Site response modeling in liquefiable soil deposits

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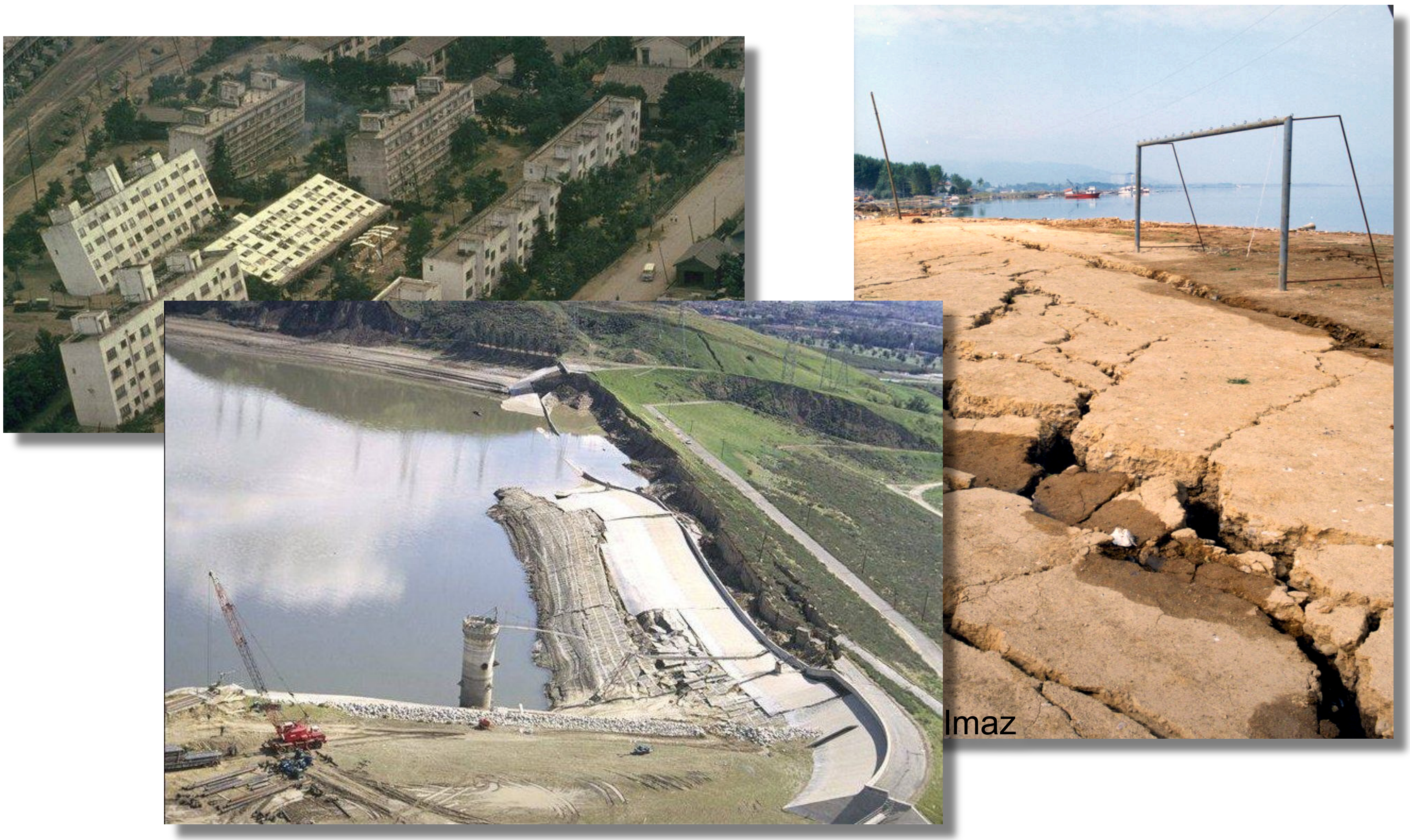
Outline

- Behavior of liquefiable soils
- Characteristics of ground motions affected by liquefaction
- Analysis of vertical arrays
- Effects of liquefaction on ground motions
- Summary and conclusions

