GAMECHANGE SOLAR
REPOWERING THE PLANET

Shook Me All Day Long: Earthquake Resilience of Solar Trackers

March 18, 2026

Agenda

1

Introduction

Why focus on seismic design and testing?

2

Seismic Basics

How does an Earthquake create load in a structure

3

Code Provisions

Overview of existing codes, standards, papers, and reviews

Review Load Path and why it may be overlooked in racking design

4

Shake Table Testing

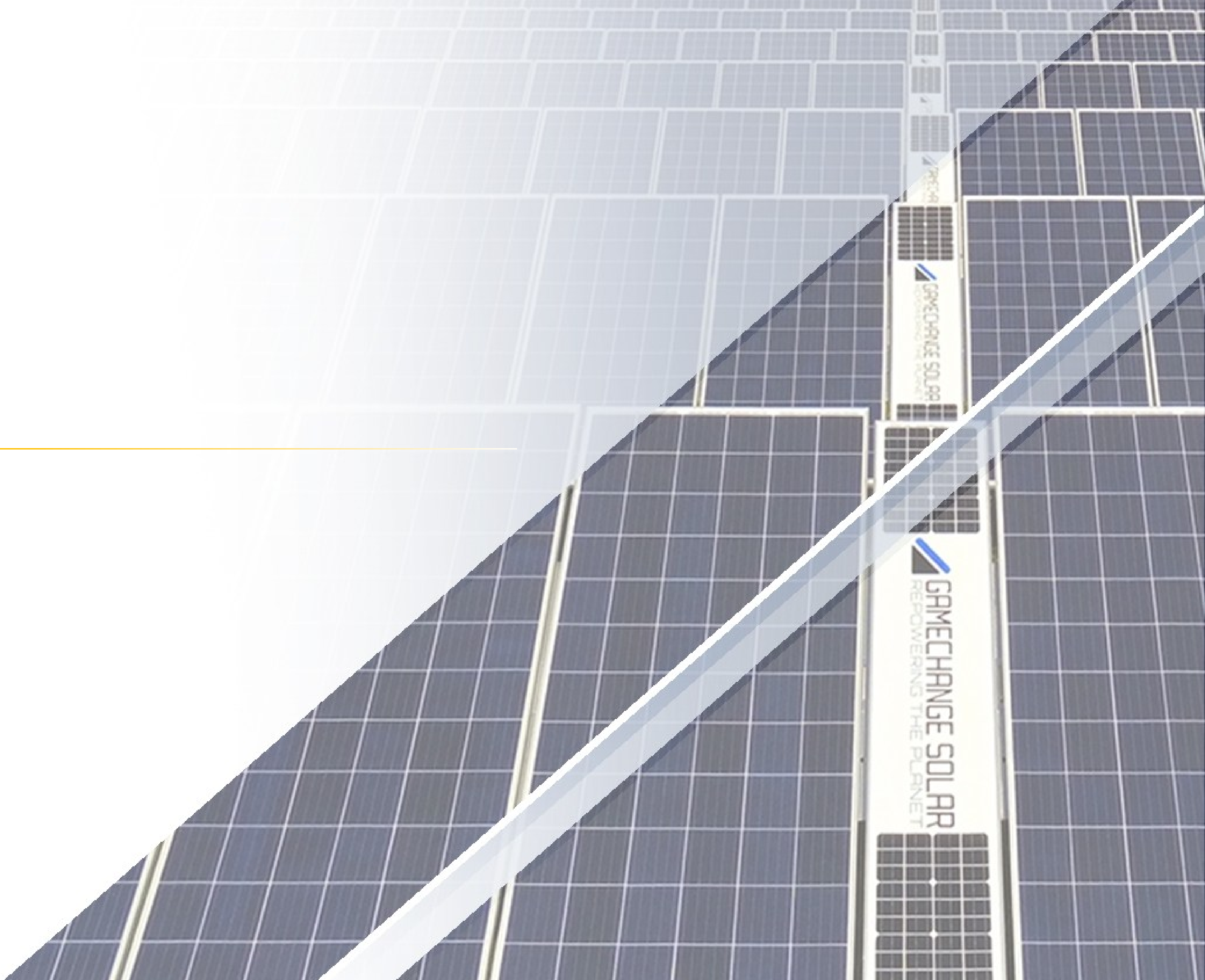
Test program and results for seismic loading

5

Future Work

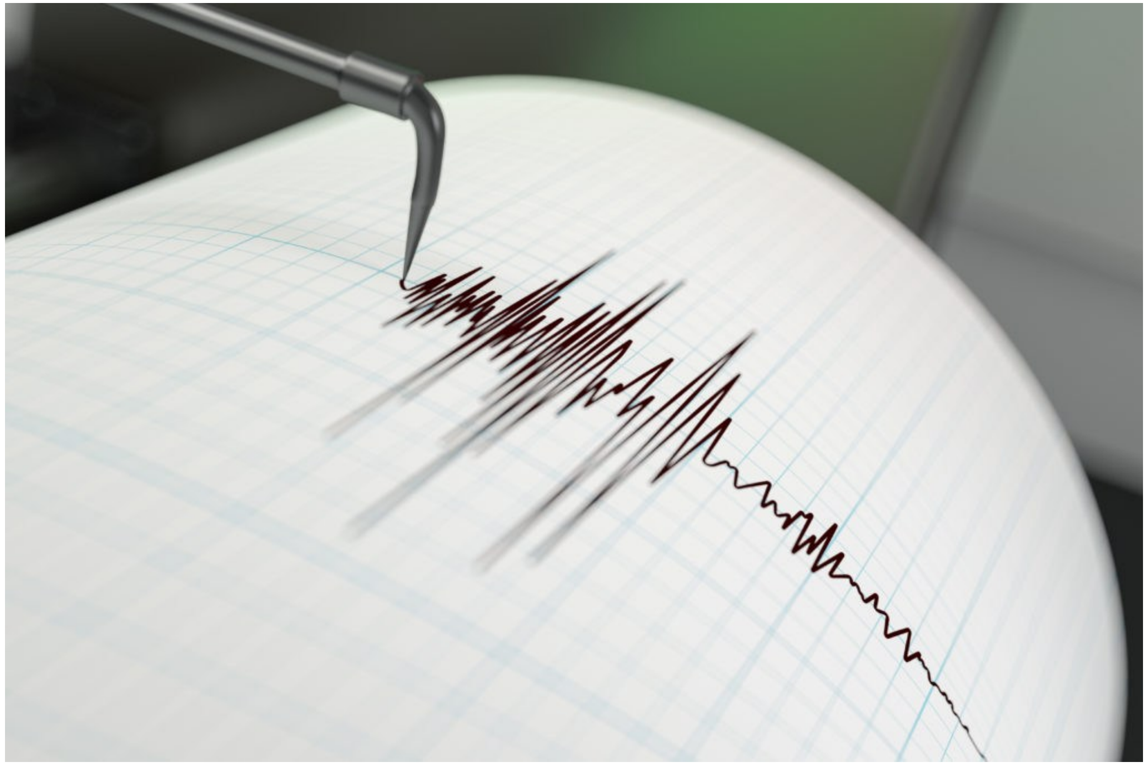
Next steps and further studies.

