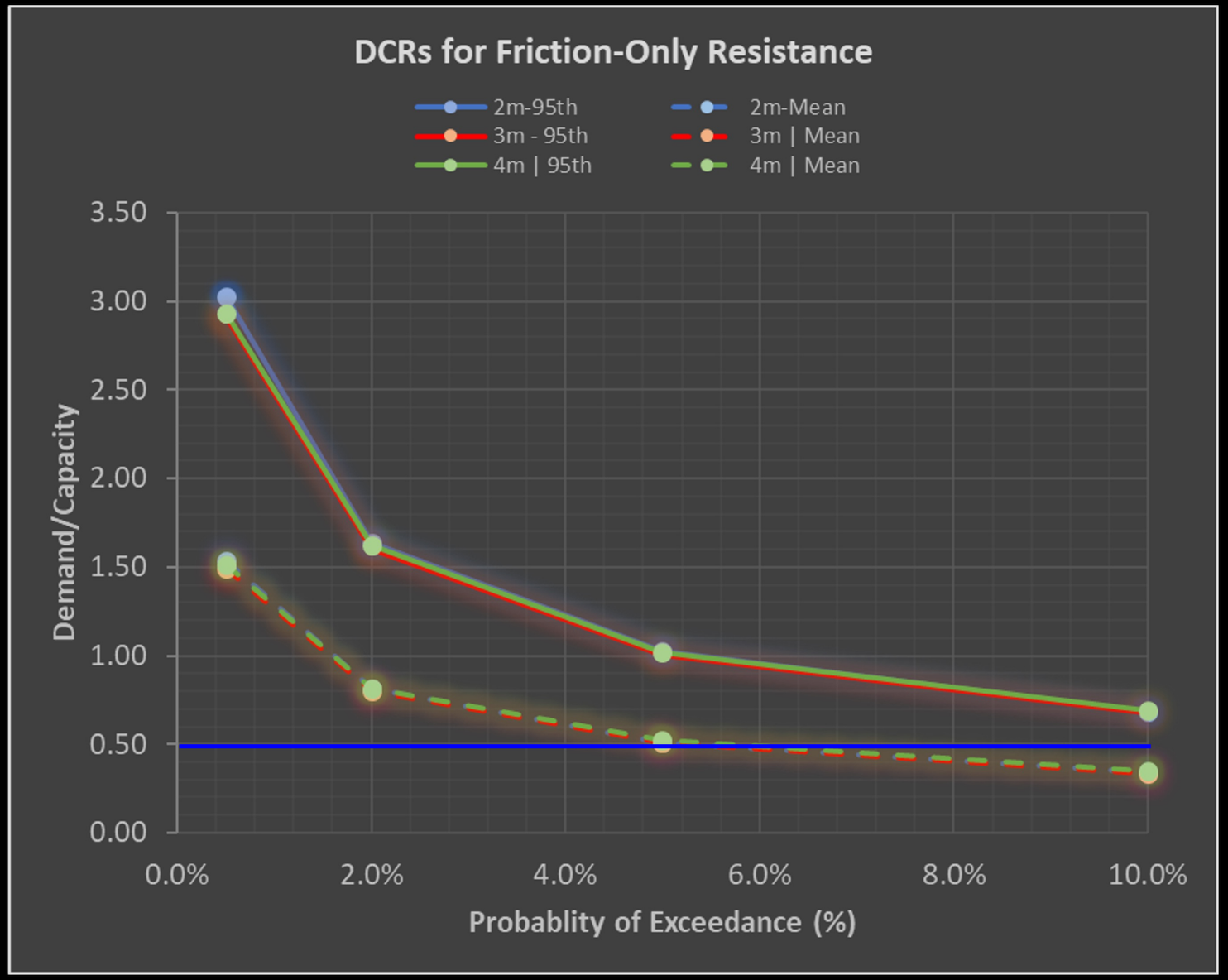


$$\frac{\text{Seismic Force}}{\text{Friction + Force}} = \frac{\text{Demand}}{\text{Capacity}}$$