Soil Liquefaction

Widely recognized for potential to cause ground failure



Soil Liquefaction

Ground response is also important

Soil Liquefaction

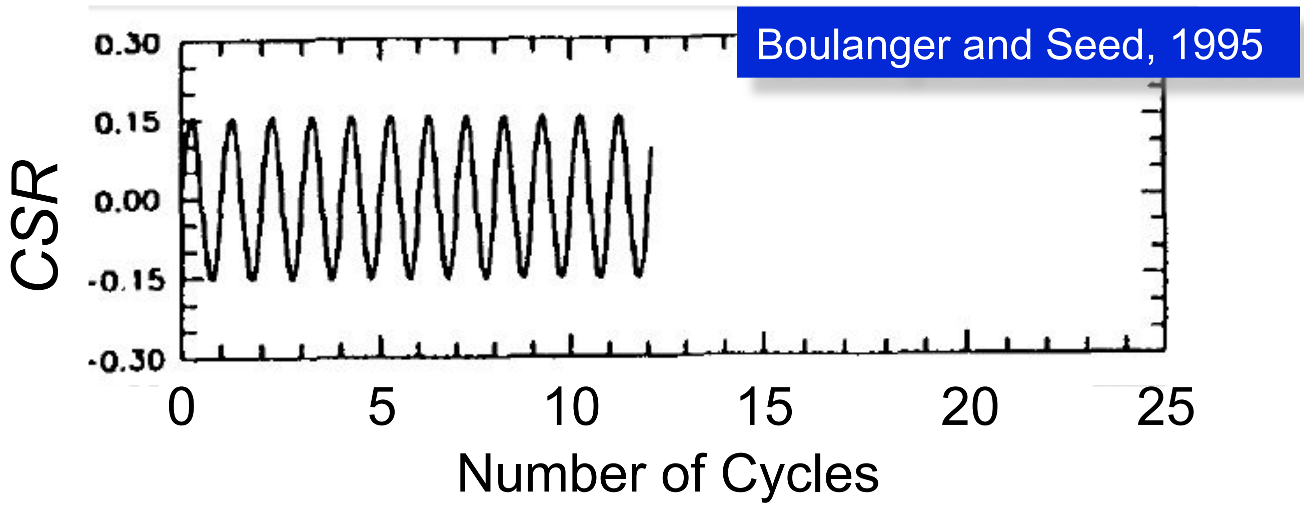
Laboratory testing

Cyclic triaxial

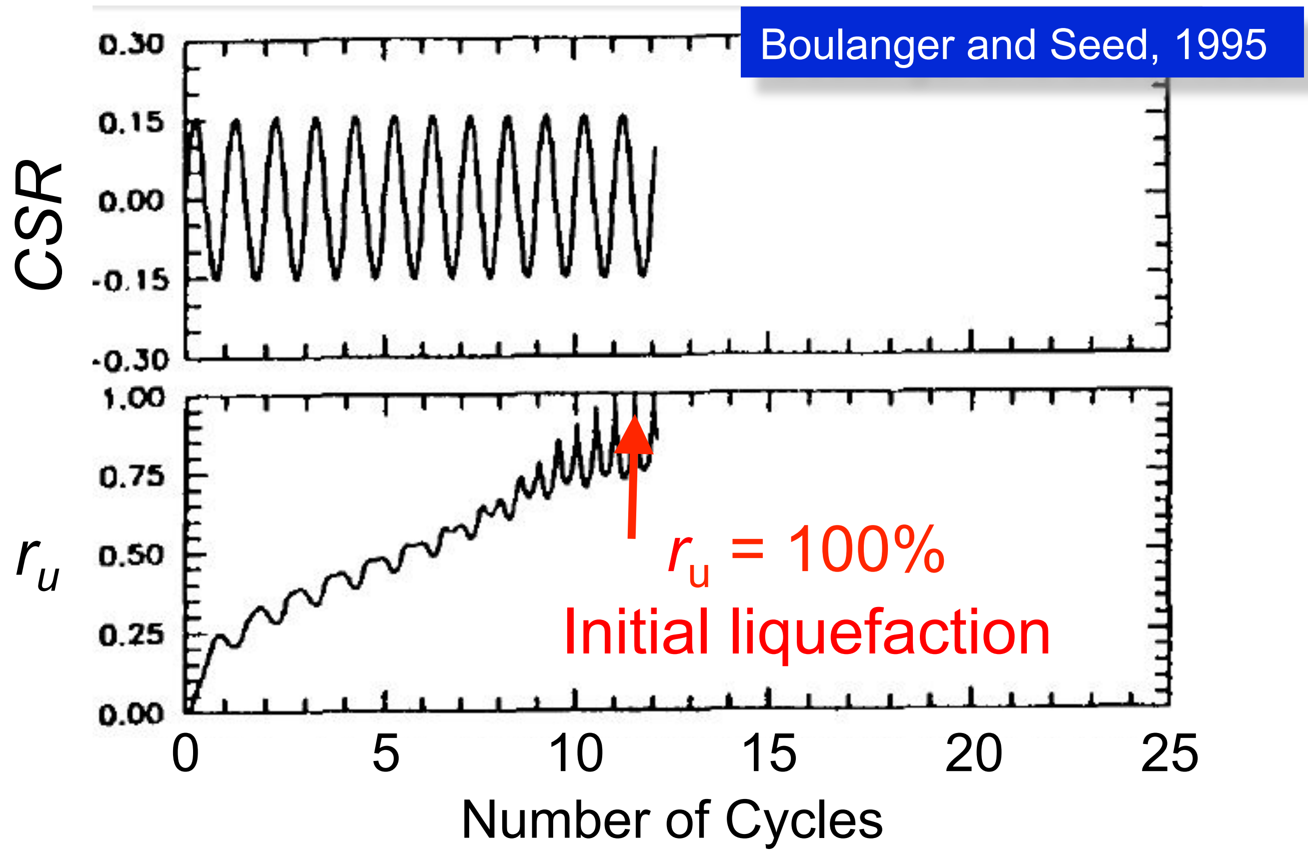
Cyclic simple shear

Geocomp