Introduction

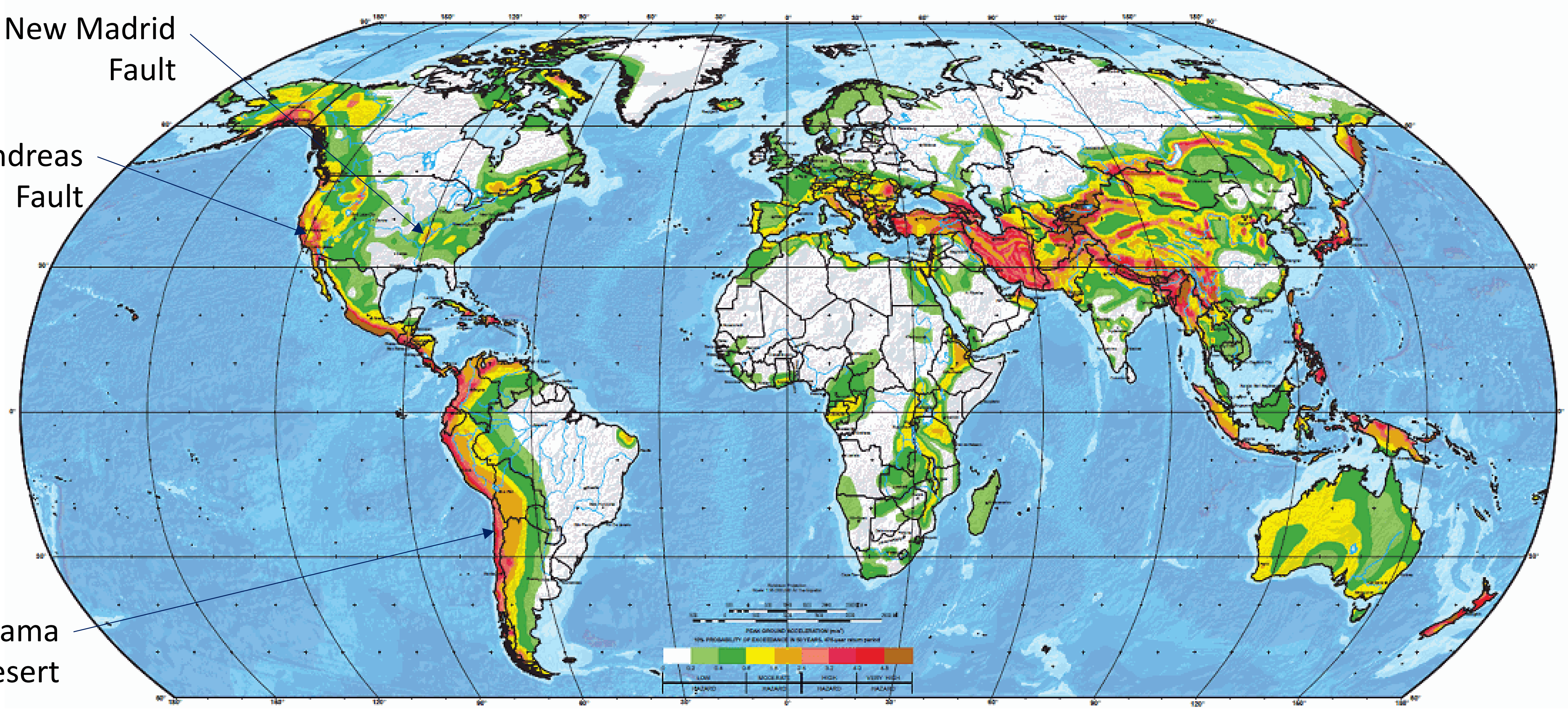


The Need for Shake Table Testing

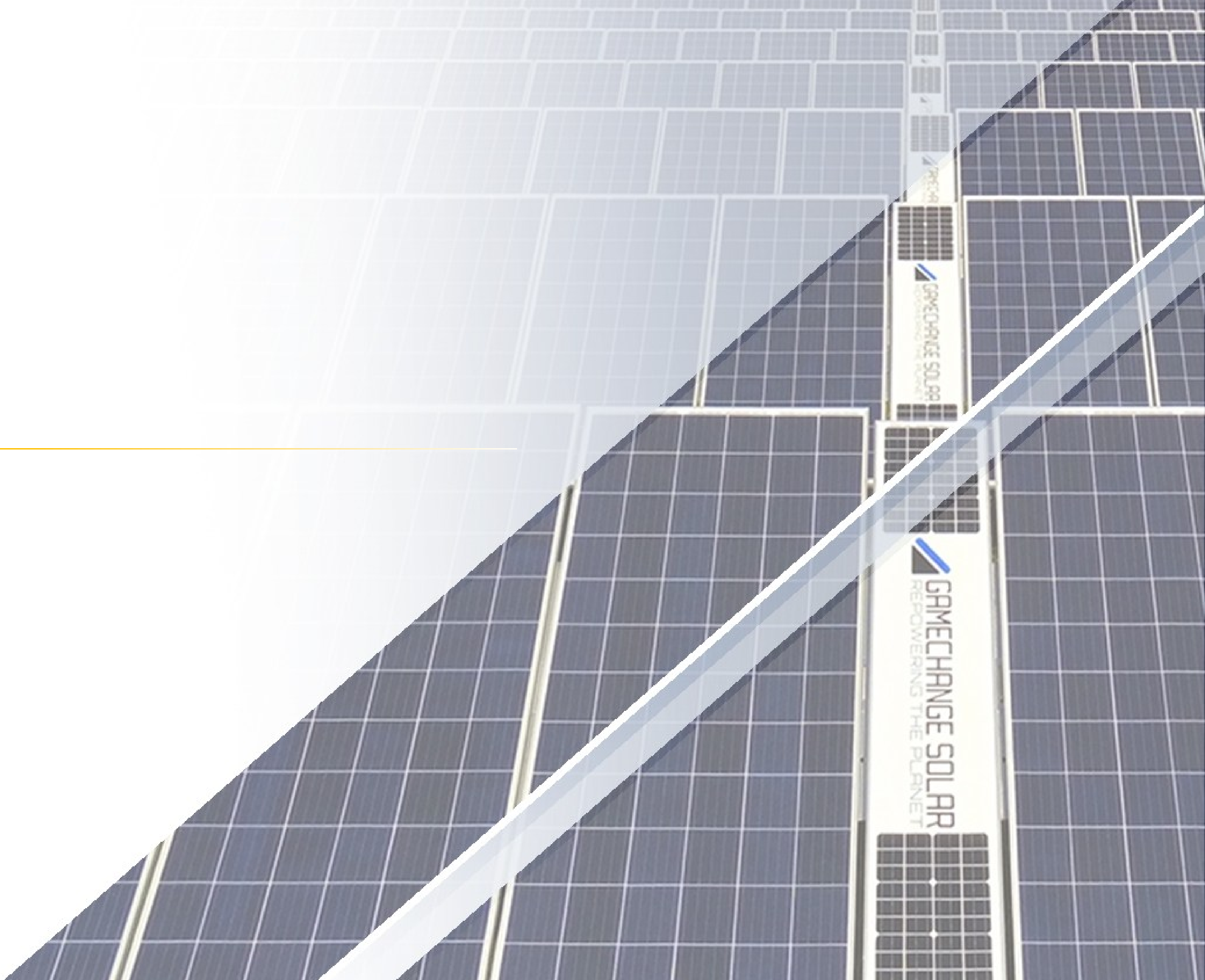
- Growing Interest in Solar in Seismic Sensitive Areas
- Earthquake loads need to be considered
- Very limited field data of how modern solar arrays perform in earthquake events
- Analytical models and scale testing but no full-scale testing
- How does a modern solar array perform during an earthquake?



Building Solar in Earthquake Prone Regions



Seismic Basics



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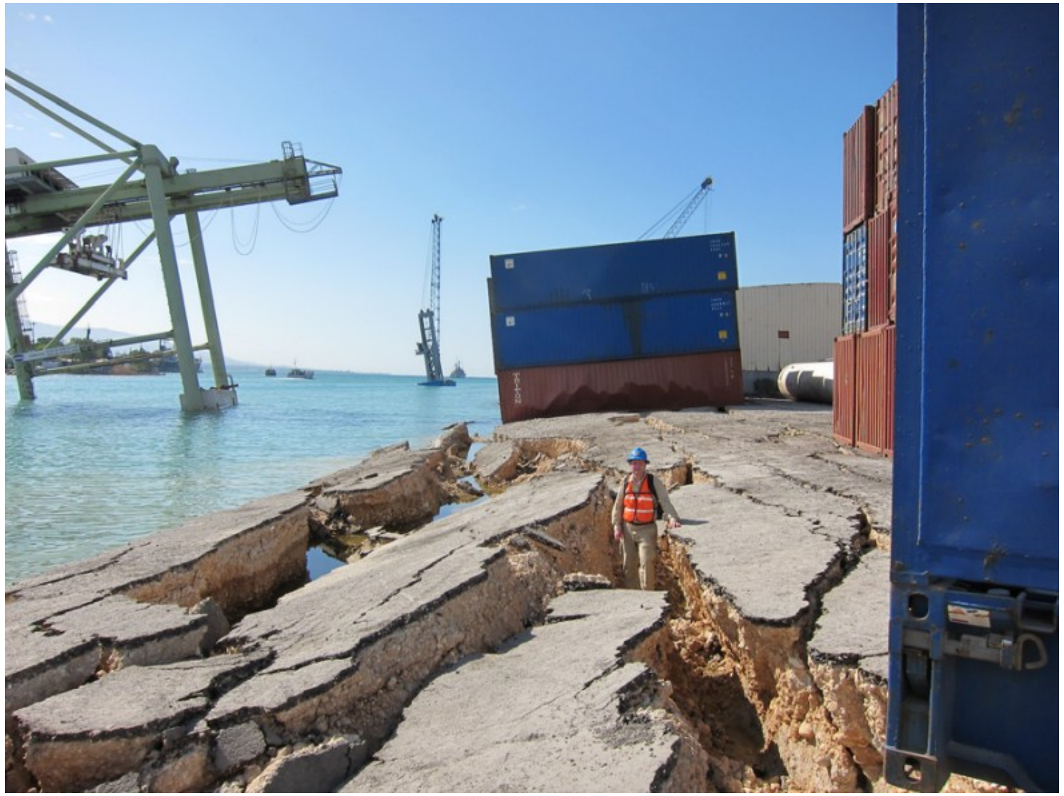
Seismic Concepts: High-Level Overview

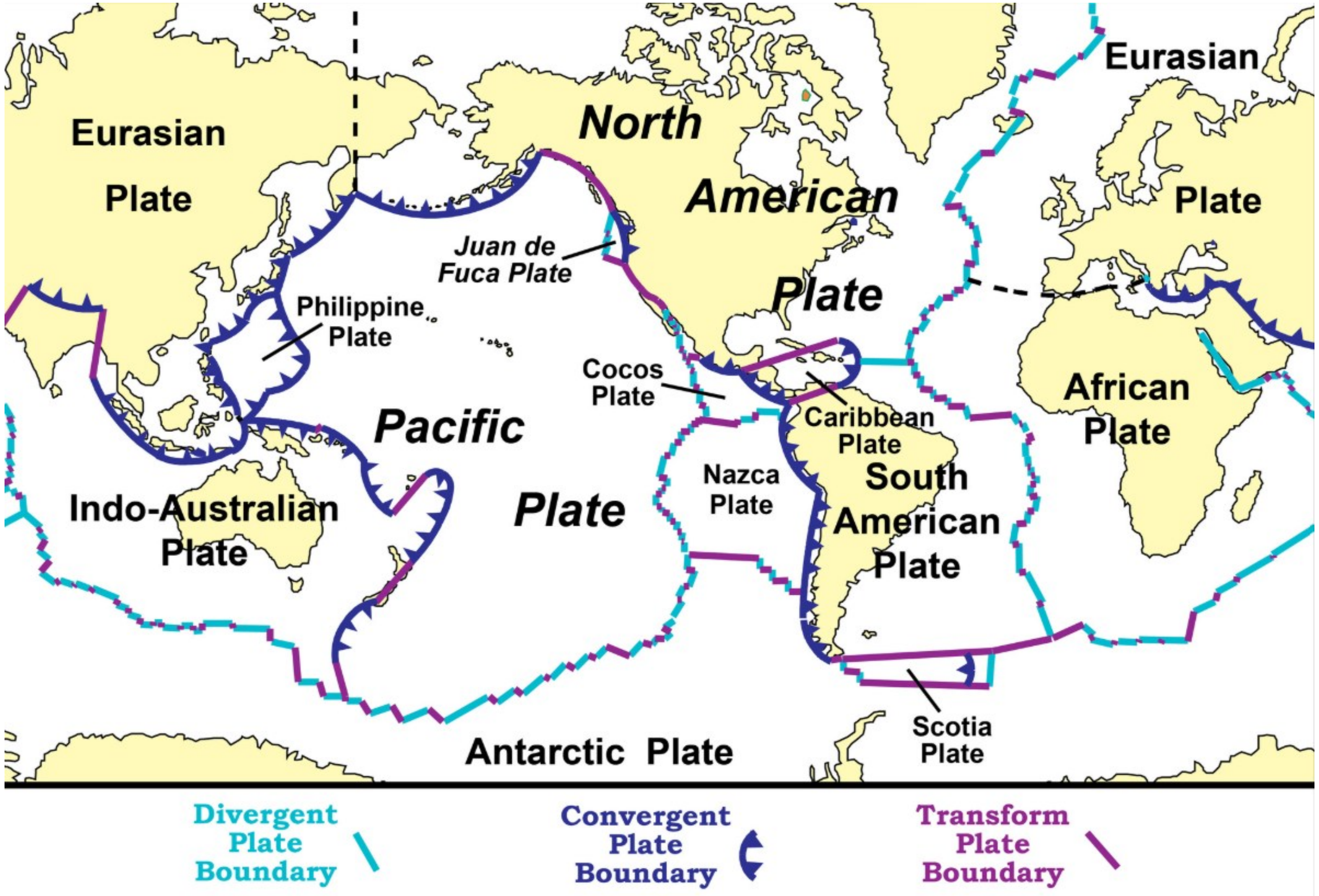
- Earthquake sources and ground motion
- Types of source waves
- Structural dynamic response
- Role of local geology and soils
- Example: 2010 Haiti earthquake



Earthquake Sources

Where ground motions come from

- Earthquakes caused by movement along **tectonic plate boundaries**
- Stress accumulates along **faults** in the Earth's crust
- **Elastic rebound**: sudden slip in fault releases stored energy
- Energy radiates outward as **seismic waves**



