Wind Loads for Utility Scale Photovoltaic Power Plants

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In Scope or Out of Scope?

In scope for this study:

- Utility scale (large-scale) ground mount
- Fixed tilt
- Single Axis Trackers
- Repetitive rows

Not in scope:

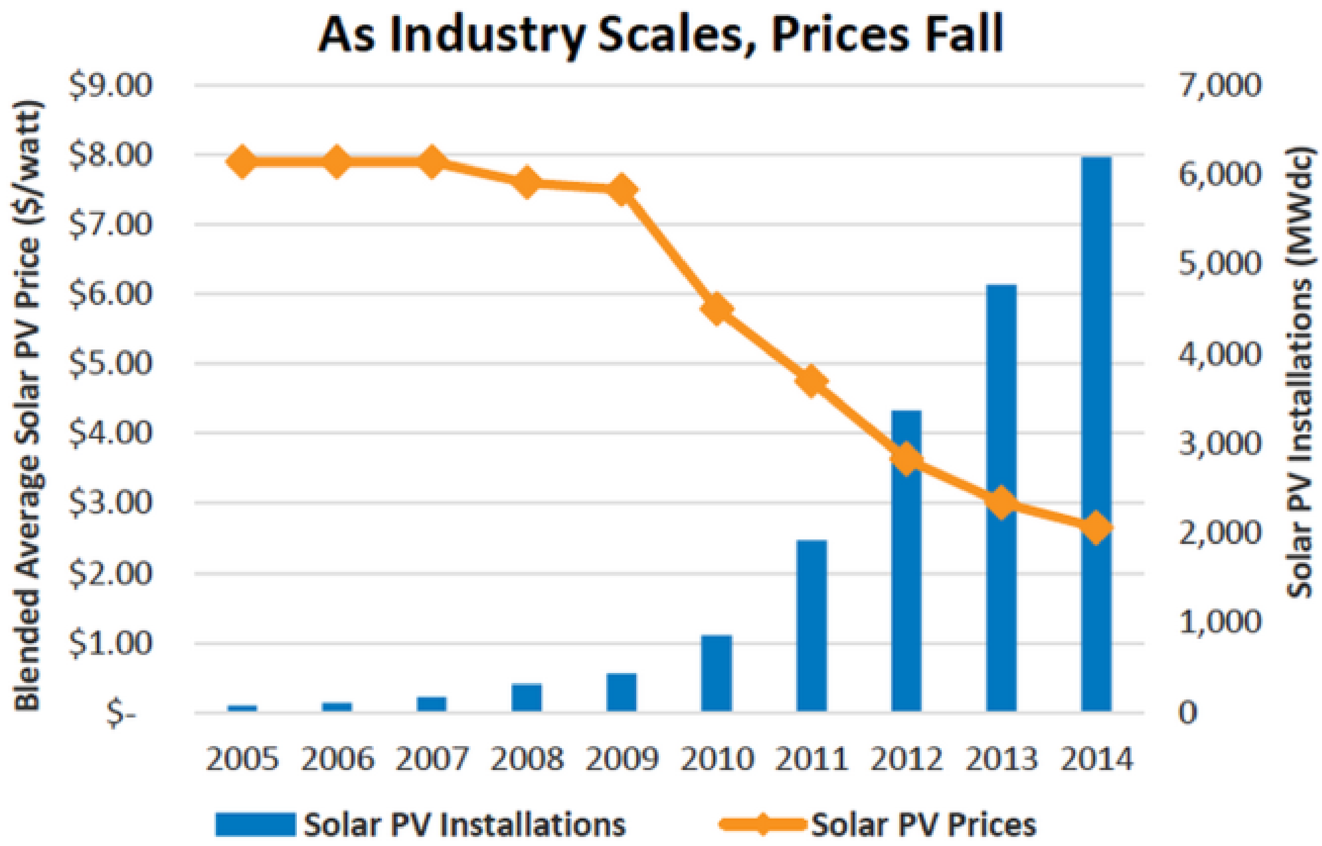
- Dual-axis trackers

Not in scope:

- Parking lot canopy structures

Solar PV Industry Growth and Cost Reduction

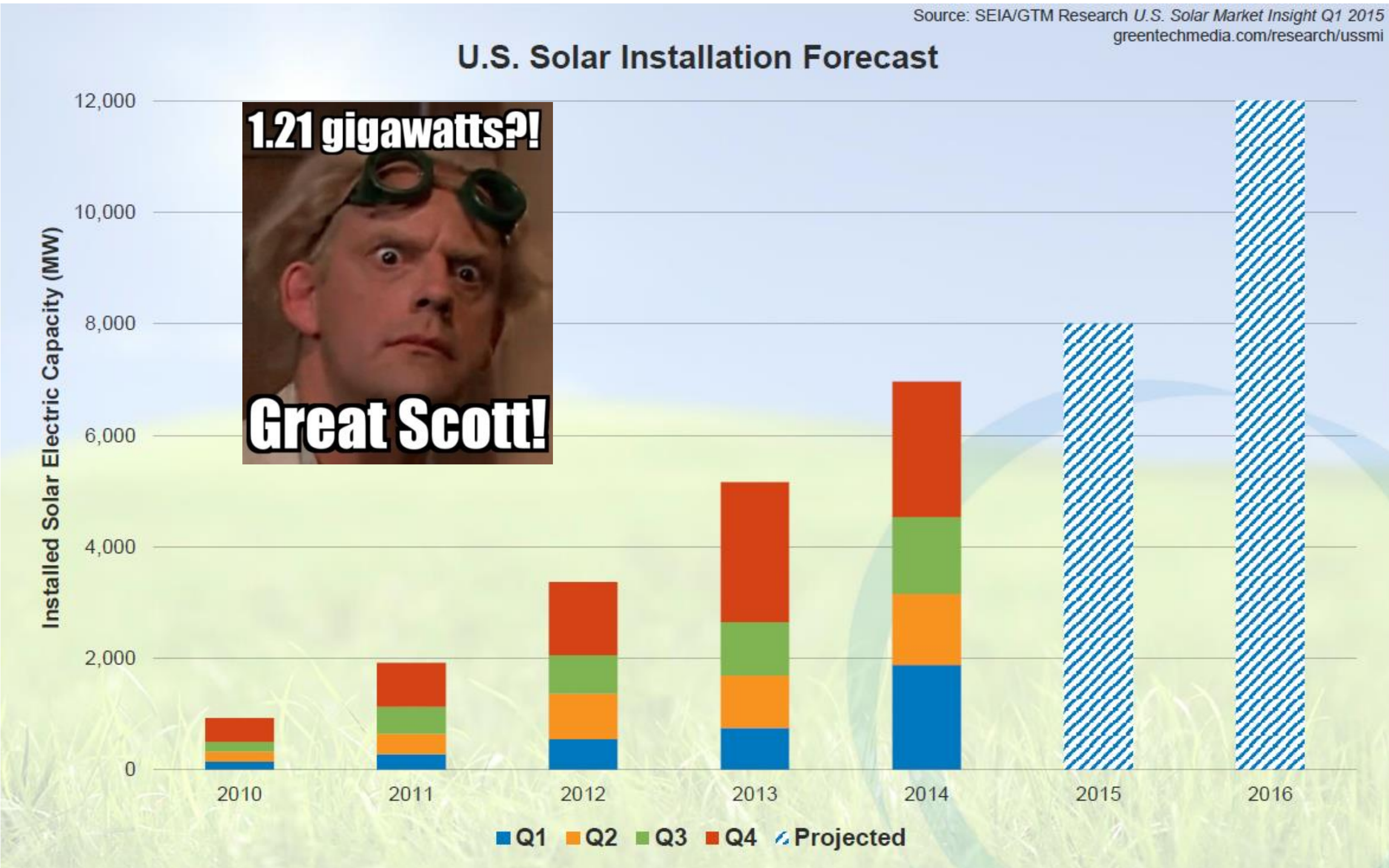
- Increased demand translates to decrease in cost
- Solar industry strives to further reduce cost; achieve grid parity