Soil Liquefaction

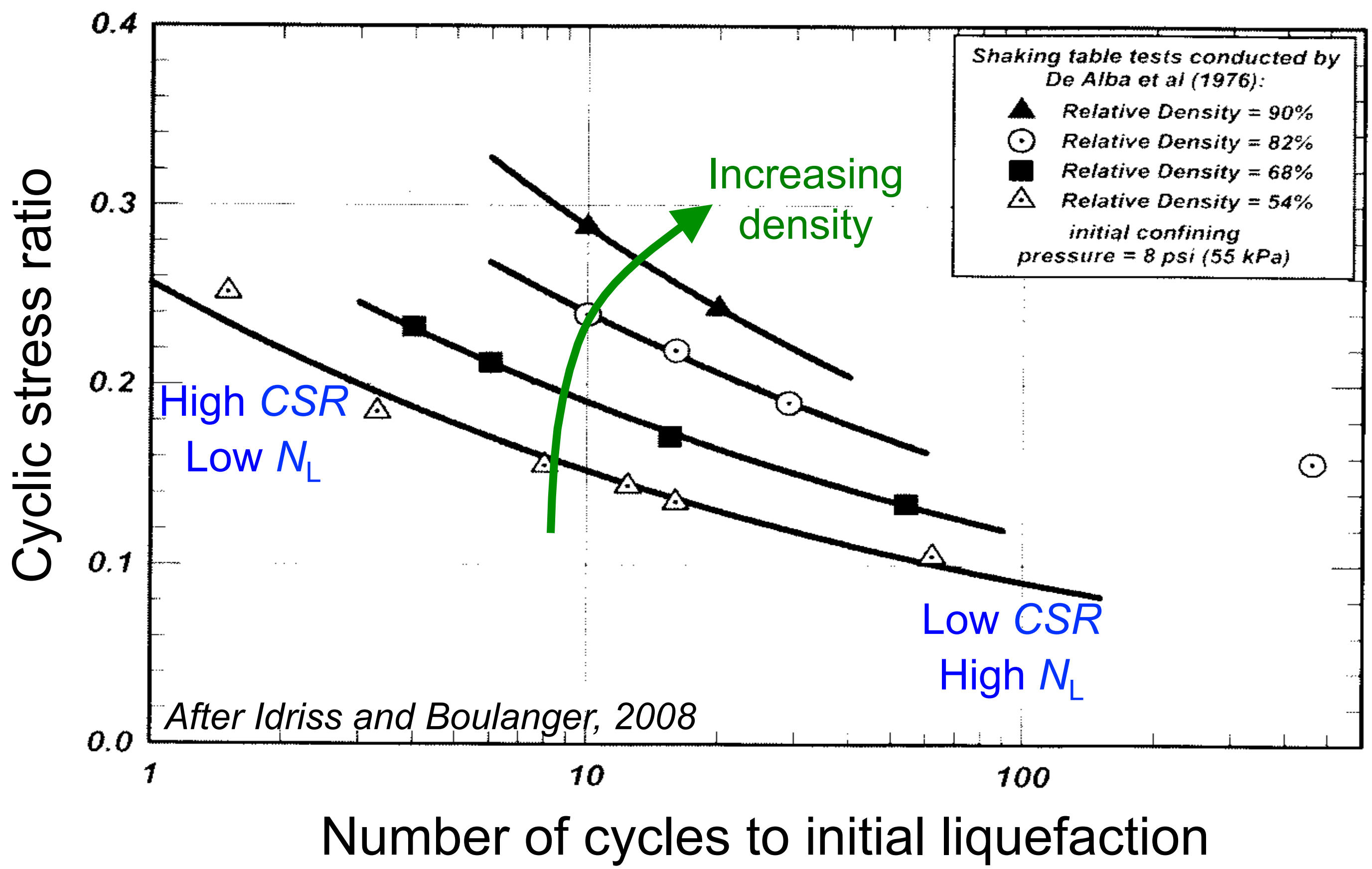


Soil Liquefaction



Soil Liquefaction

Typical behavior – harmonic loading



Soil Liquefaction

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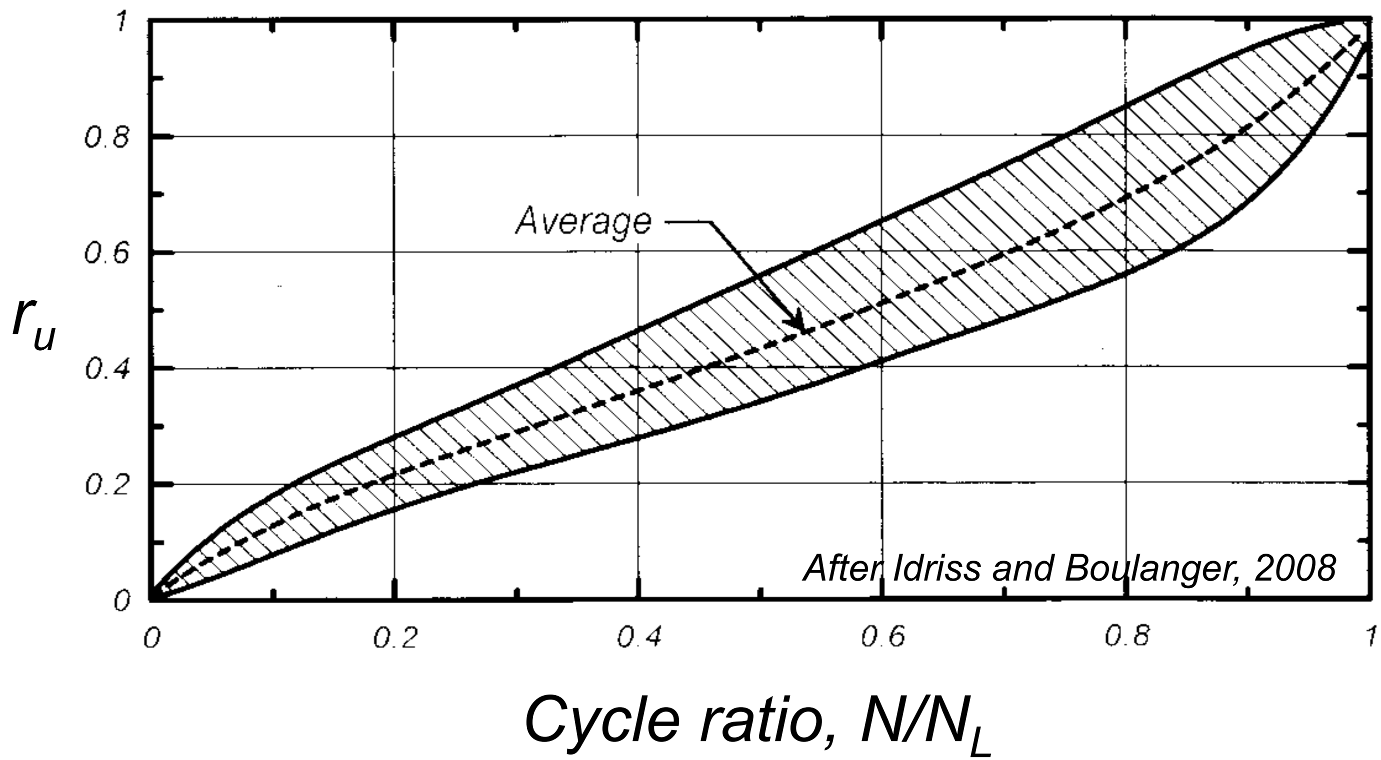
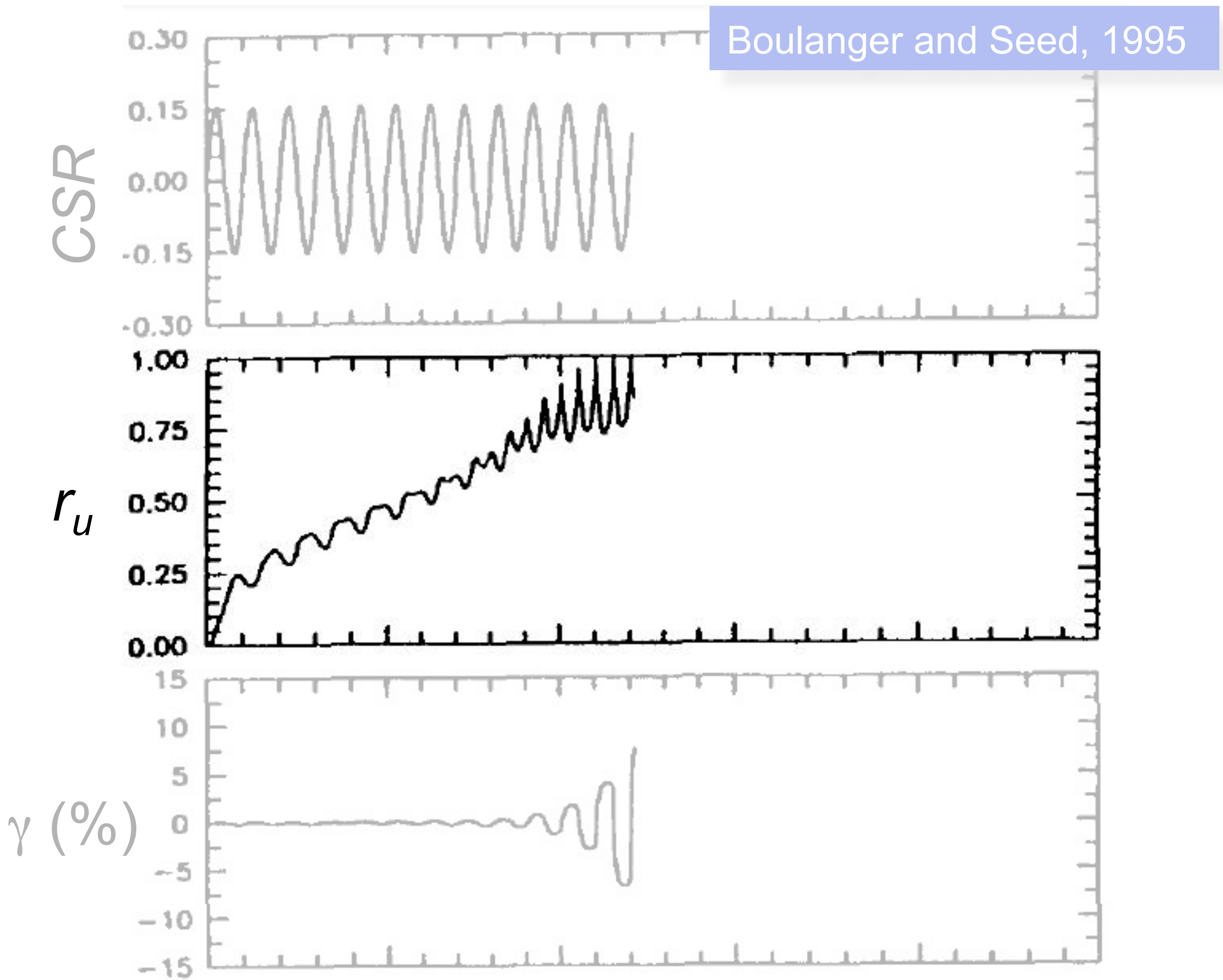