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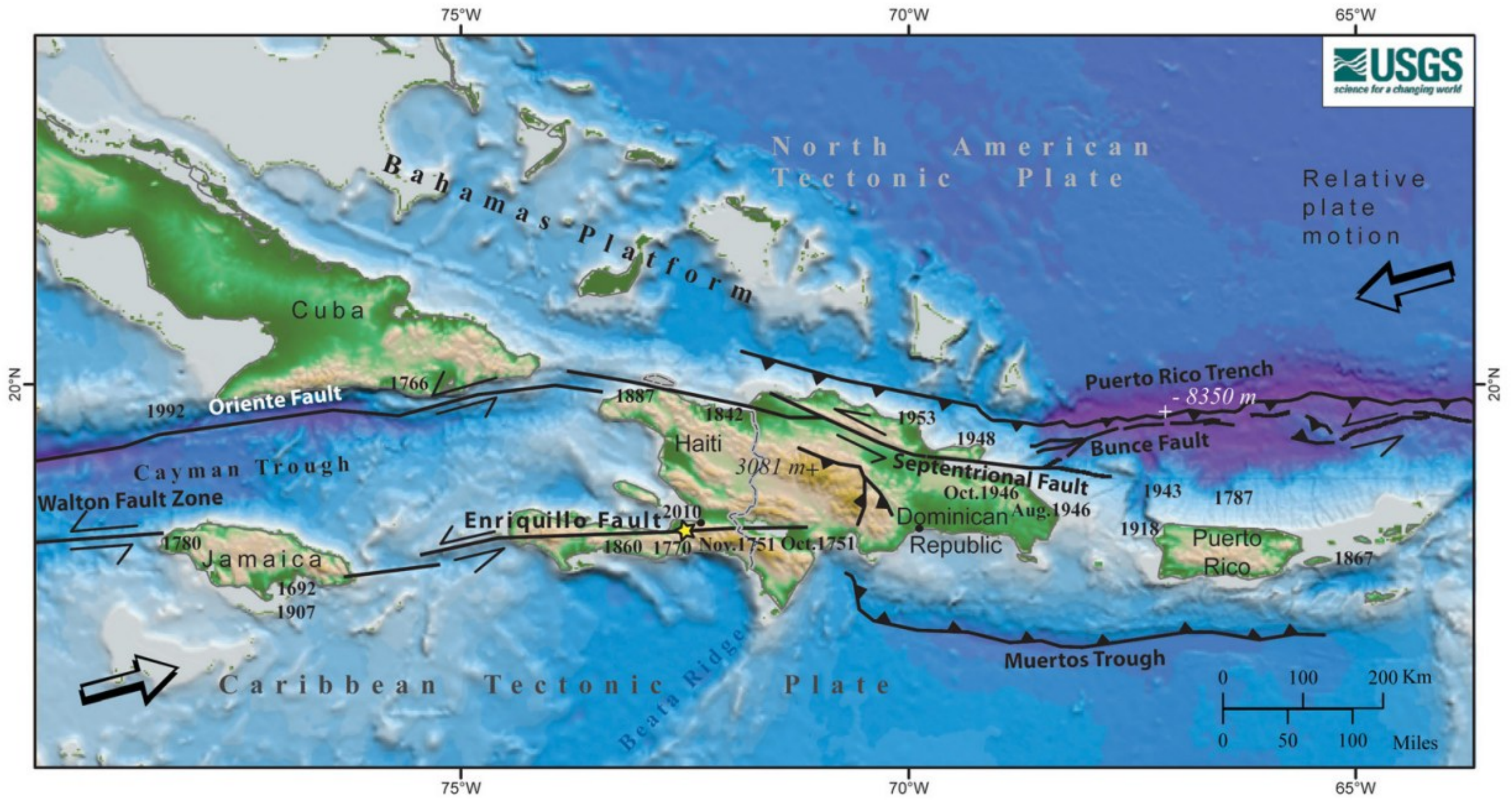
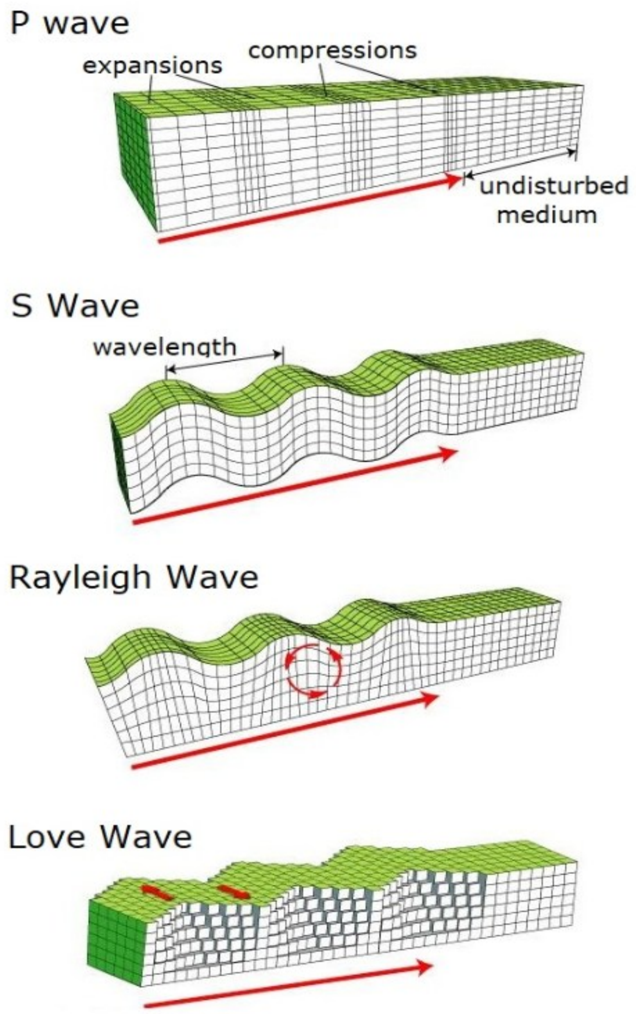


Types of Seismic Waves

Wave Types that Cause Ground Motion

- Body Waves
  - P-waves: compressional, fastest
  - S-waves: shear motion, slower
- Surface Waves
  - Love waves: horizontal side-to-side-motion
  - Rayleigh waves: rolling motion

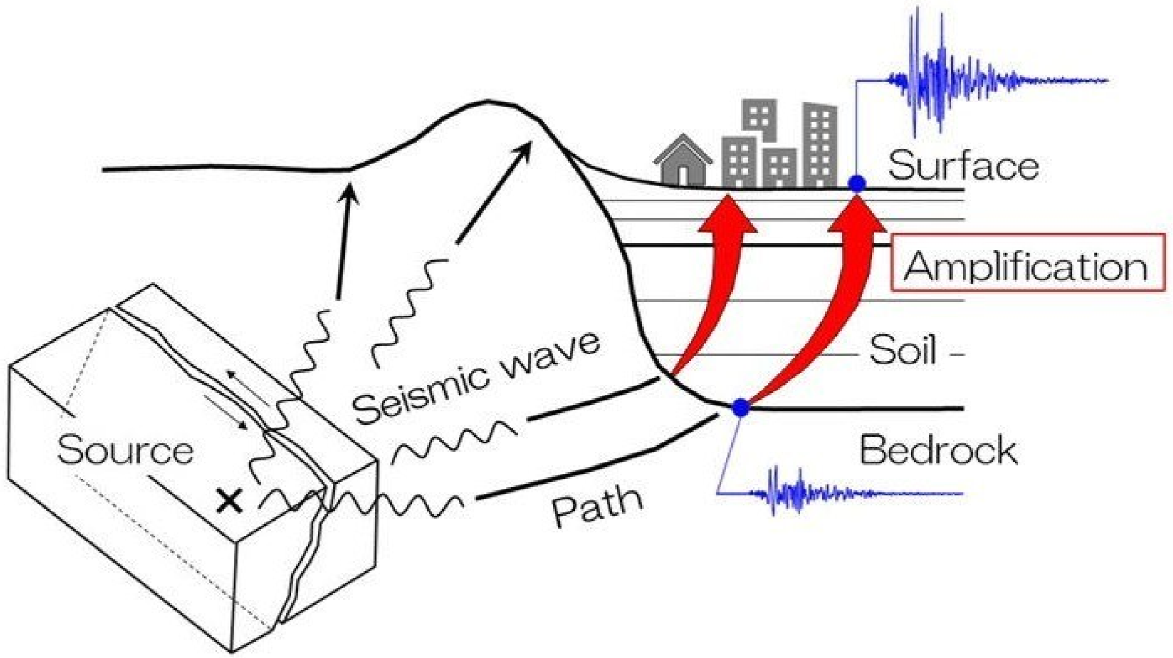
Surface waves often produce the **largest ground displacements**



What Controls Ground Motion

Key Drivers of Earthquake Motion:

- **Magnitude** (energy released at source)
- **Distance** from the fault rupture
- **Depth** of the earthquake
- **Local geology / soil conditions**
- Two nearby sites can experience **very different levels of ground shaking**



Example: Haiti Earthquake

2010 Haiti Earthquake

- Magnitude 7.0
- Epicenter ~25 km from Port-au-Prince
- 280,000 buildings collapsed/damaged

Damage patterns influenced by:

- Soft alluvial soils
- Ground motion amplification
- Construction practices

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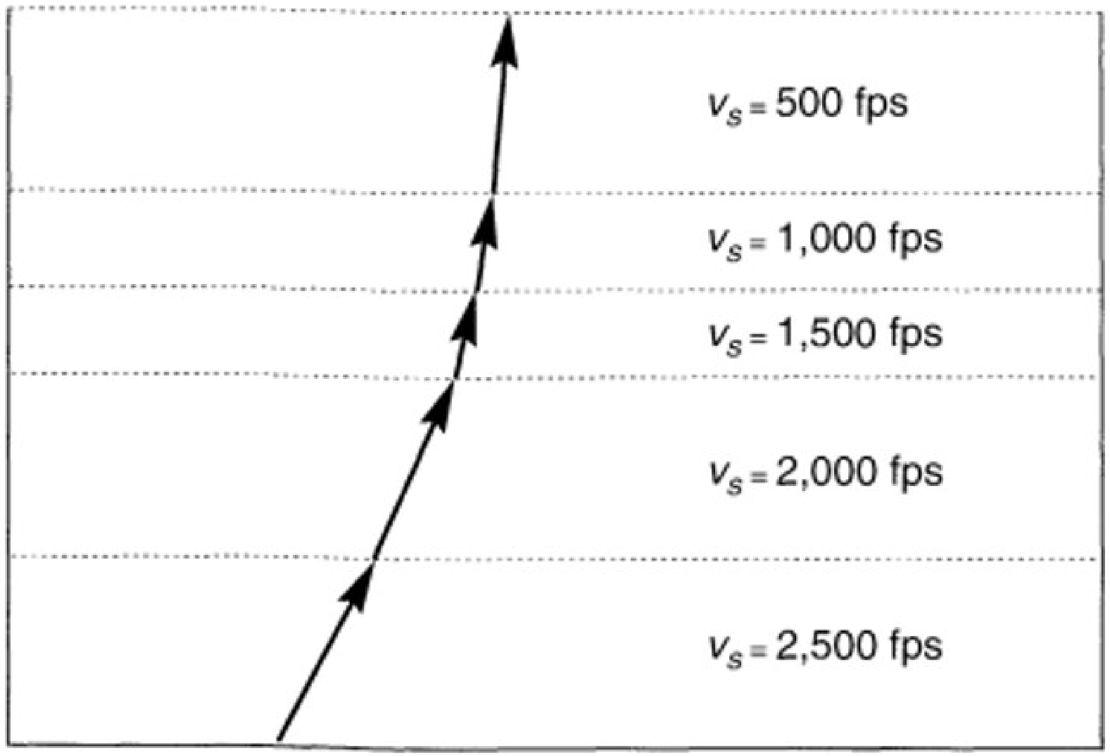
Why Soft Soils Amplify Shaking