Source: SEIA/GTM Research: *U.S. Solar Market Insight*

Projected Solar PV Industry Growth

- Federal Investment Tax Credit (ITC) expected to sunset
- Installed PV capacity in U.S. projected to be 12 GW by 2016



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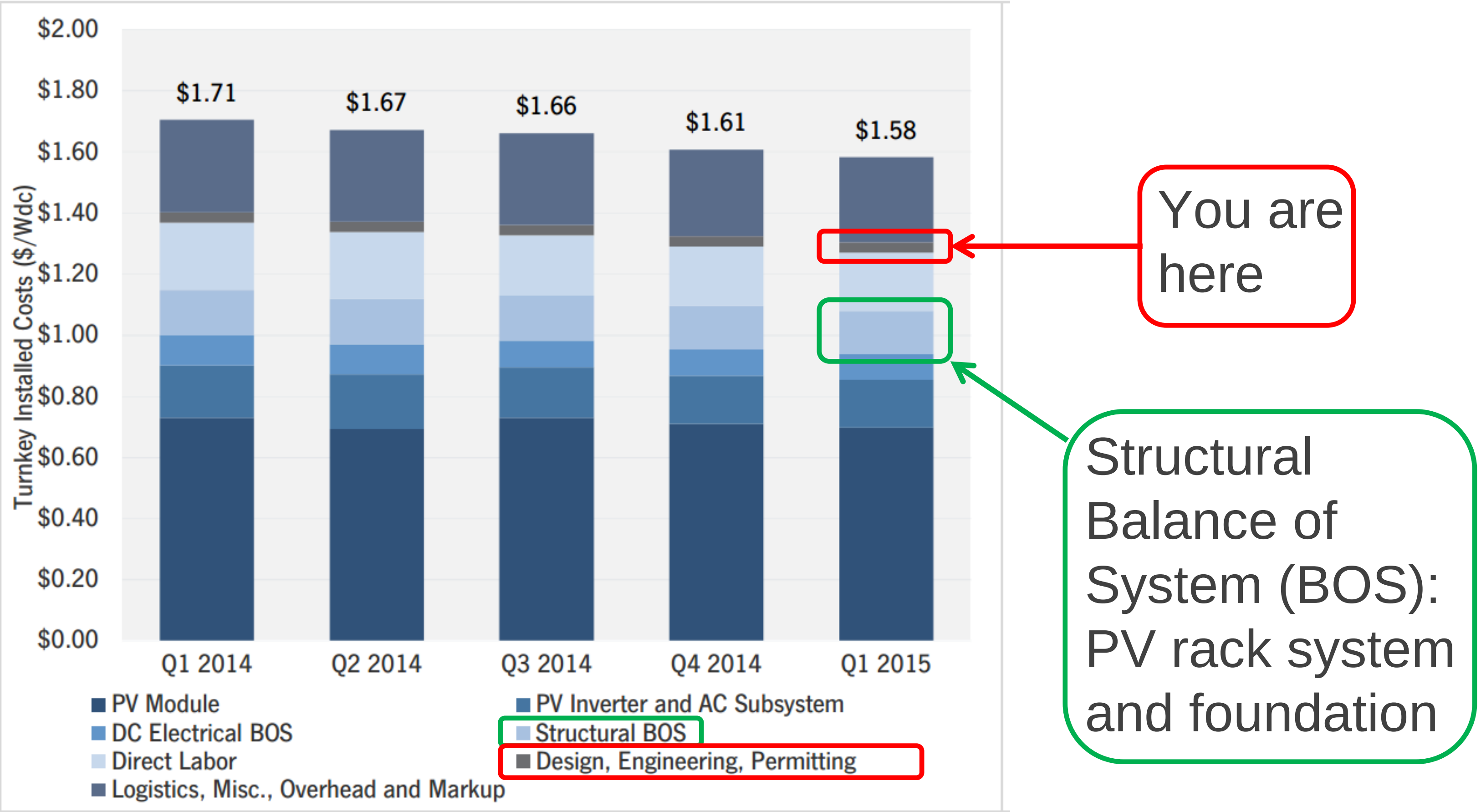
Reduction of Solar PV Turnkey Installed Cost

- Turnkey Installed Cost continues to decrease
- Engineers focus on reducing Balance of System (BOS) cost



Source: SEIA/GTM Research: *U.S. Solar Market Insight*

Introduction: What have we learned?