Structural Analysis
Catenary Dome

Response Spectrum - Results

- Insufficient Friction Resistance
- Base Shear Offsets Foundation Depth Effect
- Safety Factor ≥ 2.0 (DCR ≤ 0.5)



Structural Analysis

Catenary Dome

Response Spectrum

Dynamic Analysis

High Frequency/Short Period Structure

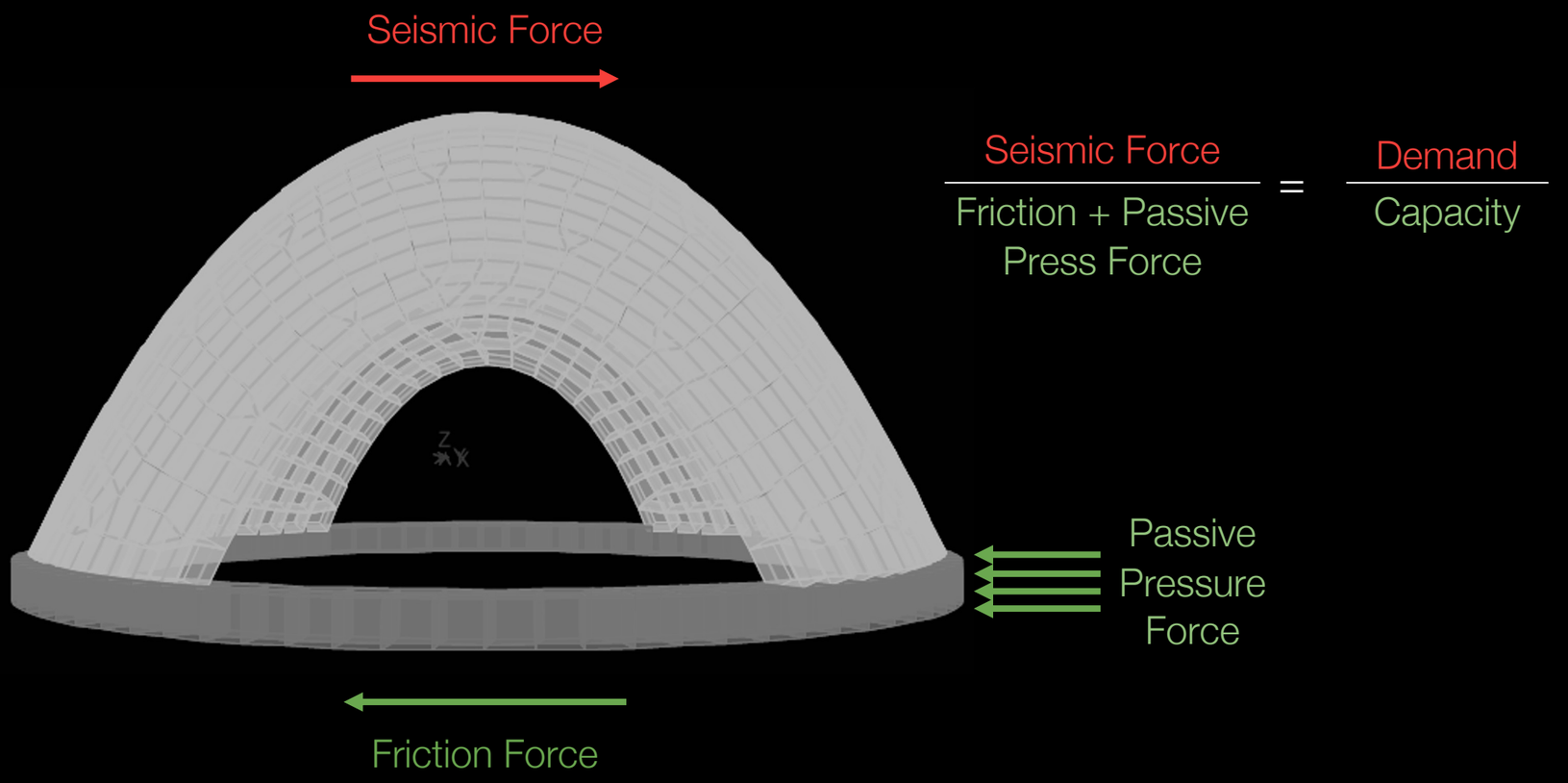
Geometrical Nonlinearity not included

Bearing Pressure due to Structural Weight

Structural Sliding

Assumed Regolith Coefficient of Friction = 0.2

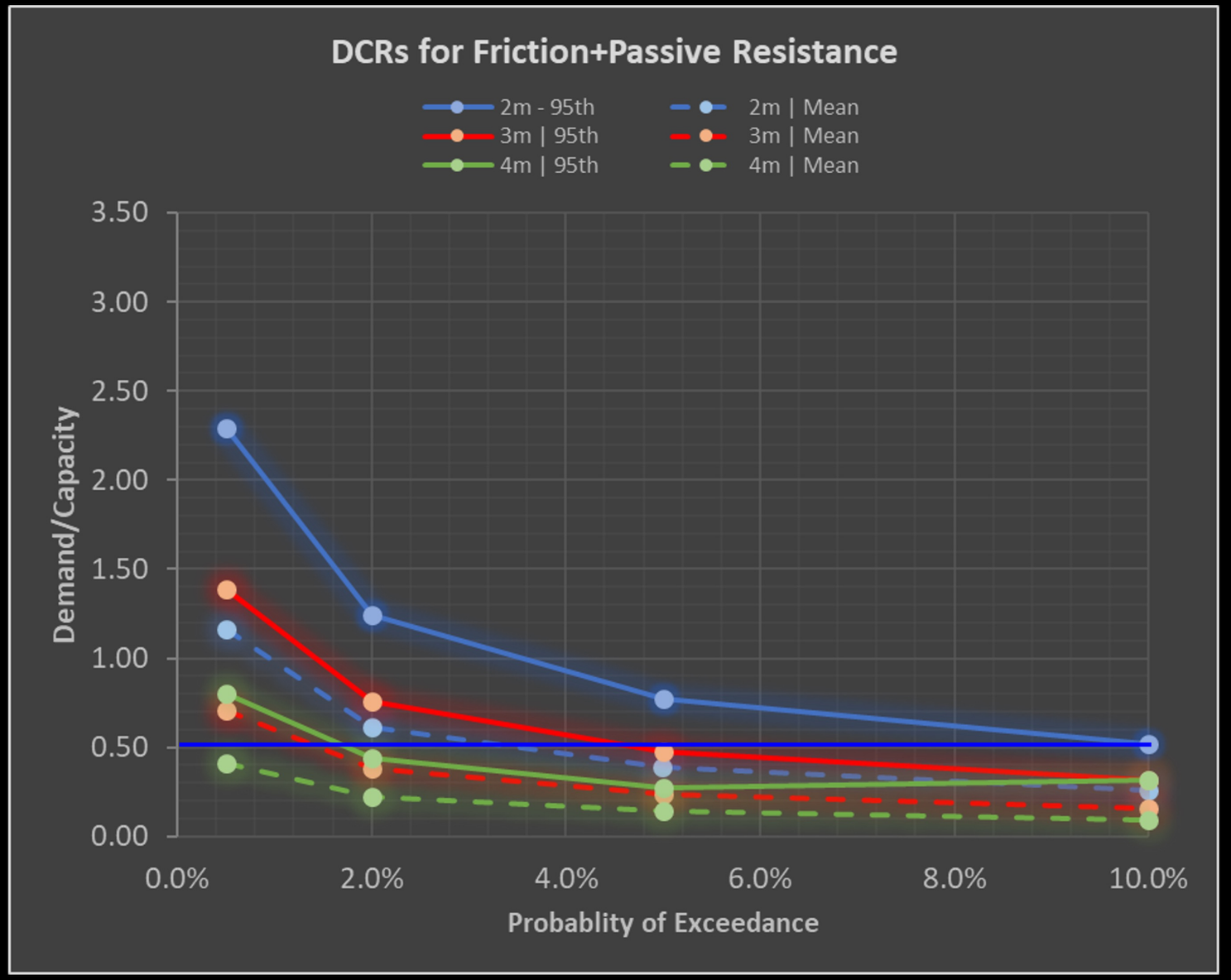