Ground Motion Amplification

Soft soils amplify motion through several mechanics:

Impedance Contrast

- Seismic waves slow down when entering looser soil from denser material
- Energy conservation increases the motion's amplitude



Higher shear velocity (v_s) = denser soil

Resonance

Resonance occurs when the frequency of external loading matches the natural frequency of a system

For earthquakes:

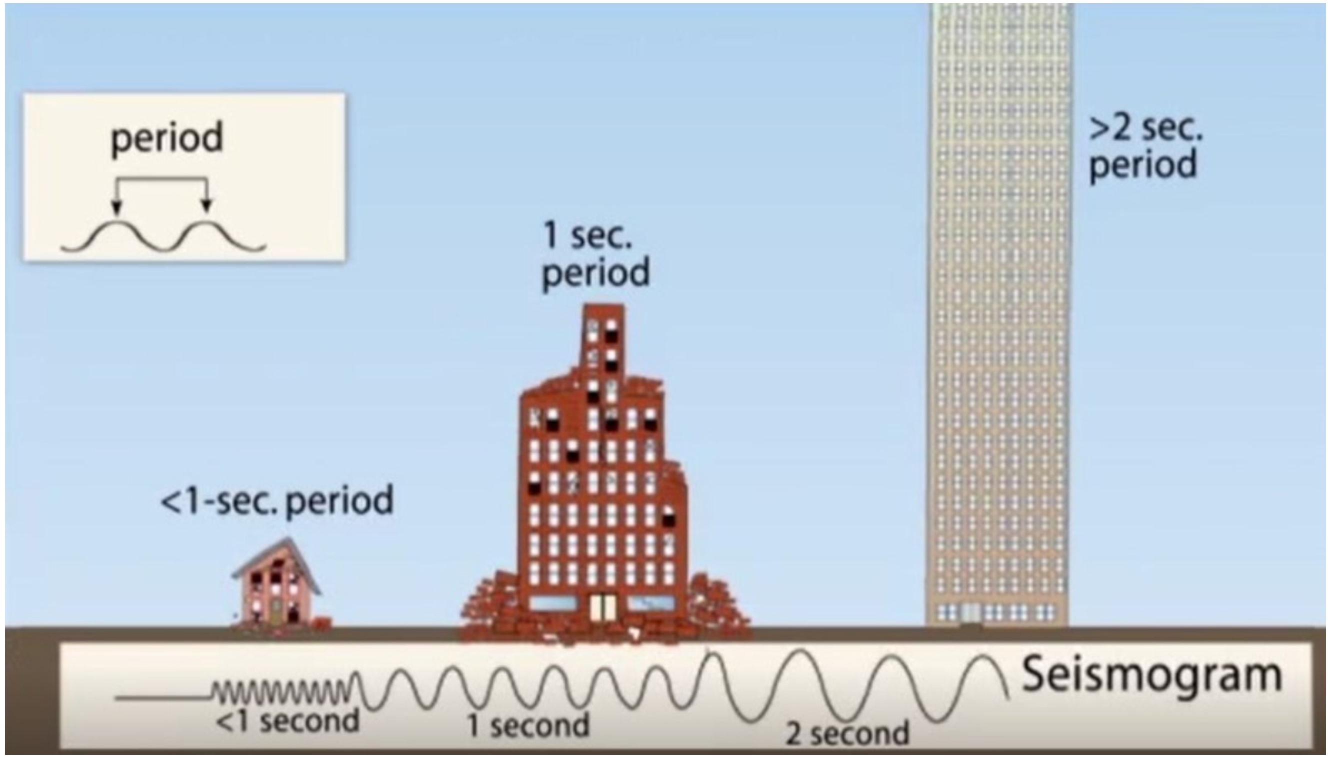
- Ground motion contains many unique frequencies
- Both soils and structures have natural frequencies

When frequencies align, **vibration amplitudes increase**

Resonance can occur in:

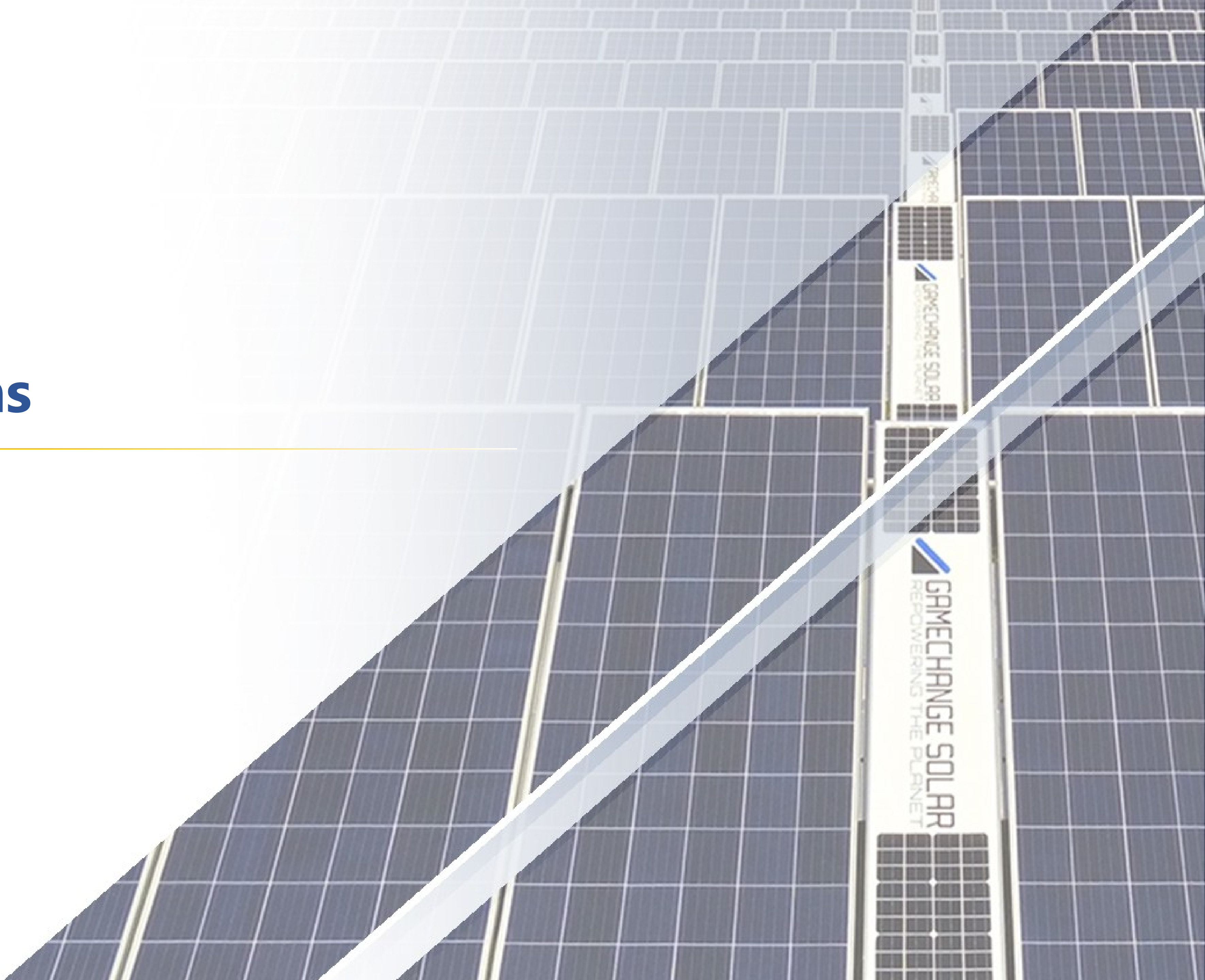
- Soil layers
- Structures
- The combined soil-foundation-structure system

Resonance



Example: *a tall, flexible structure with a natural frequency of 0.5 Hz may experience large swaying if the earthquake contains strong energy near that frequency*