- Industry efforts to reduce cost have resulted in reduced steel sections and rack systems that are more flexible
- Although structural failures are rare, failures have been observed in code-compliant solar PV structures
- Failures have occurred at wind speeds much less than design wind speed
- Dynamic resonance of PV system owing to frequency matching of natural frequency with vortex shedding frequency

Terminology

- Module or Panel
- Portrait or Landscape
- Fixed Tilt
- Single Axis Trackers
- Table
- Chord Length

Single-Axis Trackers (SATs)

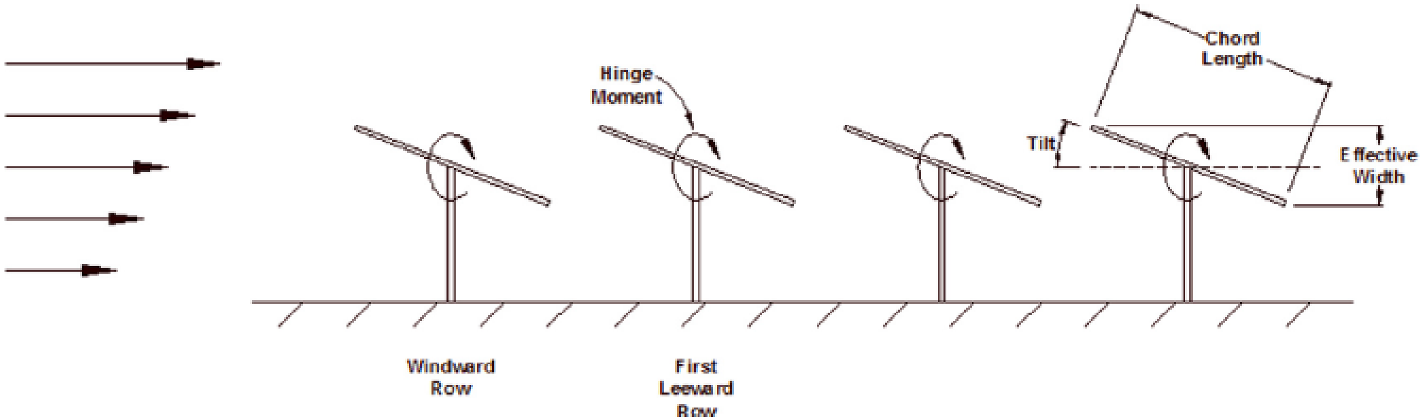
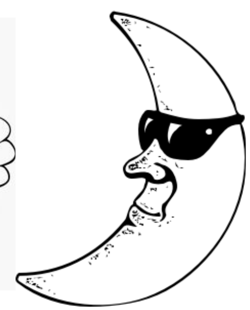
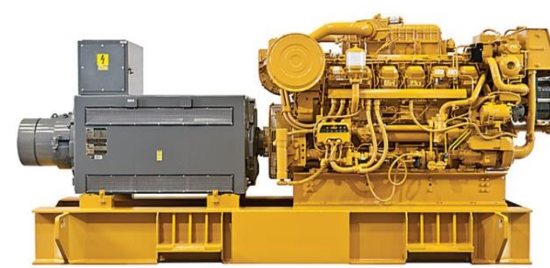


Fig. 1. Nomenclature for ground mount. Positive tilt shown.

ASCE 7-10 Risk Category (RC) Table 1.5-1

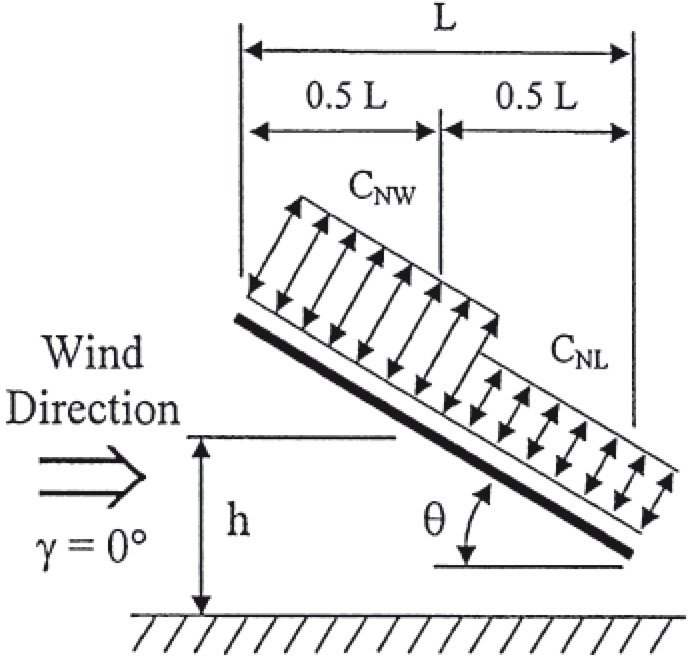
- Risk Category I (one): Buildings and other structures that represent a *low risk to human life* in the event of failure
- ~~RC II: Not I, III, or IV~~
- ~~RC III: Buildings and other structures, the failure of which could pose a *substantial risk to human life*~~
- ~~RC III: Not RC IV, with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure (IBC: “power generating stations”)~~
- ~~RC IV: Essential facilities~~
- ~~RC IV: Required to maintain functionality of essential facilities~~



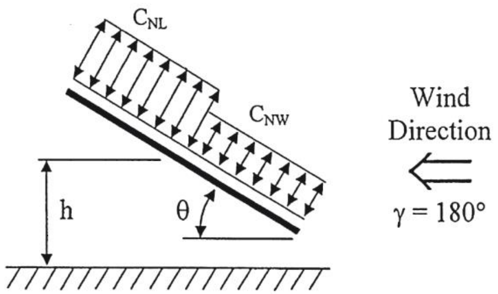


ASCE 7-10 Wind Procedures

- For PV modules, module clamps, and fasteners, use Chapter 30 Components & Cladding, Figure 30.8-1
- For MWFRS, use Chapter 27 Directional Procedure
- Figure 27.4-4 Monoslope Free Roofs
- Gust Effect Factor, G=0.85?
- Sheltering prohibited?
- Chapter 31, Wind Tunnel Procedure



ASCE 7-10 Fig. 27.4-4



Atmospheric Boundary Layer Wind Tunnel

- Rules
  - ASCE 7
  - specific
- Results
  - zones
  - GC_N

Gust Effect Factor

ELSEVIER

Journal of Wind Engineering
and Industrial Aerodynamics 77&78 (1998) 673–684

JOURNAL OF wind engineering AND industrial aerodynamics

On the formulation of ASCE7-95 gust effect factor

Giovanni Solari[a,*], Ahsan Kareem[b]

678 G. Solari, A. Kareem/J. Wind Eng. Ind. Aerodyn. 77&78 (1998) 673–684

Finally, if it is assumed that surface exposed to wind is very small for a rigid point structure, h and b approach zero and $\tilde{L}_0 = 0$ (Eq. (8)) and $Q = 1$ (Eq. (21)). Therefore

$$G = 1. \tag{26}$$

Why is G = 1 for small structures?