Soil Liquefaction



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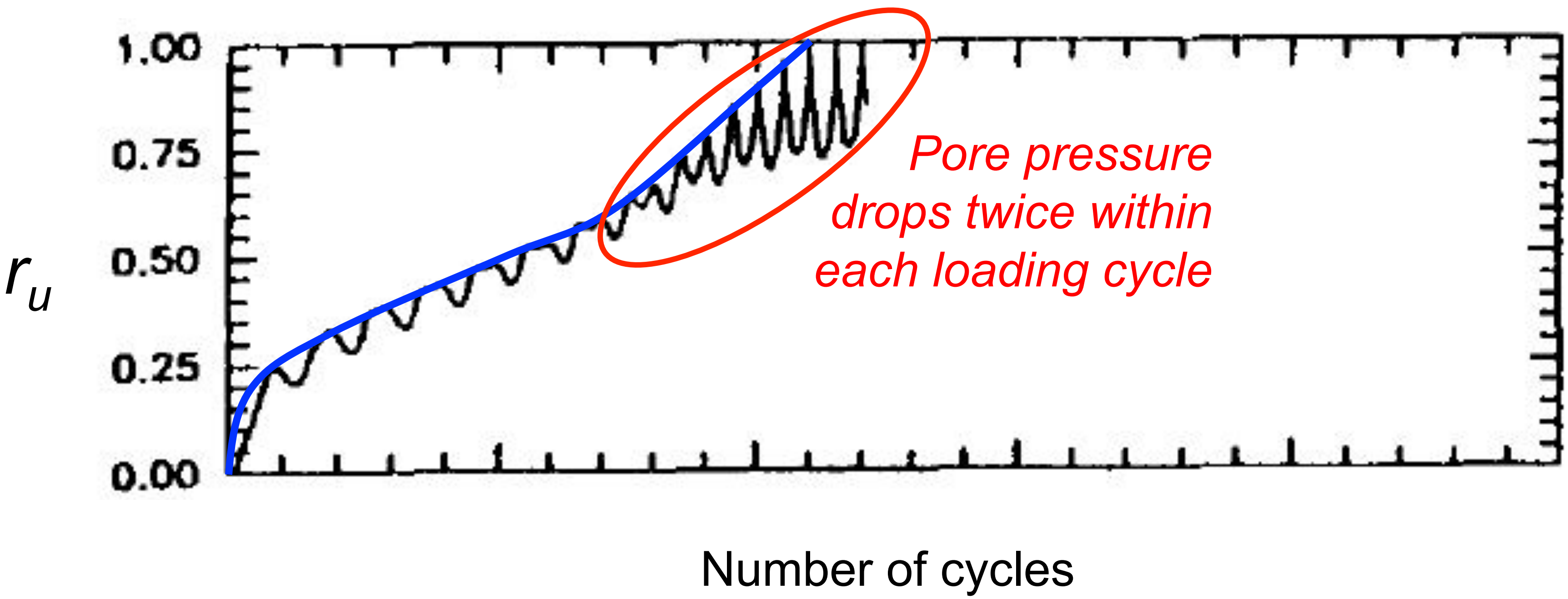
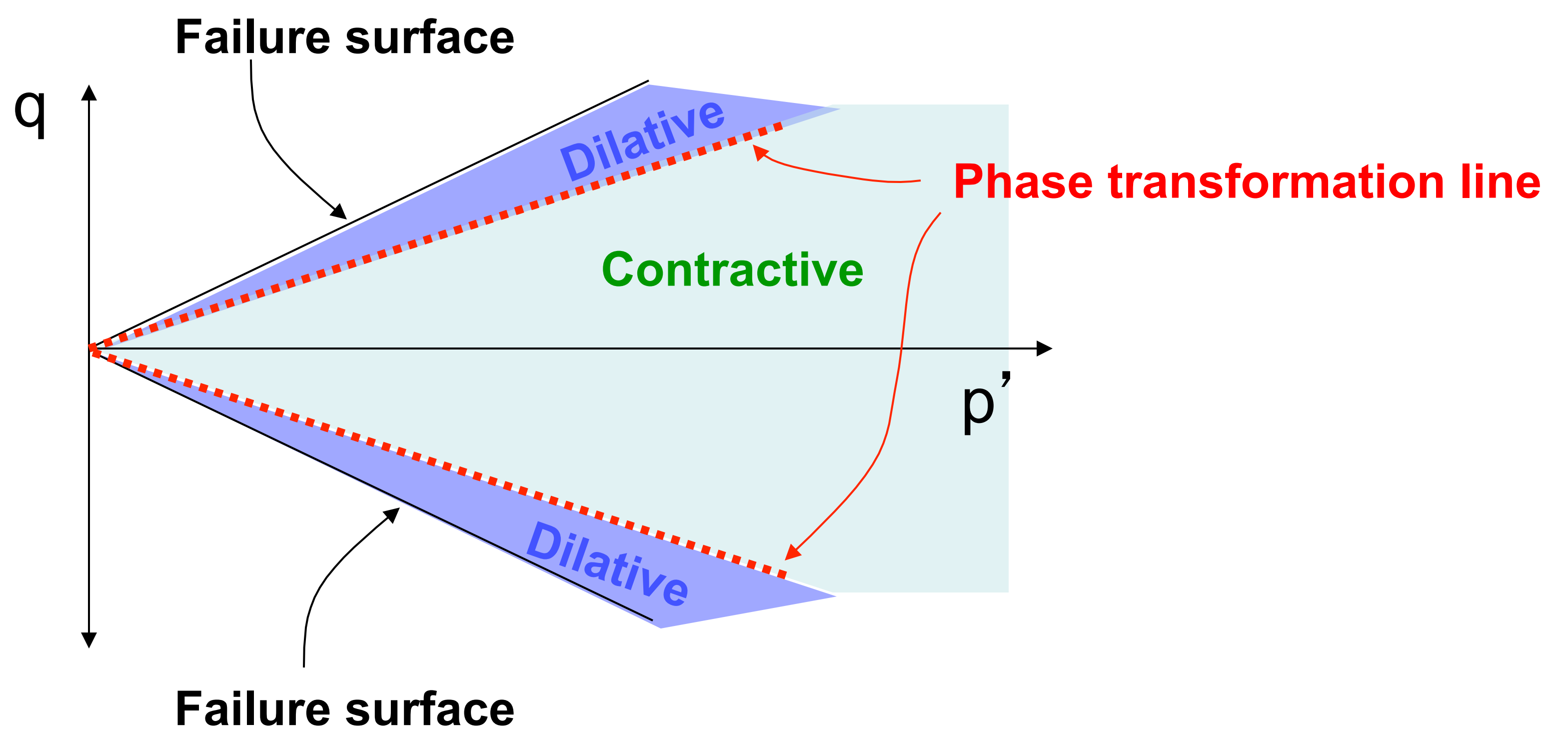