Passive Pressure Force



Structural Analysis
Catenary Dome

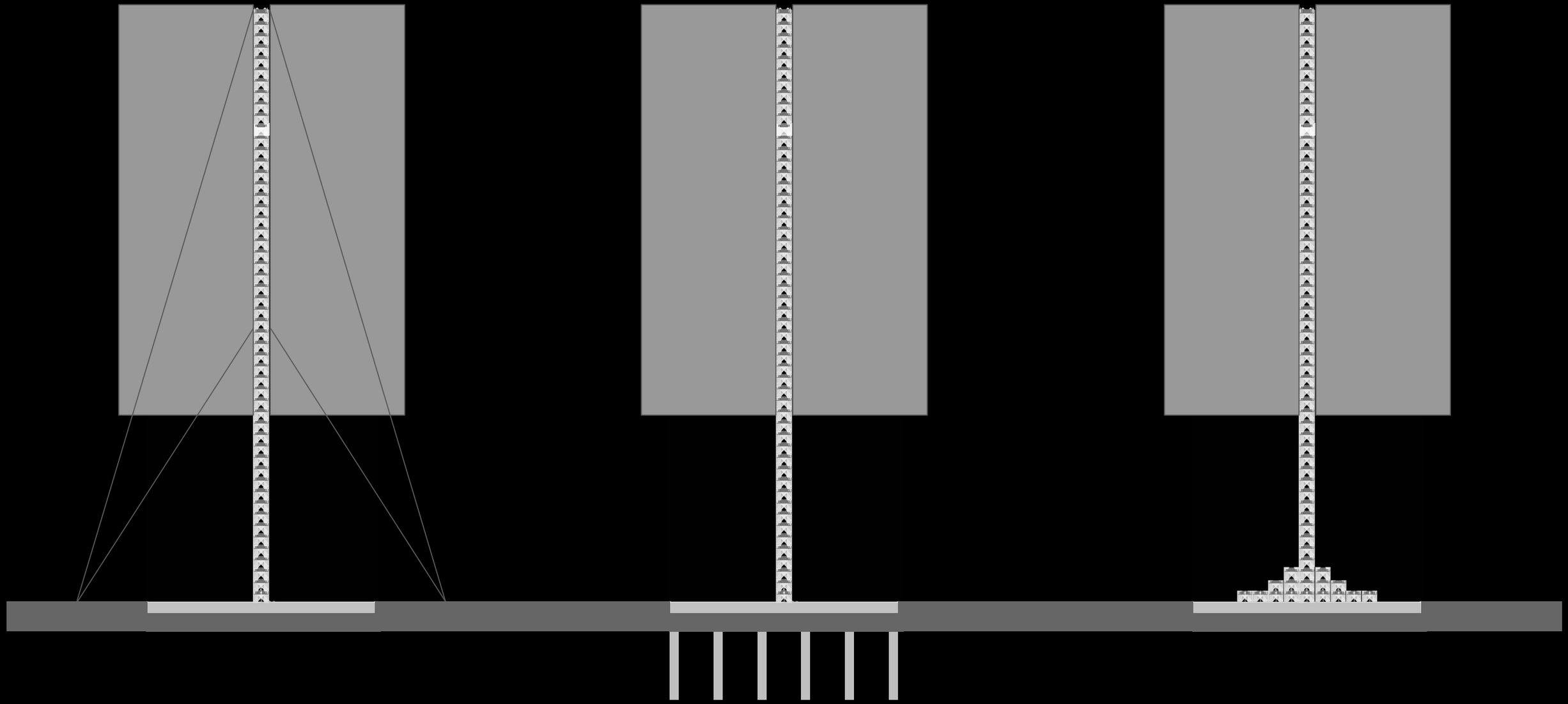
Response Spectrum - Results

- Combination of Friction and Passive Resistance
- Passive Resistance Depth Dependent
- Safety Factor ≥ 2.0 (DCR ≤ 0.5)