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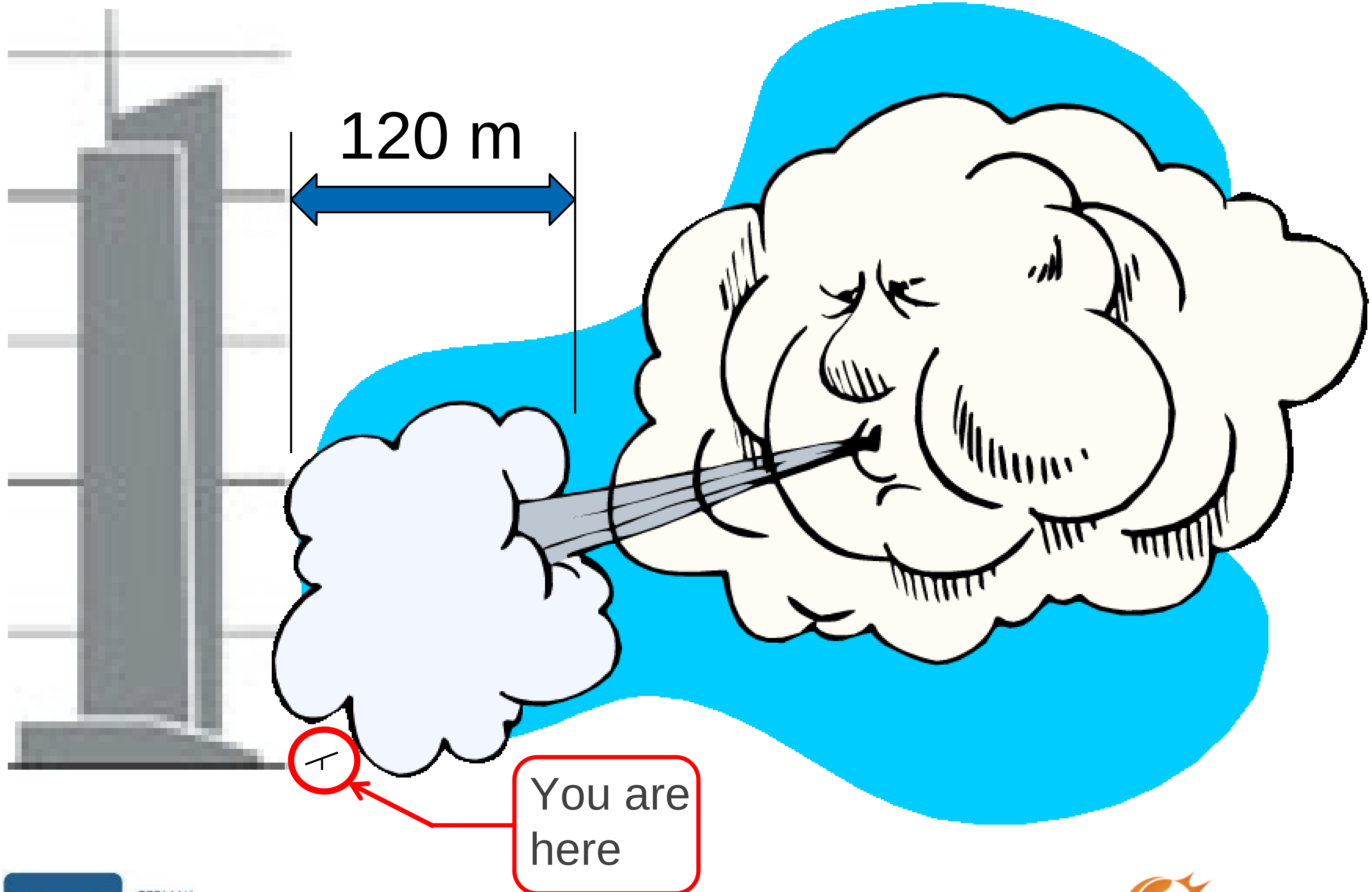
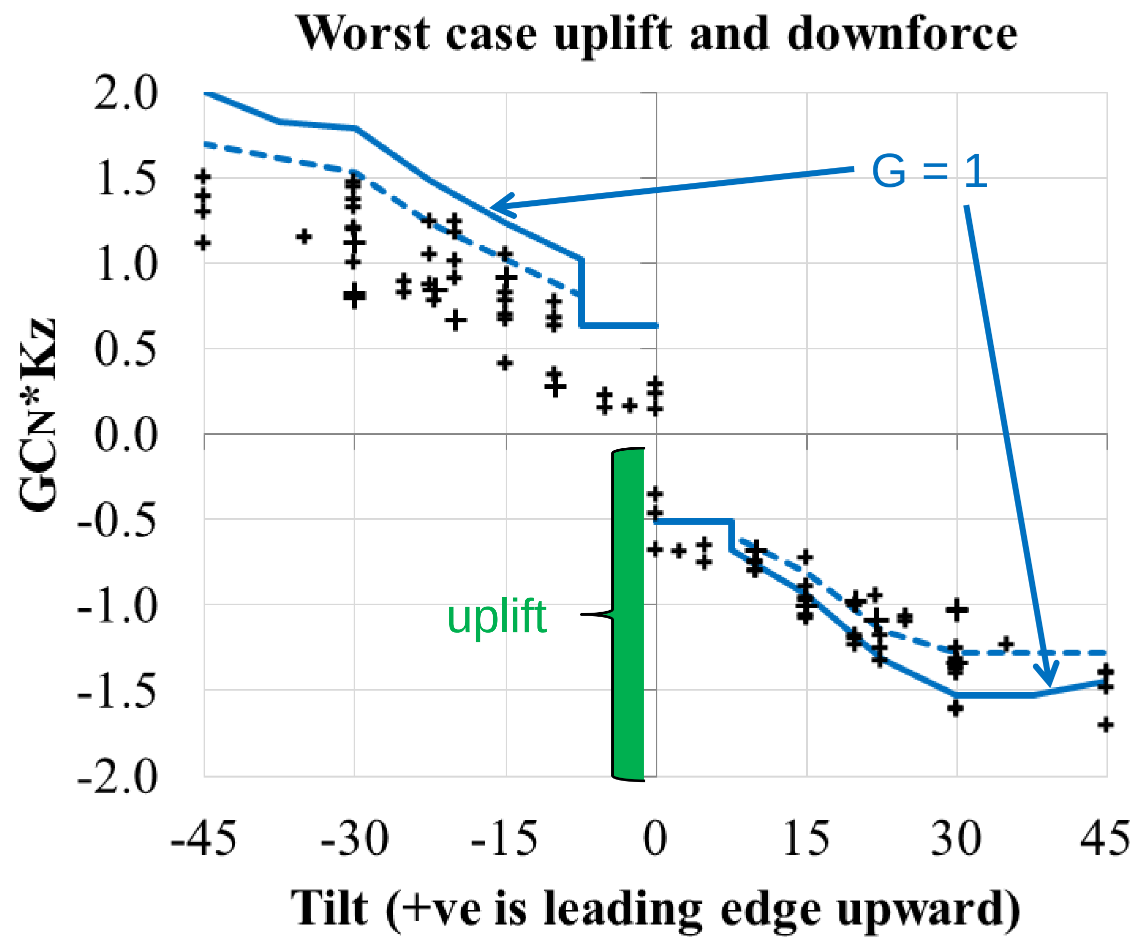
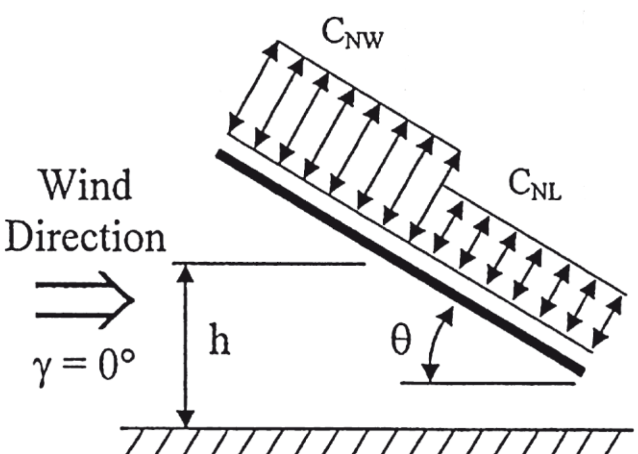
3-Second Gust at 90 mph