Effects of Liquefaction

Phase transformation

- Contractive behavior – *u* increases, *p*' decreases
- Dilative behavior – *u* decreases, *p*' increases



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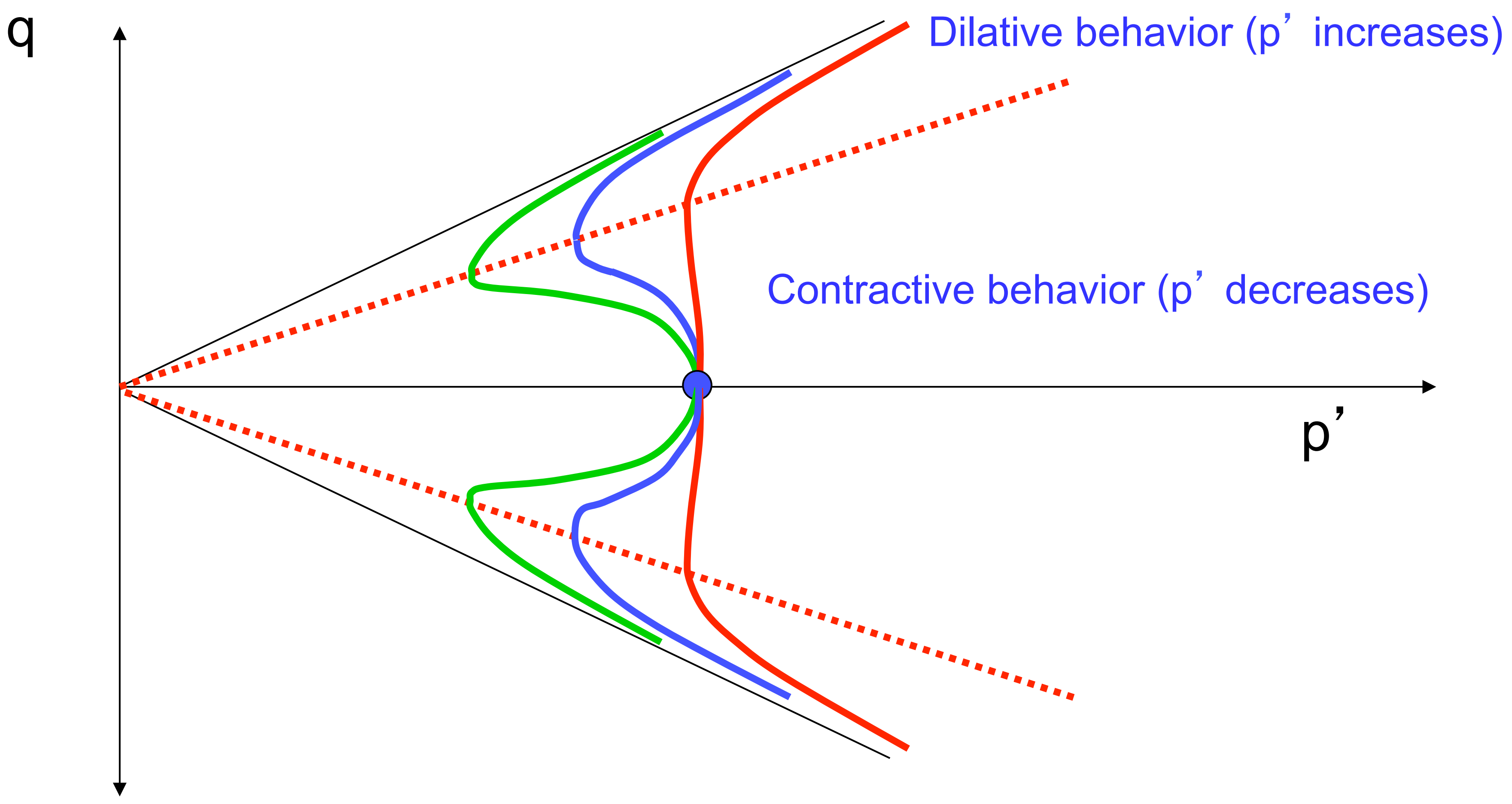