Structural Analysis

Potential Solutions - Tall Lunar Tower



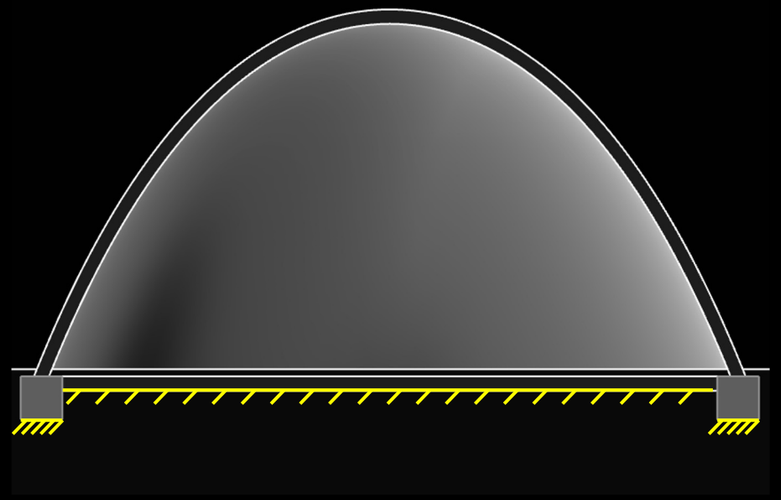
Addition of Guy-Wires

Addition of Substructure Tiedowns

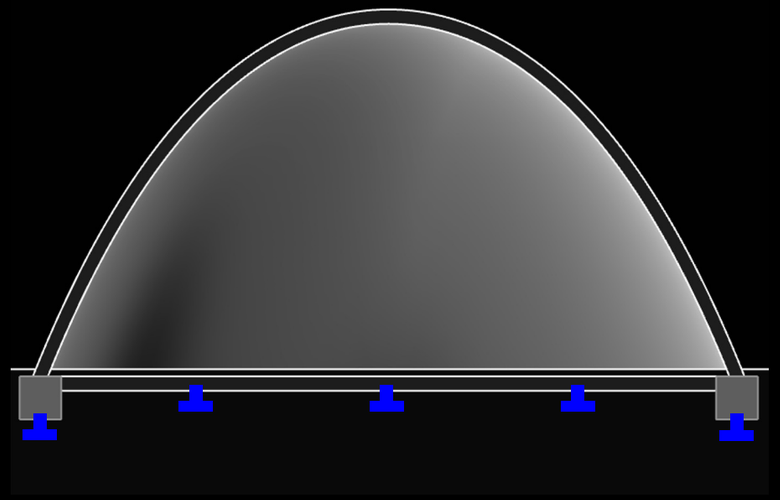
Addition of Ballast for Load Distribution