Comparison of ASCE 7 and Wind Tunnel

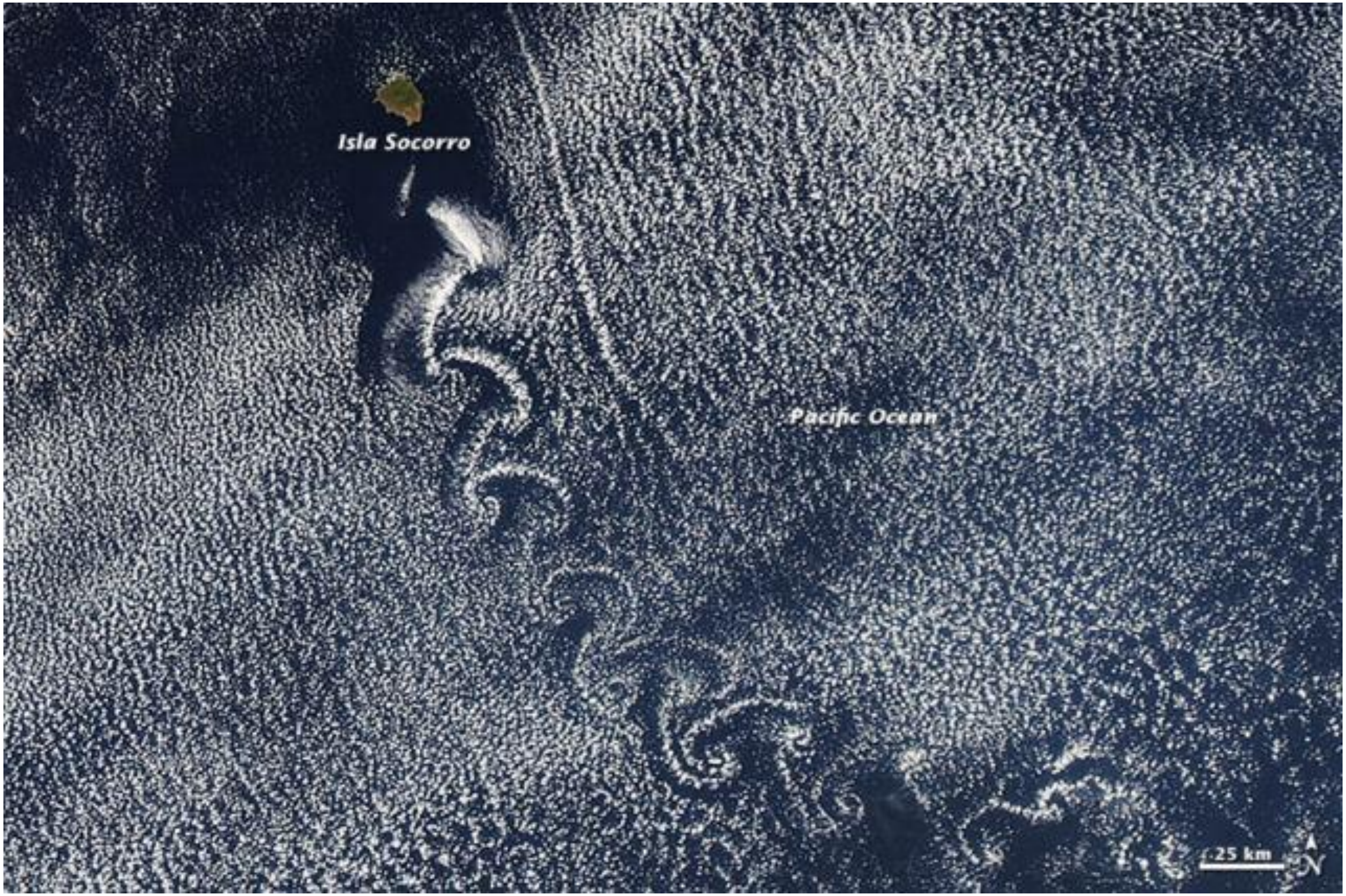
- G=1 works better?
- Accidental match
- Scatter
- Some load cases unrealistic