Code Provisions



Seismic Design Overview

Collect Site Data

↓

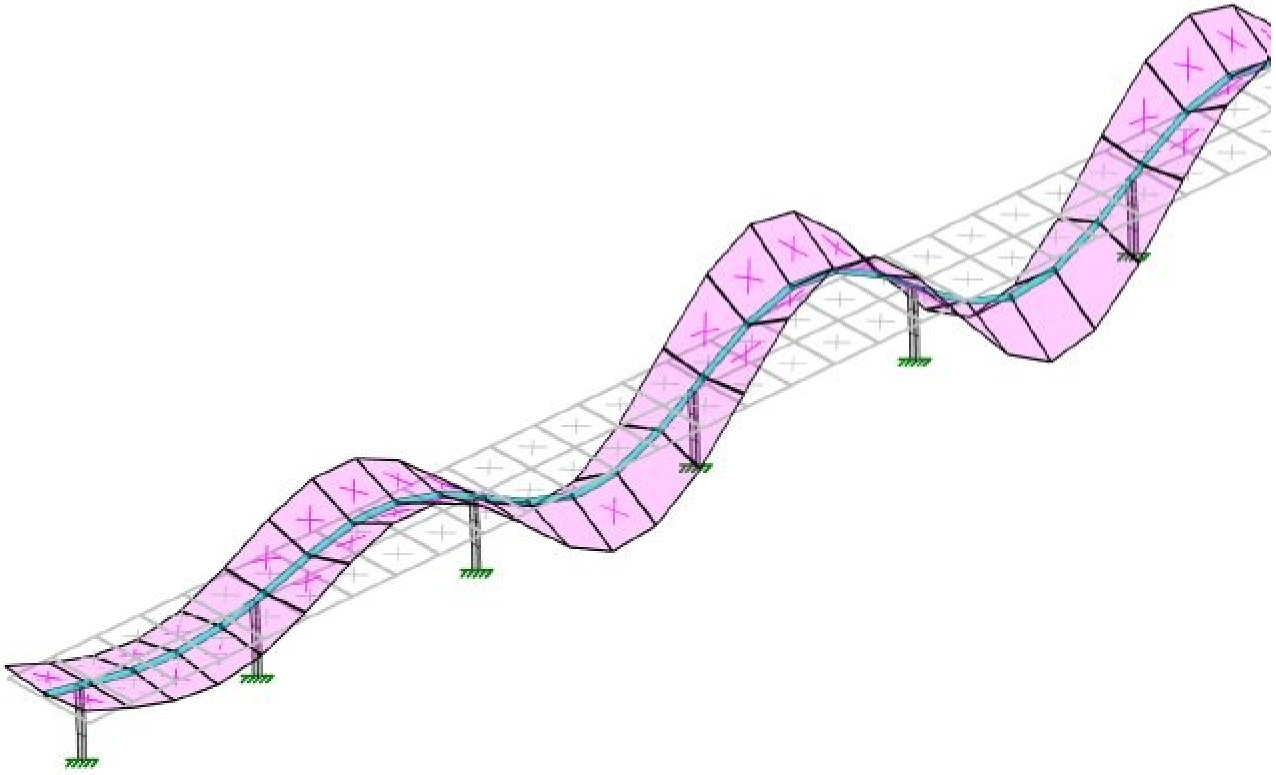
Compute Seismic Force

↓

Identify Load Path

↓

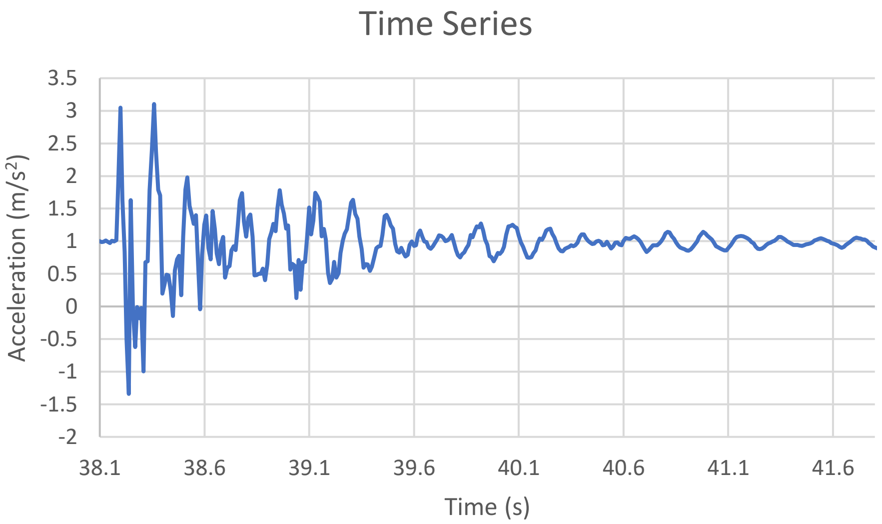
Confirm Components have Sufficient Capacity



Focus on Sites with Weak Soil

- Exception per ASCE7 Section 20.3.1
- GCS performed pluck test on full scale table in field
- Measured frequency of 4.58-4.68 Hz and 5.27-5.37 Hz for the 1st and 2nd modes
- Also produced a theoretical model using software RISA

EXCEPTION: For structures that have fundamental periods of vibration equal to or less than 0.5 s, site response analysis is not required to determine spectral accelerations for liquefiable soils. Rather, a site class is permitted to be determined in accordance with Section 20.3 and the corresponding values of F_a and F_v determined from Tables 11.4-1 and 11.4-2.



White Paper

- GCS authored White Paper summer of 2024
- DNV Peer Review:
- GCS Supplied:
  - White Paper
  - Pluck Test results
  - RISA based Analytical Model
- DNV's conclusion:

  DNV notes the presented study demonstrates the tracker system meets the requirements of ASCE 7-16 to avoid the need for site response analysis for soils vulnerable to potential failure or collapse under seismic loading, such as liquefiable soils or sensitive clays, etc.

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White Paper:

EXPERIMENTAL MODAL ANALYSIS (EMA) FOR LATERAL STRUCTURAL NATURAL FREQUENCY DETERMINATION ON SINGLE AXIS TRACKERS

Release Date:
July 31st, 2024

Authors:

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This report was compiled in part based on analysis of data collected by GameChange Solar LP ("GameChange") from third party solar PV project owners and installers and from observations of GameChange personnel. The report is presented as-is without any warranties or guarantees as to the accuracy of the information presented herein. GameChange will not be responsible for any parties relying on the information or conclusions in this report.

Earthquake Load Calculated per Code

- Seismic Load is a function of
  - Soil Type (Seismic Site Class)
  - Likely ground accelerations
  - Fundamental Period of Structure
  - Weight of Structure
  - Energy dissipation: Idealize Trackers as "Inverted Pendulum" type structures

12.8.1 Seismic Base Shear. The seismic base shear, V, in a given direction shall be determined in accordance with the following equation:

$$V = C_s W \qquad (12.8\text{-}1)$$

where

C_s = the seismic response coefficient determined in accordance with Section 12.8.1.1, and
W = the effective seismic weight per Section 12.7.2.

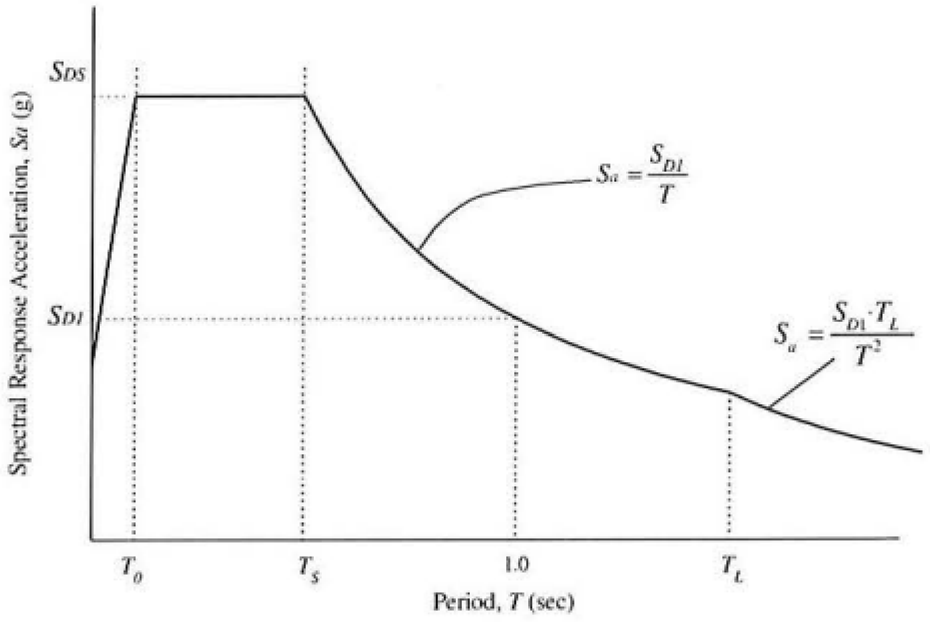


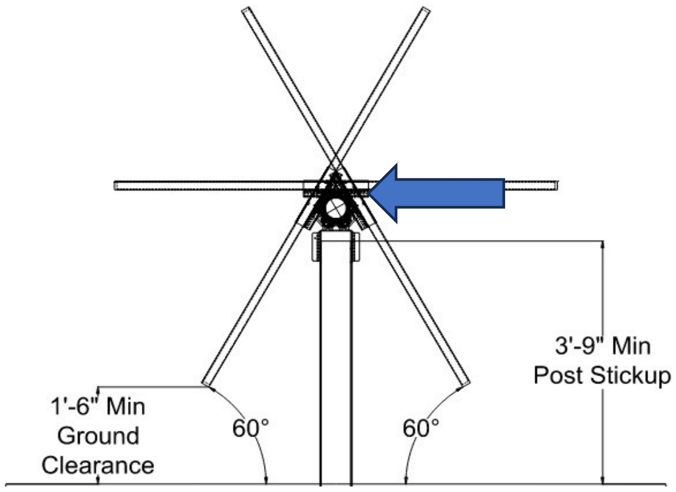
FIGURE 11.4-1 Design Response Spectrum

Load Path:

- Engineer needs to check all components that transfer earthquake force to ground
- Must account for forces both parallel and perpendicular to the row
- Trackers:
  - Parallel: North – South
  - Perpendicular: East - West
- Fixed Tilt
  - Parallel: East - West
  - Perpendicular: North-South

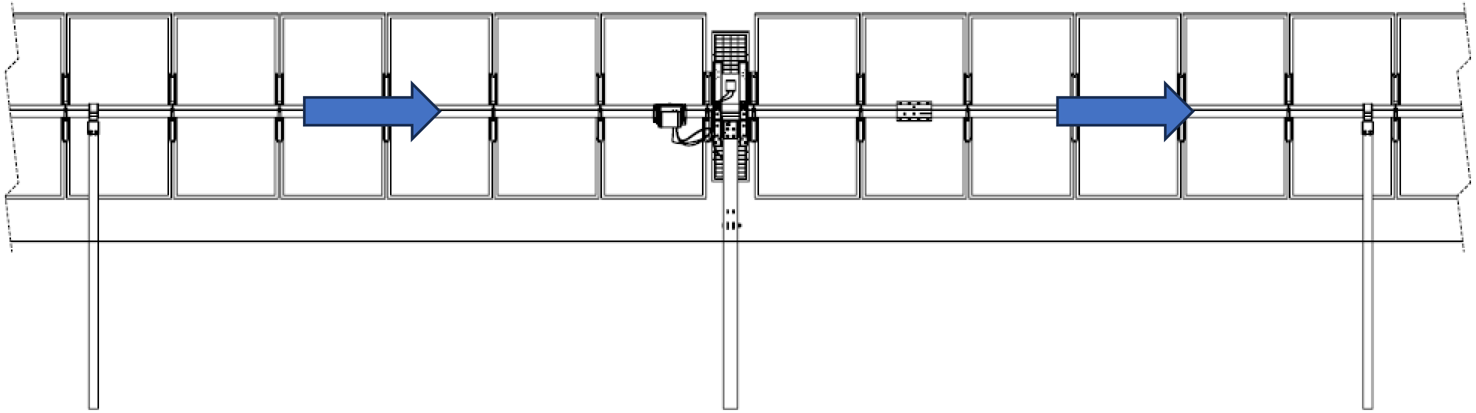
Load Path: Trackers

East - West



- Clearly established load path for wind design
- Wind often governs over seismic

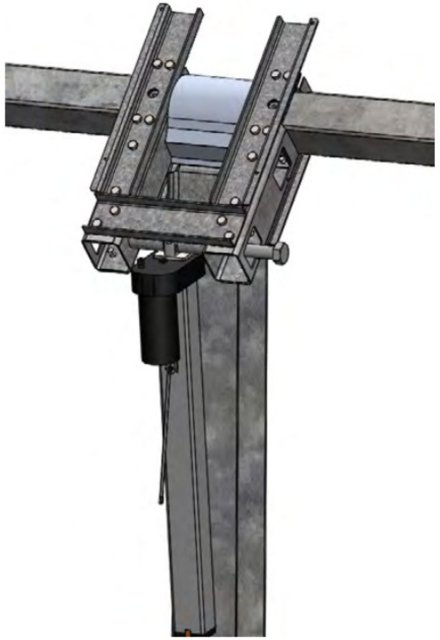
North - South



- Is there means to transfer North-South loads to the ground?
- If bearings restrain tube, account for thermal expansion / contraction