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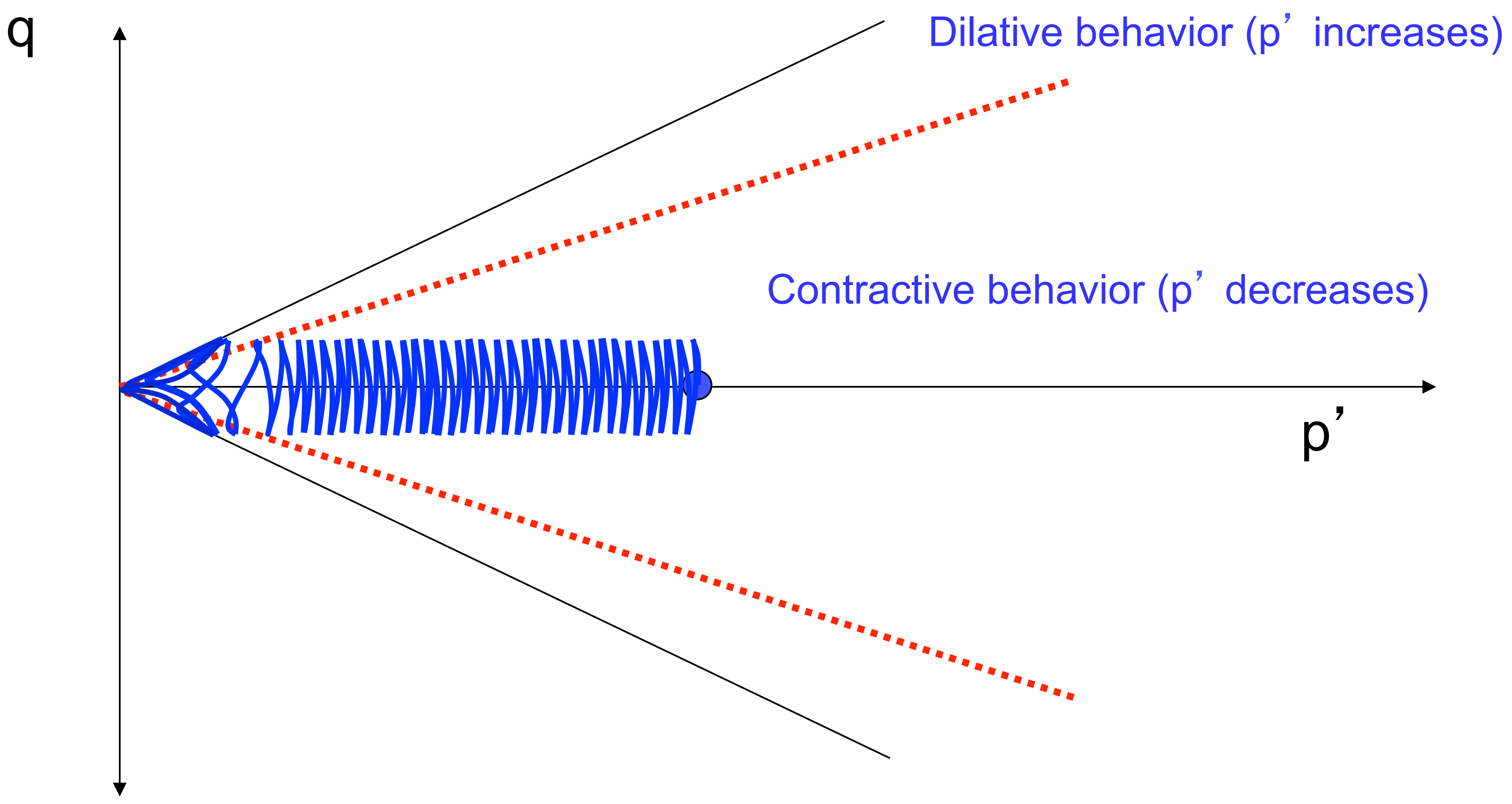