Rigid versus Flexible or Dynamically Sensitive

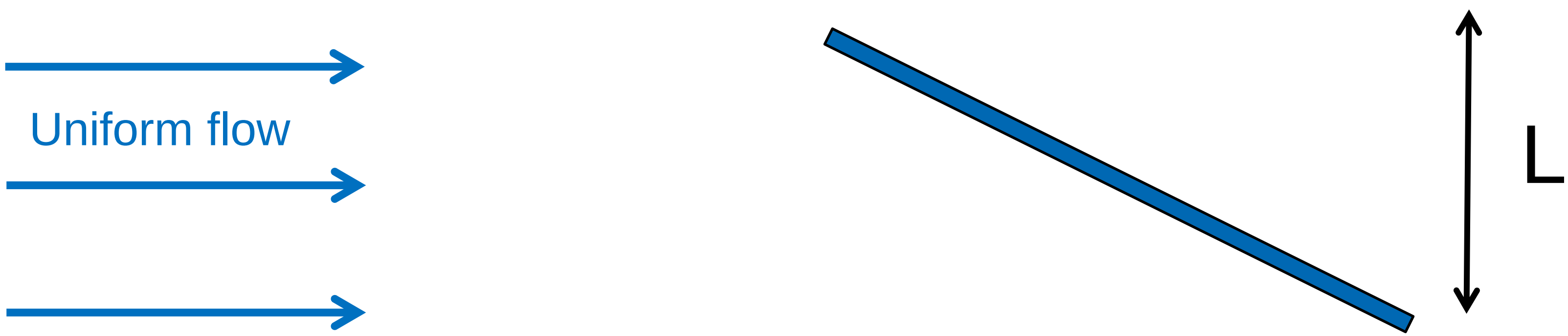
Dynamic Effects of Wind – Vortex Shedding



What is the Frequency of Vortex Shedding?

$$St = \frac{fL}{U} = 0.15$$

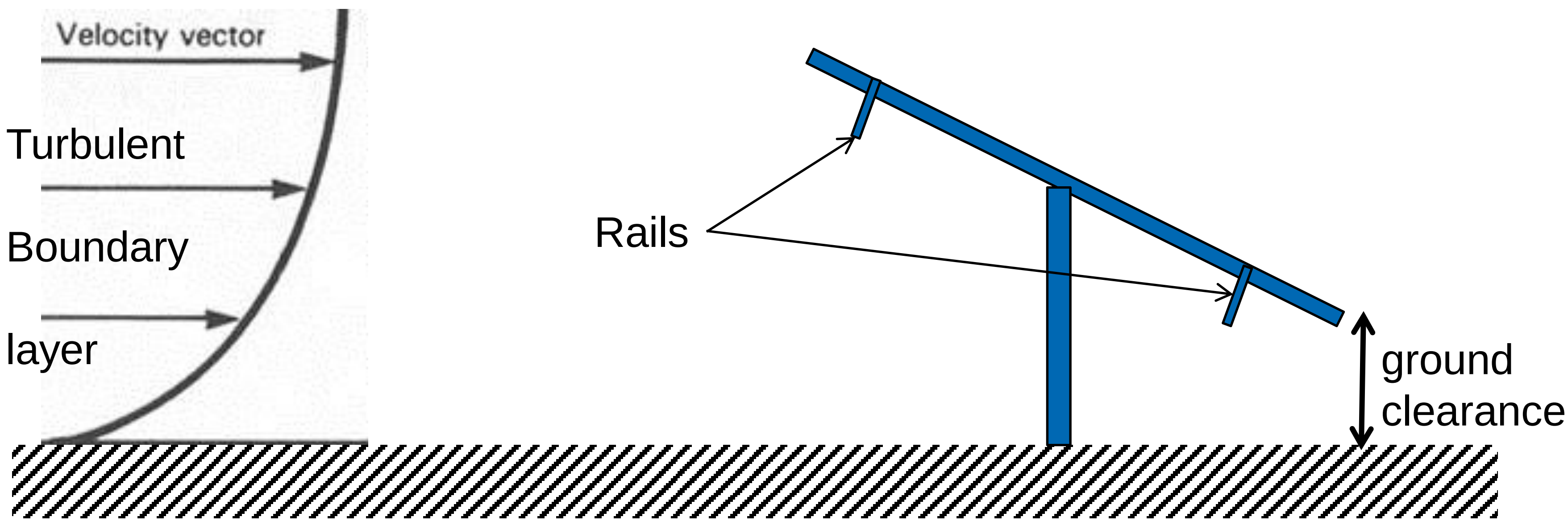
where U = mean wind speed



What is the Frequency of Vortex Shedding?