Structural Analysis

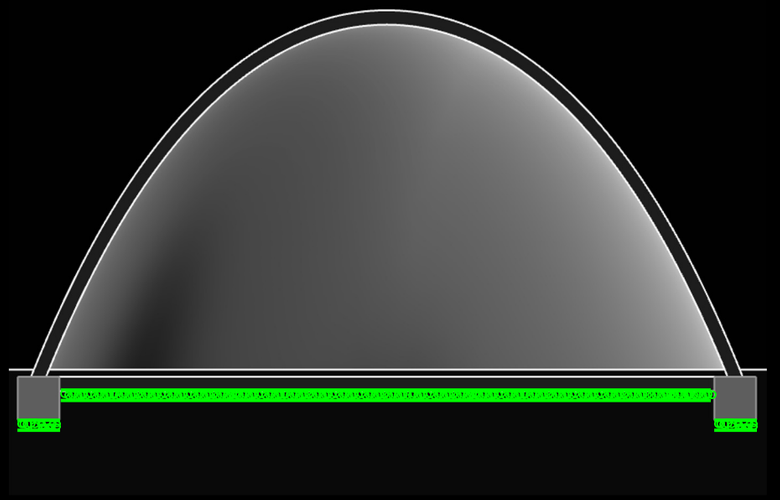
Potential Solutions - Catenary Dome



Increase in Foundation Friction

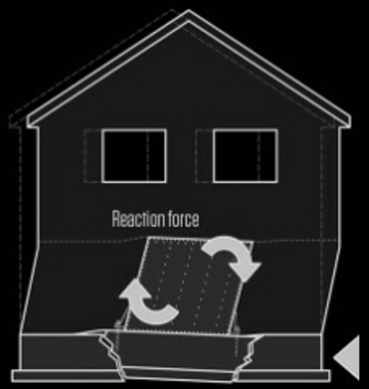


Addition of Shear Keys



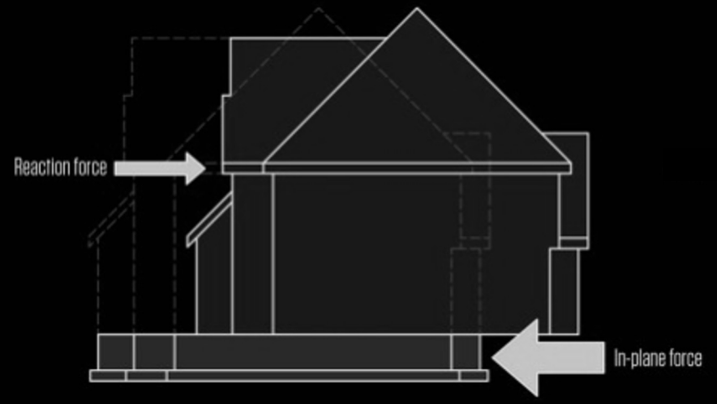
Seismic Isolation Plane

Lunar Effects of Seismic Force



Overturning

Toppling from uplift.

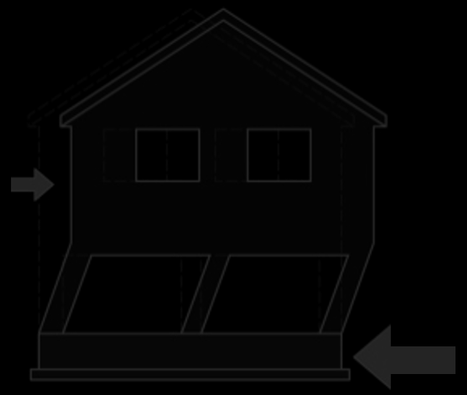


Sliding

Lateral movement at base.

Fatigue

Crack growth failure.



Soft-Story Failure

Weak lower level collapse

Racking

Distorted vertical frame.

Conclusion

Risk Category I	Buildings & other structures that represent a low hazard to human life in the event of failure
Risk Category II	Buildings & other structures that represent a sustained hazard to human life in the event of failure
Risk Category III	Buildings and other structures designated as Essential Facilities

Demand

- *What is the probability that the ground motion will exceed certain level?*
- *How frequent would we expect this level of shaking to occur?*

Performance

- *What level of damage is acceptable for a specific building Risk Category?*
- *How much repair is acceptable?*

	Fully Operational	Functional	Life Safety	Near Collapse
Frequent (10% in 50 years)		×	Unacceptable Performance in New Buildings	×
Occasional (5% in 50 years)			×	
Rare (2% in 50 years)				×
Very Rare (0.5% in 50 years)				

Standard Occupancy Buildings

Emergency Response Facilities

Safety Critical Facilities