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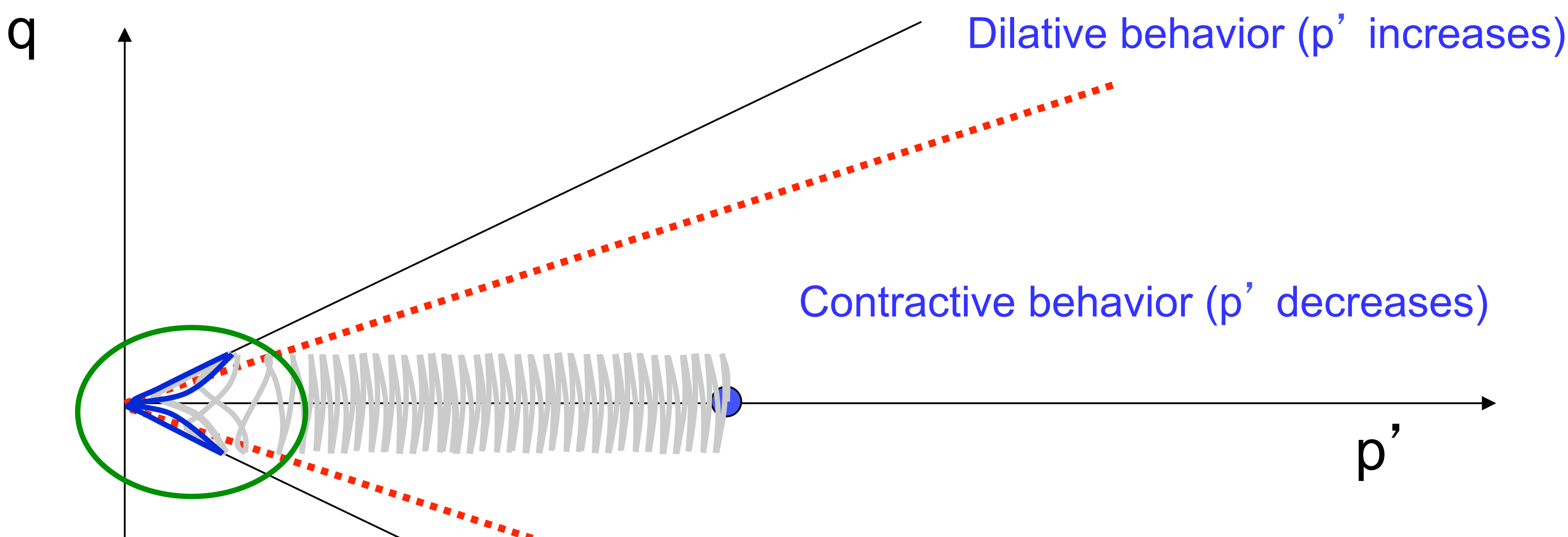
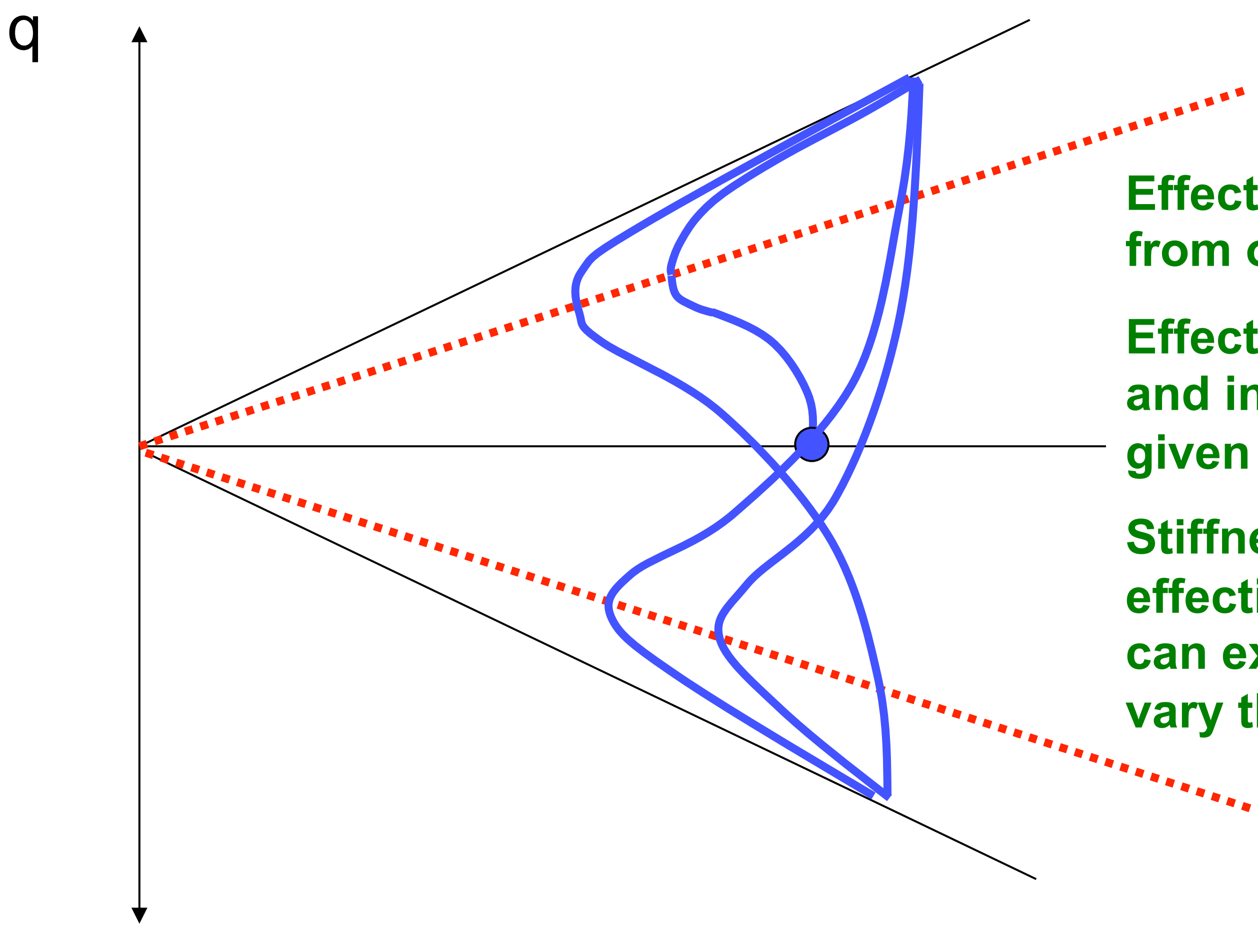