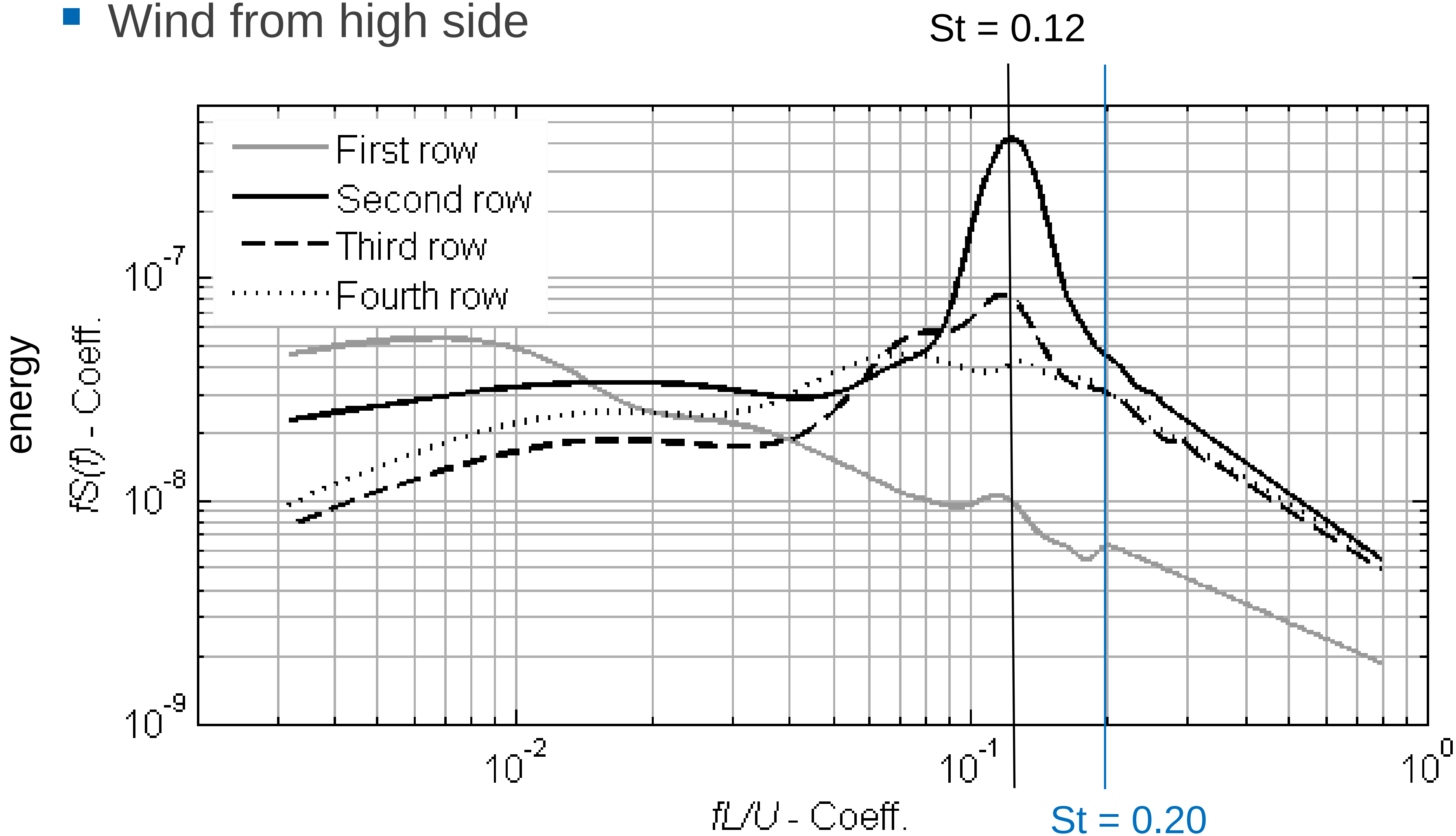
$$St = \frac{fL}{U} = 0.05\ to\ 0.20$$

where U = mean wind speed



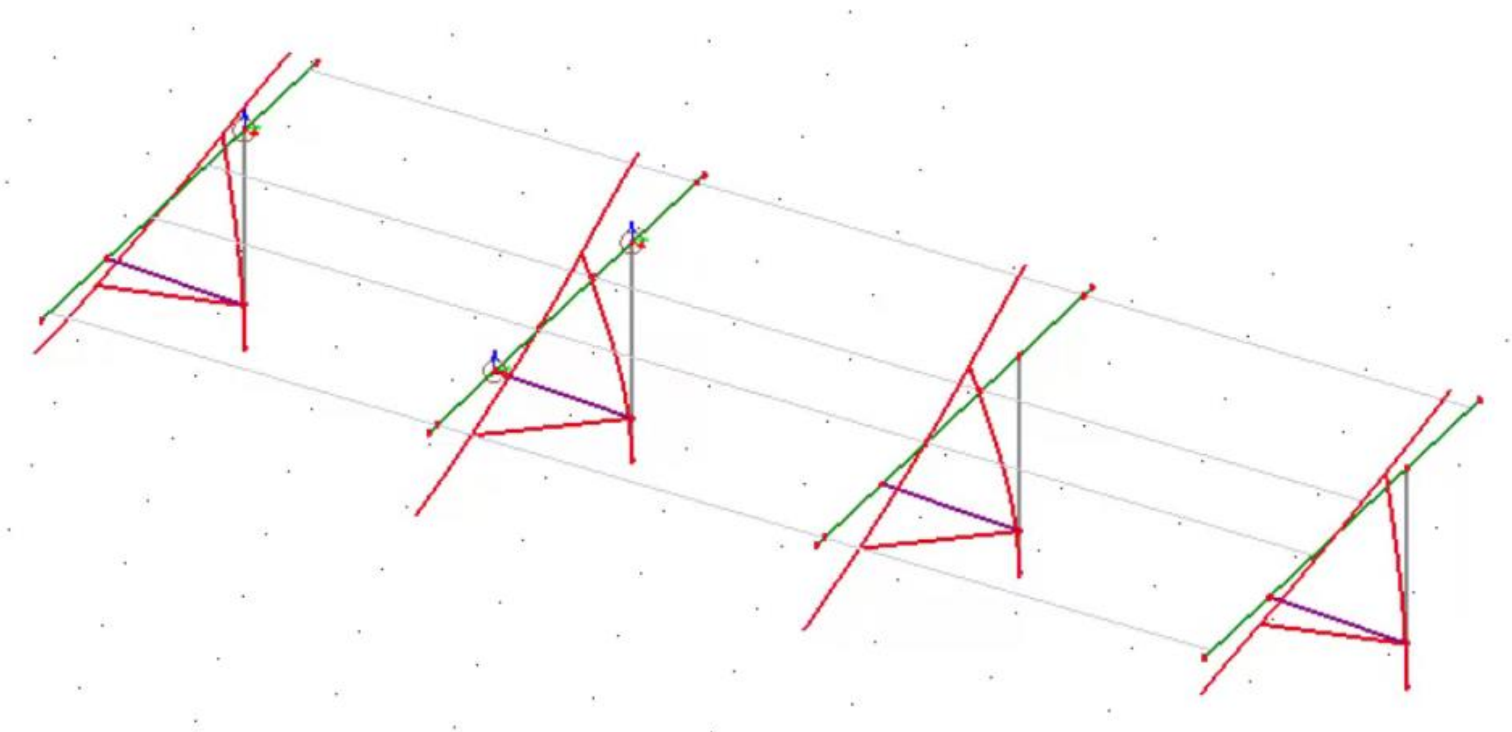
Dynamic Effects of Wind – Vortex Shedding