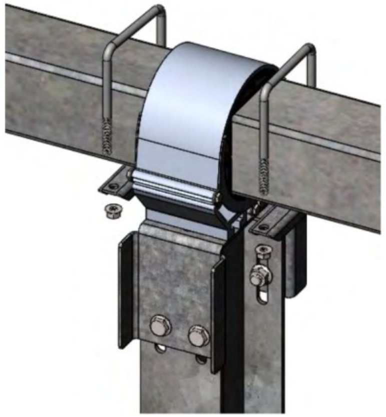
North - South Load Path: Genius Tracker

Bearing Connection at Motor



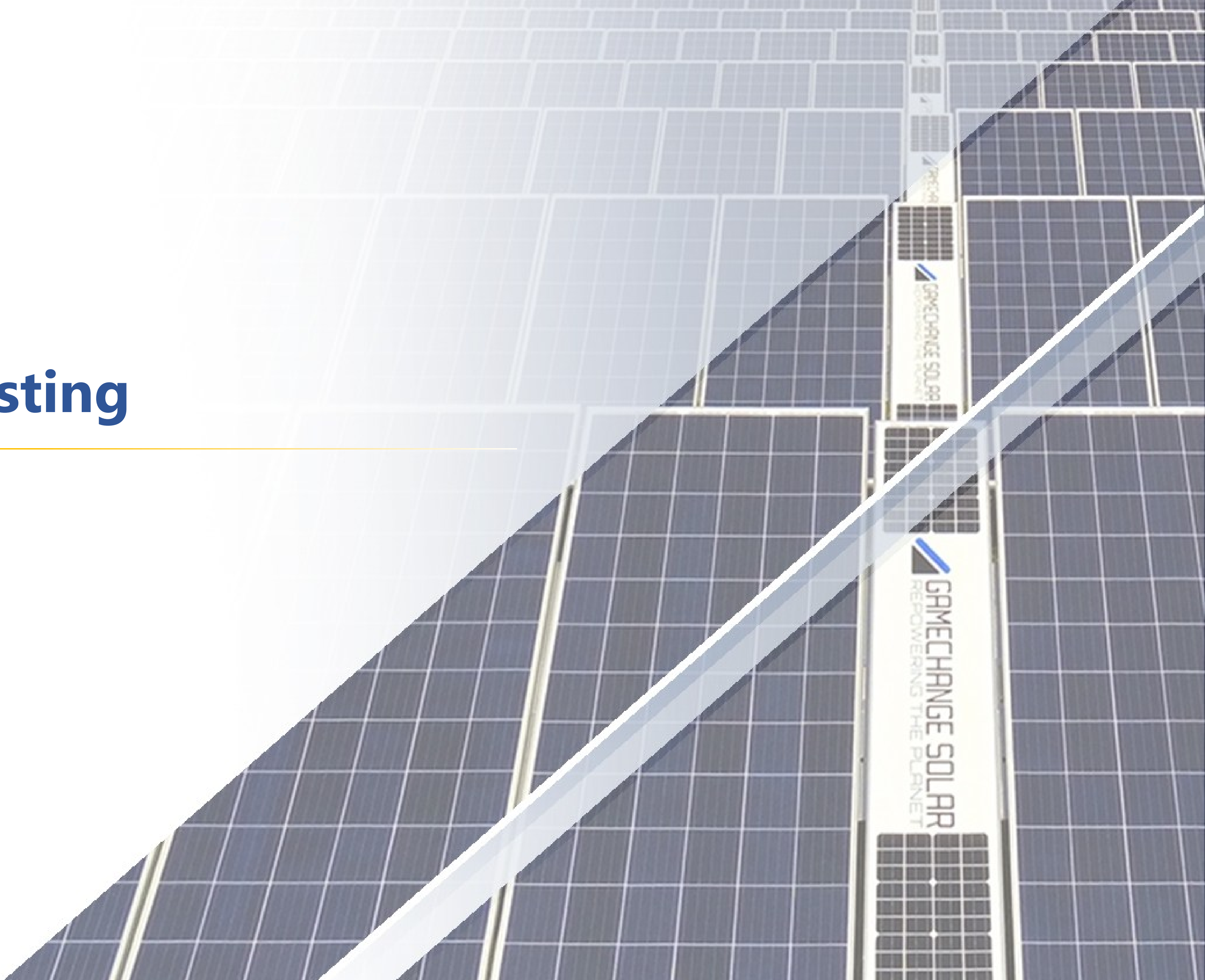
- Bearing connection transfers All North-South oriented loads
  - Downslope
  - Earthquake
- Fixed point for thermal expansion

Seismic Capture Plates



- Engages when earthquake moves table North-South to transfer load to post
- Dash-pot style design allows for thermal expansion and contraction

Shake Table Testing



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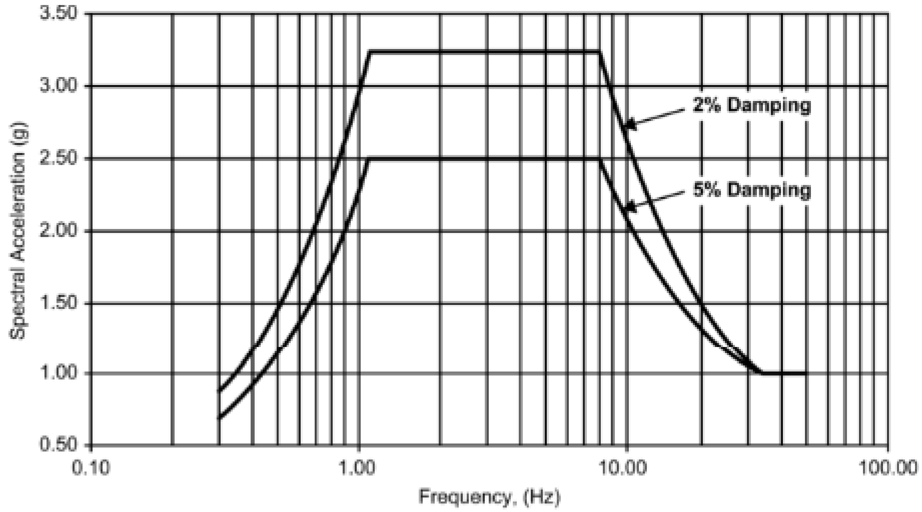
Test Program

- Goal of Testing: Observe how PV modules and racking system respond to earthquake shaking.
- Standard Components: Actuator, tube, bearing etc.
- Seismic Captures
- Performed at UC Berkley Pacific Earthquake Engineering Research Center (PEER) Lab.
- IEEE 693 “IEEE Recommended Practice for Seismic Design of Substations”
  - Broadband White Noise Excitation.
  - 50% Low Performance Level (PL)
  - 100% High Performance Level (PL)
- Flat and High Tilts



Spectral Accelerations, S_a (g), for Frequencies, f (Hz):

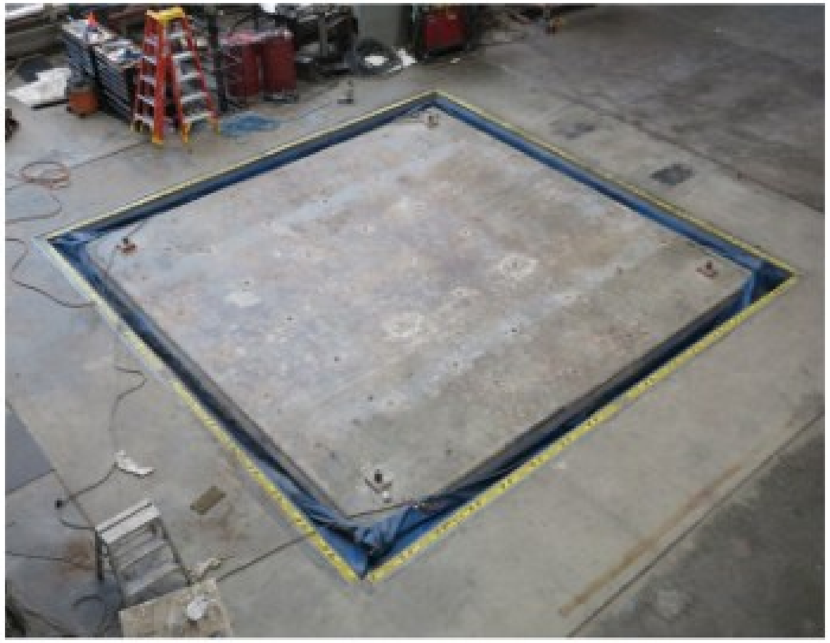
$S_a = 2.288\,\beta f$	for $0.0 \le f \le 1.1$
$S_a = 2.50\,\beta$	for $1.1 < f \le 8.0$
$S_a = (26.4\,\beta - 10.56) / f - 0.8\,\beta + 1.32$	for $8.0 < f \le 33$
$S_a = 1.0$	for $f > 33$

$\beta = (3.21 - 0.68 \ln(d)) / 2.1156$ where d is the percent damping (2, 5, 10, etc.) and $d \le 20\%$

Figure A.1— High performance level required response spectrum, 1.0 g

Test Setup

- 20′ x 20′ Shake table with outrigger
- Four 75,000 lb capacity actuators
- 39-foot-long tracker (1 post-to-post span)



Test Configurations

Module

Mechanical Parameters	
Solar Cell	Mono N-Type 182mm
No. of Cells	144 (6 × 24)
Dimensions	2278 × 1134 × 35mm(89.69× 44.65 × 1.38in.)
Weight	32.7kg(72.09lbs)
Junction Box	IP68 rated (3 bypass diodes)
Output Cable	$4mm^2$ (IEC), 12 AWG(UL) +400/-200mm (+15.75/-7.87in.) or customized
Connector	RY01 or similar
Front Cover	2.0mm (0.079in.)semi-tempered AR glass
Back Cover	2.0mm (0.079in.)semi-tempered glass
Container	31 pcs/Pallet, 620 pcs/40' HQ

- Option for additional testing with 2nd module type.