- Wind from high side

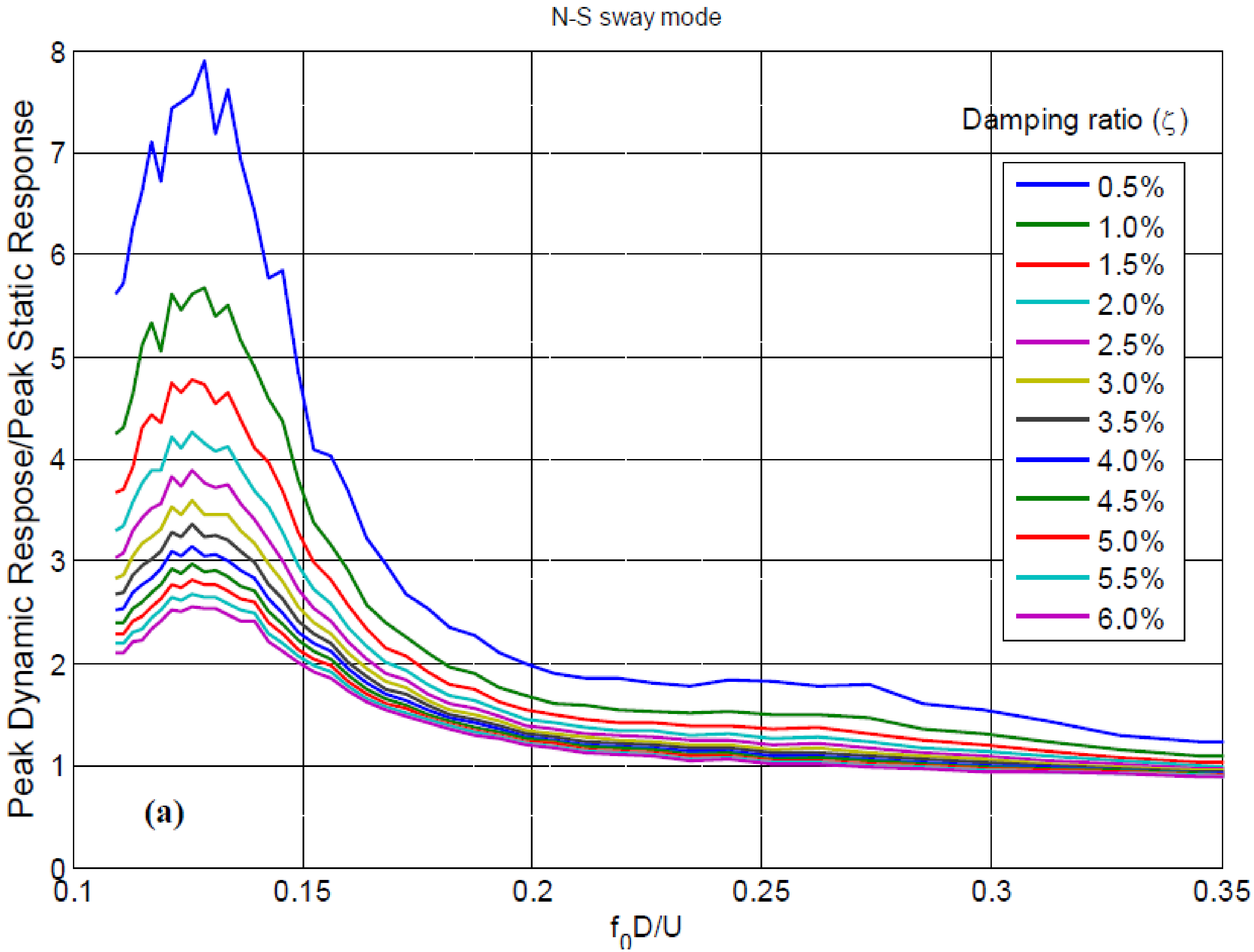


Modes of vibration

- Common mode shapes for fixed tilts

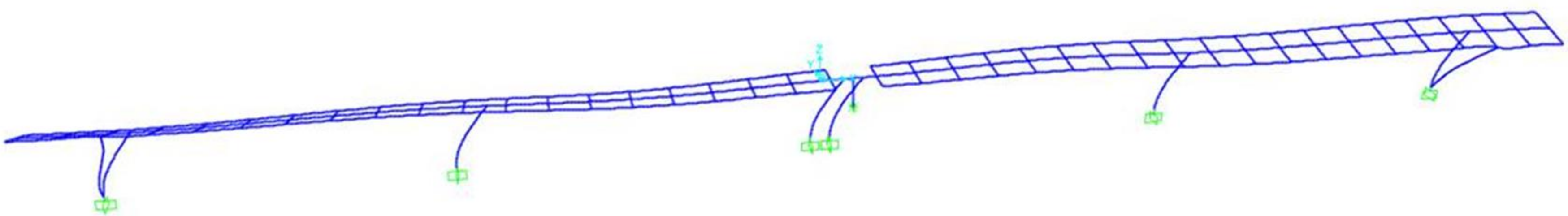


Dynamic Amplification Factor (DAF) Curves



FEA Modal Analysis

- The goal of modal analysis is to identify critical mode shapes and their associated natural frequencies
- Critical mode shapes are those with lowest natural frequencies that can be excited by wind pressure normal to the surface
- Fixed tilt often governed by N-S sway mode (inverted pendulum)
- SAT often governed by torsional mode
- With FEA model created, and knowledge of damping ratios, it is possible to produce complete dynamic analysis using wind tunnel time series data



Single Axis Tracker mode shape (torsional plus normal modes)

Field Vibration Testing of Built PV Systems

- The goal of field vibration testing is to accurately measure the natural frequencies and damping ratios of critical mode shapes
- Natural frequency data can inform initial threshold
- Damping ratios are critical for determining DAFs
- Professional field vibration testing:
  - Pluck tests or human effort
  - Informed placement of accelerometers in strategic locations
  - Direct measurement of damping ratios
- Rudimentary method:
  - Excitation by human effort
  - Video recordings of motion
  - On playback, pause video and count mouse clicks
  - Smart phone accelerometer: “There’s an app for that.”

Conclusions

- Array corner zones and edge zones are usually governed by static (unsheltered) wind pressures; interior zones are sheltered
- Array interior zones can be governed by dynamic amplification if natural frequency matches vortex shedding frequency
- Natural frequency threshold of 1 Hz for rigid vs. flexible is not appropriate for ground mounted PV rack structures
- The simplest *initial* threshold is lowest natural frequency of 4 or 5 Hz, but this is variable with rack geometry and wind speed
- A better threshold to minimize dynamic amplification of load is Strouhal number ("reduced frequency") $fL/U > 0.20$
- Gust effect factor G should be set to 1.0
- Dynamic sensitivity analysis can be (and should be) performed
- Damping ratio must be measured on built systems in the field

Questions?

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