Racking

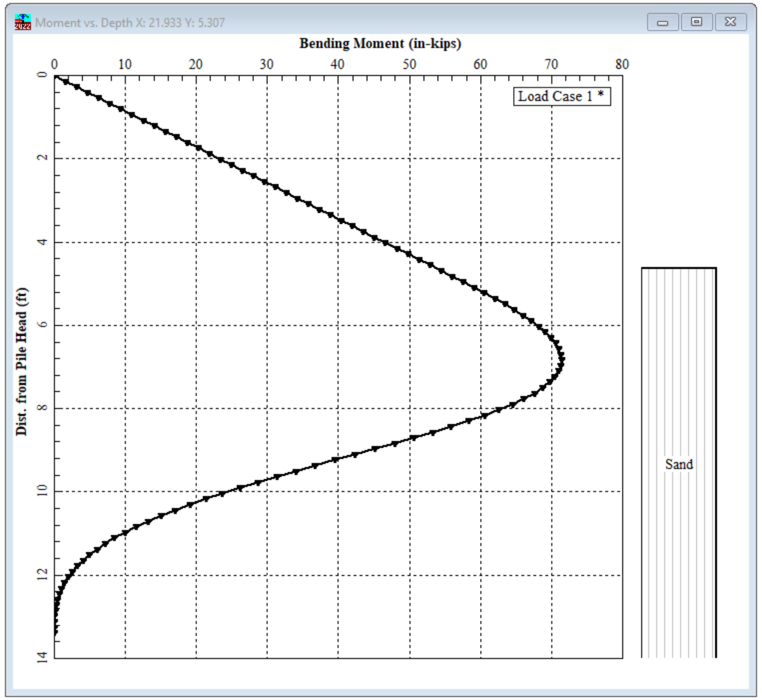
		Tilt Angle	
		0º	60º
Mount	Speed Clamp	1a	1b
Mount	Purlin	2a	2b

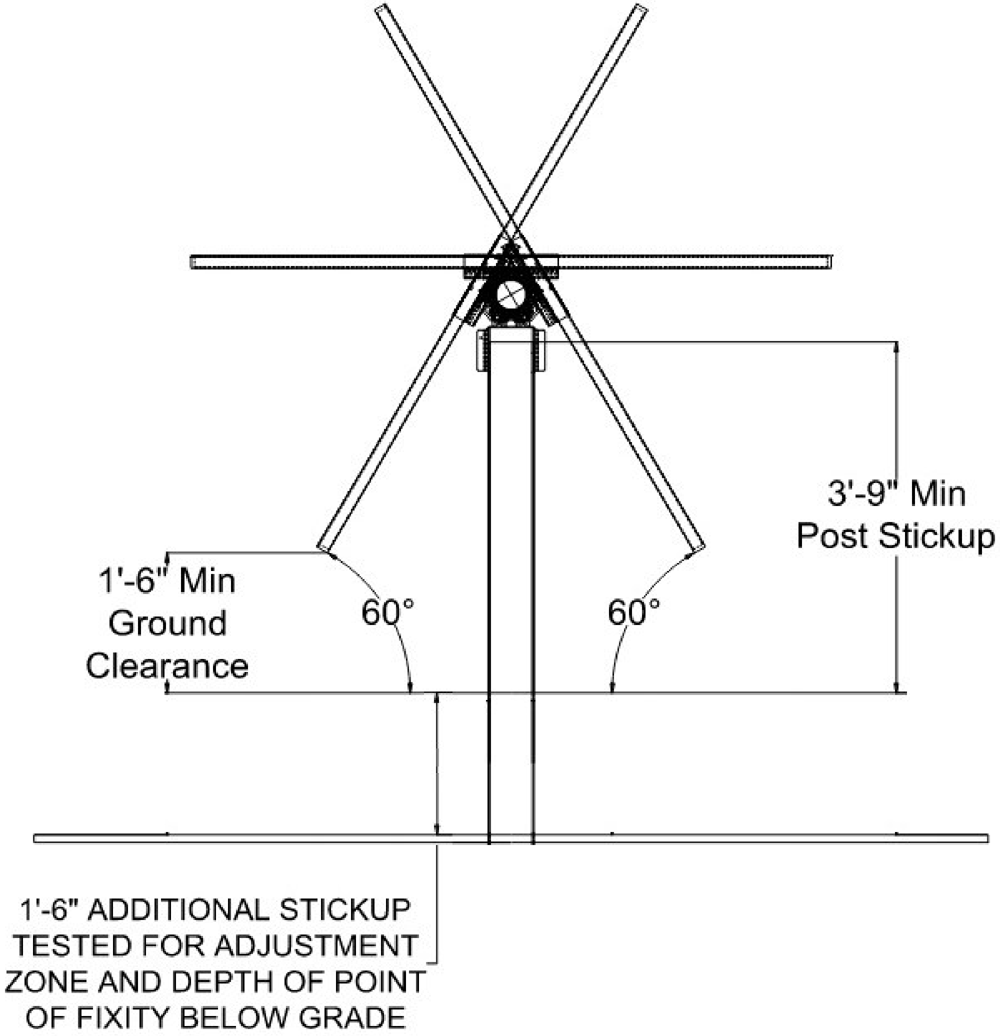
SpeedClamp

Purlin

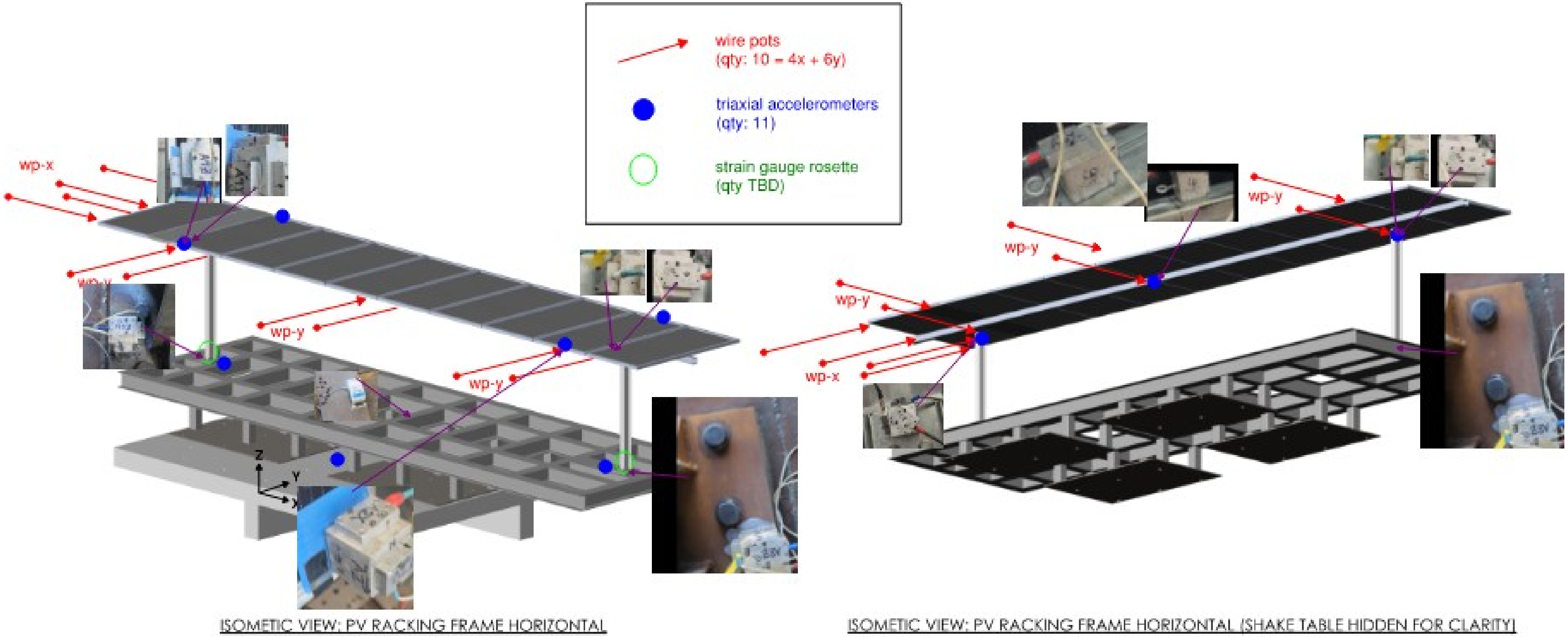
Fixed vs. posts in soil

- Point of Maximum moment for posts in soil occurs below grade.
- Post reveal increased so connection to outrigger was at roughly the same distance below row tube.





Test Instrumentation



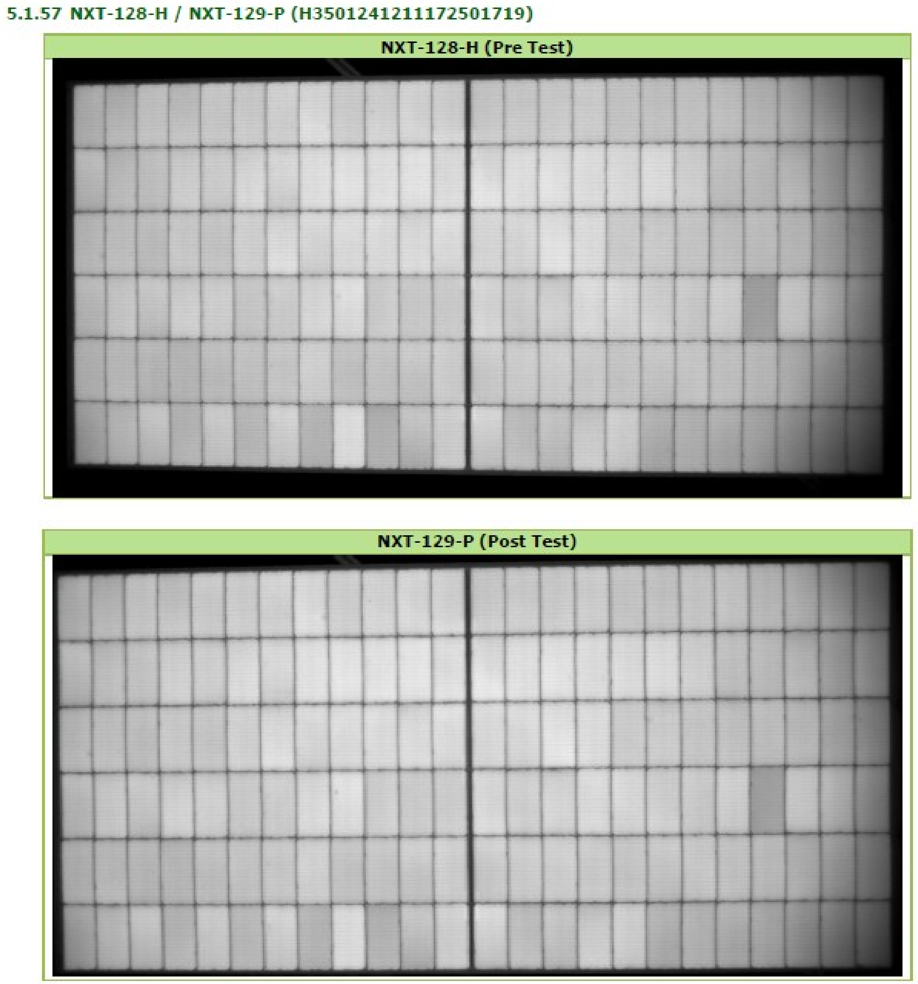
Sensor mounting locations.

Shake Table Testing – Flat Tilt

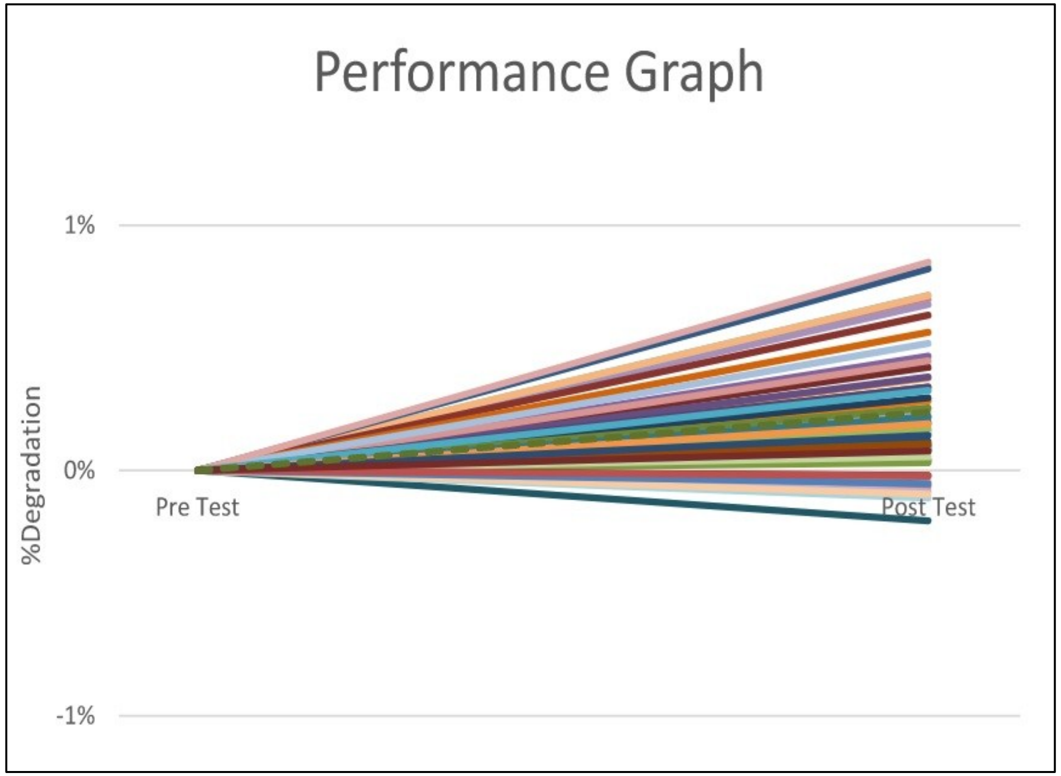
Shake Table Testing – High Tilt

Test Results – Module Micro-Cracks

- RETC performed inspections performed before and after shake table
  - Visual Inspection
  - Electroluminescence
  - Maximum Power Determination – Front
  - Maximum Power Determination – Back

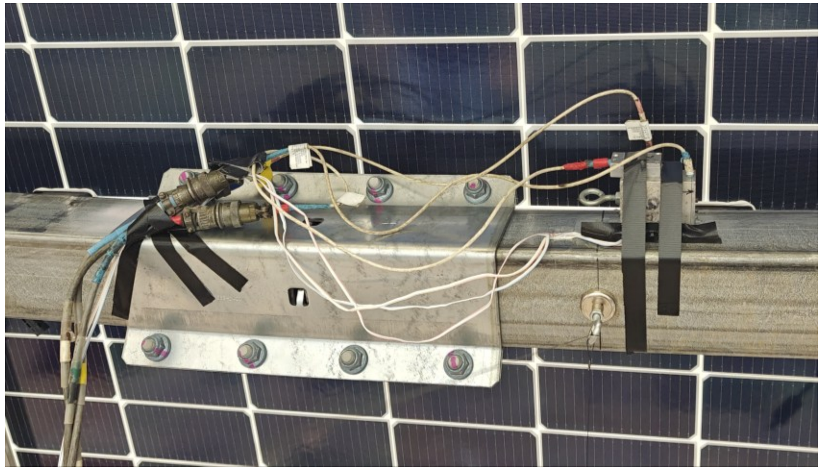


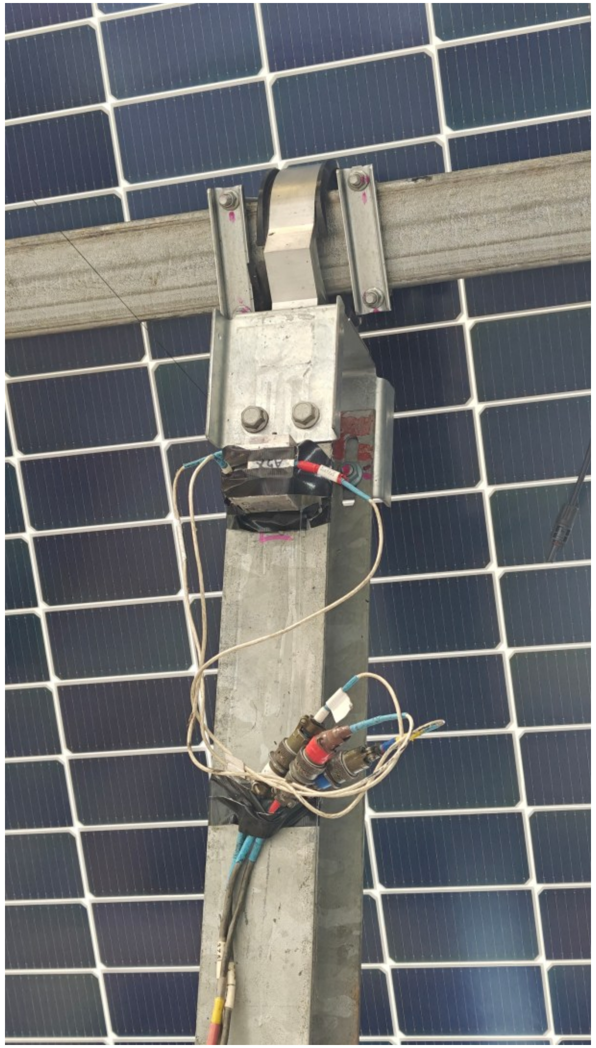
Test Results – Module Power Output



Test Results – In Lab

- Favorable Results
- No damage to:
  - Posts
  - Bearings
  - Tubes
  - Purlins
- Clear indications that Seismic Capture Plates were engaged.
- Open question if just testing one span impacted results of test 1b.



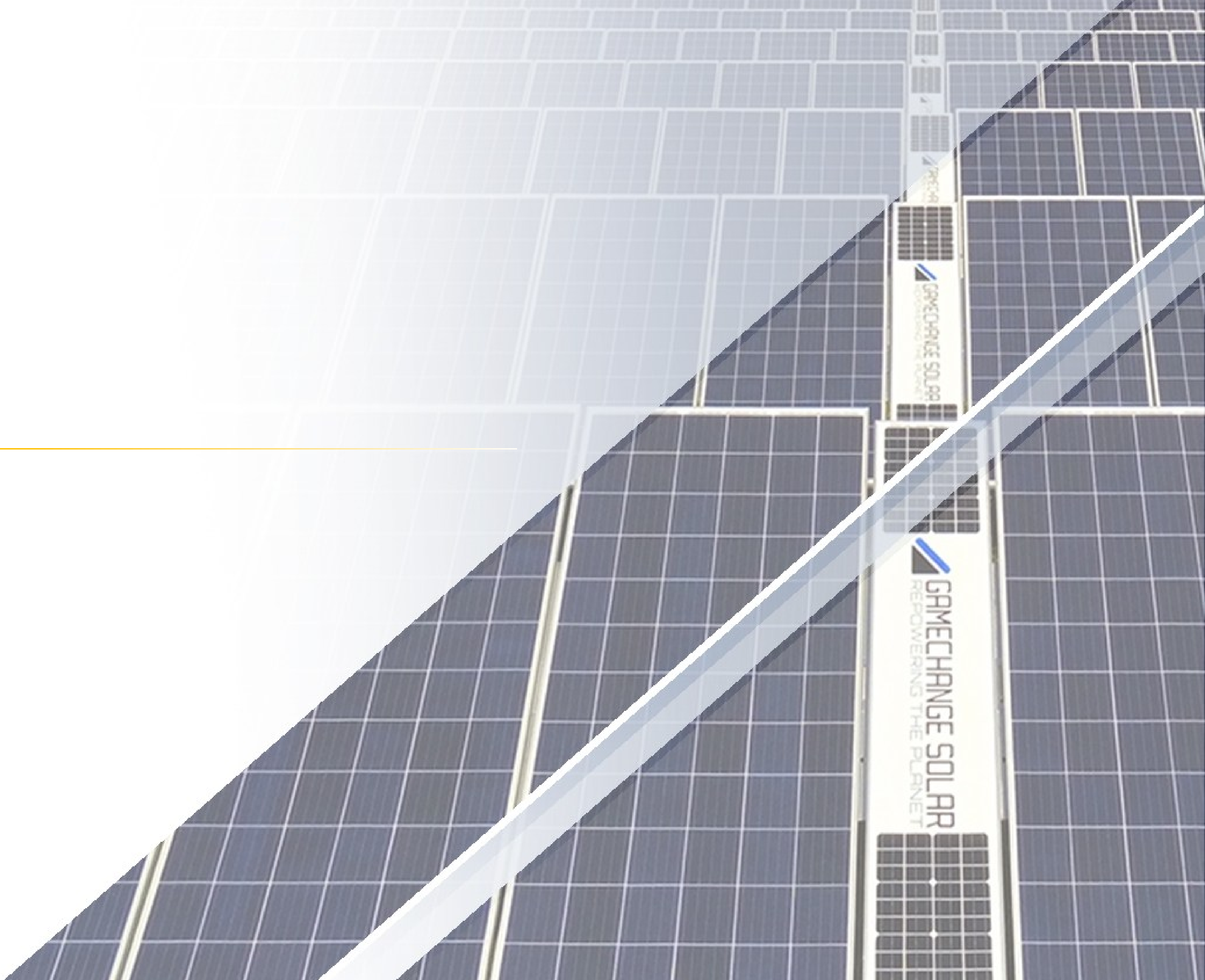


Racking Results – 3rd Party

- Inspection performed by RETC
- Function test per applicable parts of IEC 62817 Clause 9.2
- Visual Inspection
  - Actuators
  - Controllers
  - Tubes
  - Bearings
  - Posts

> “Based on our visual inspection and function test performed with reference to IEC 62817:2014+A1:2017, Clause 9.2, the GameChange Solar Genius Tracker single-axis solar tracker system is in good physical and operating condition. - *RETC*

Future Work



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Future Work

1. Different Module Types
2. Additional Shake Table Testing for more than one span
3. Account for N-S table slope
4. Posts in soil boxes
5. Actual results of a seismic event

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THANK YOU

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