Eventually, effective stress path stabilizes

Experimental evidence shows that strains continue to increase

Additional softening occurs due to destruction of soil fabric

Effects of Liquefaction

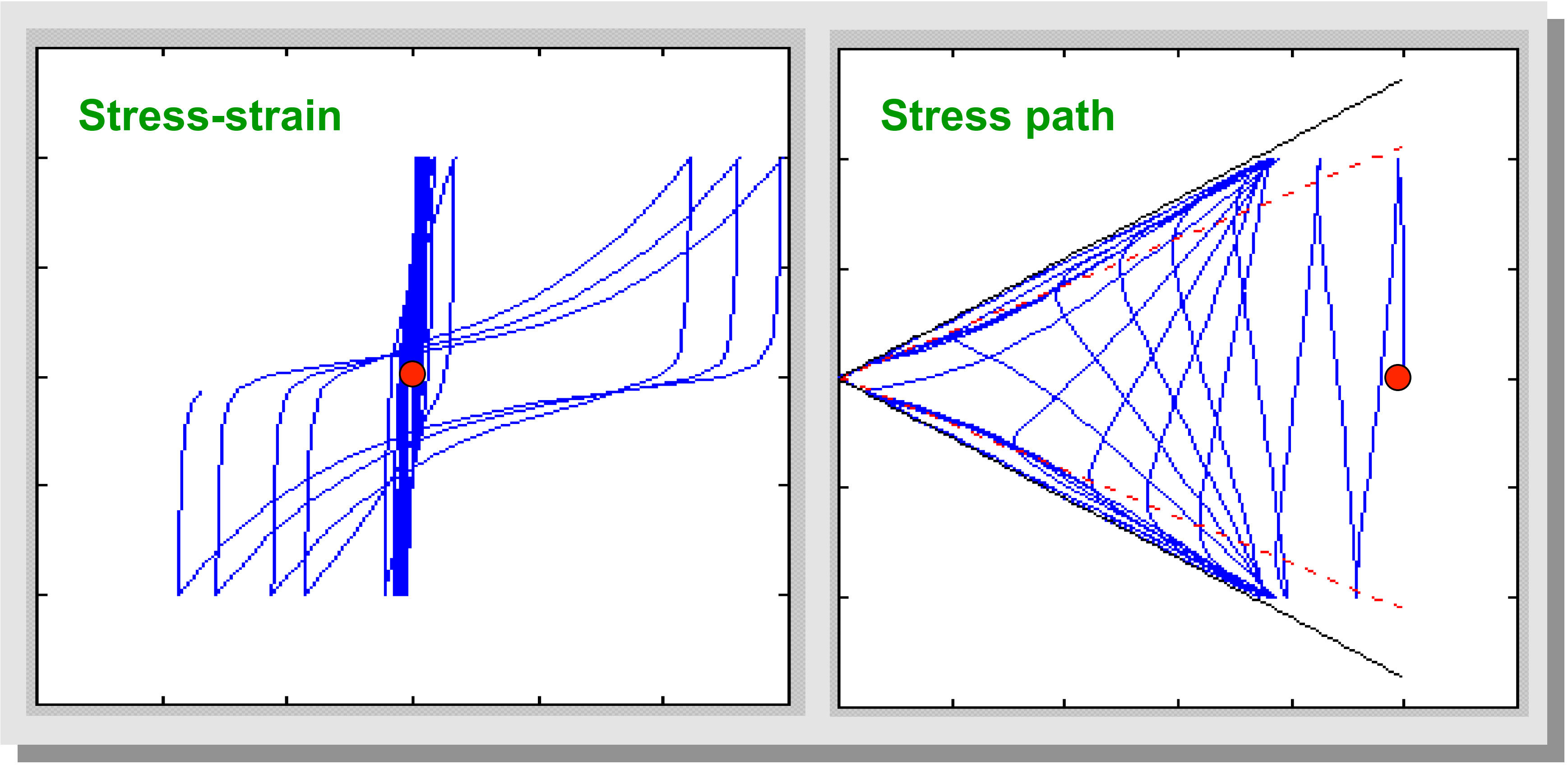


Effective stress decreases from one cycle to the next

Effective stress decreases and increases within a given cycle of loading

Stiffness depends on effective stress, so we can expect stiffness to vary throughout loading

Effects of Liquefaction



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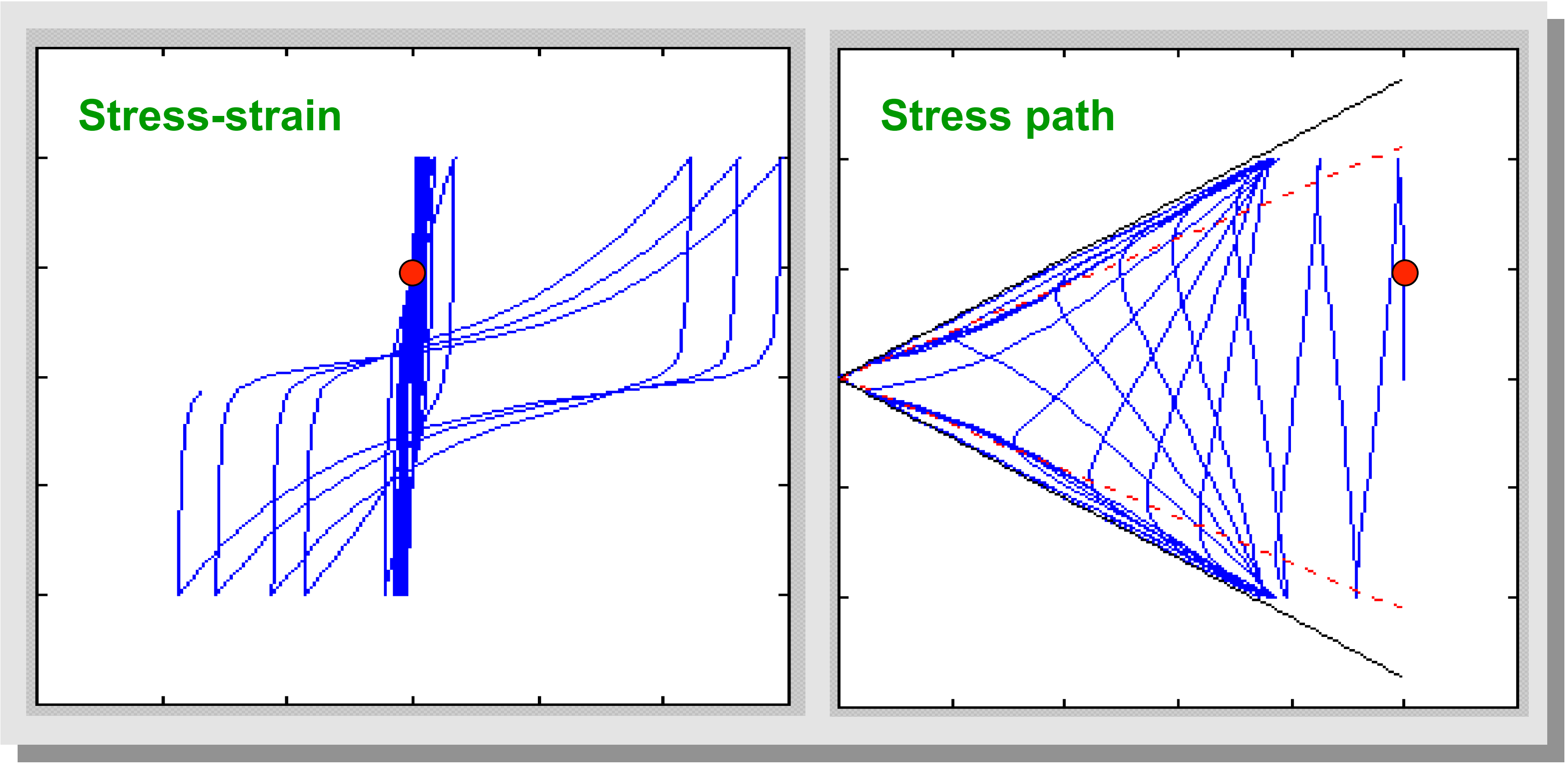

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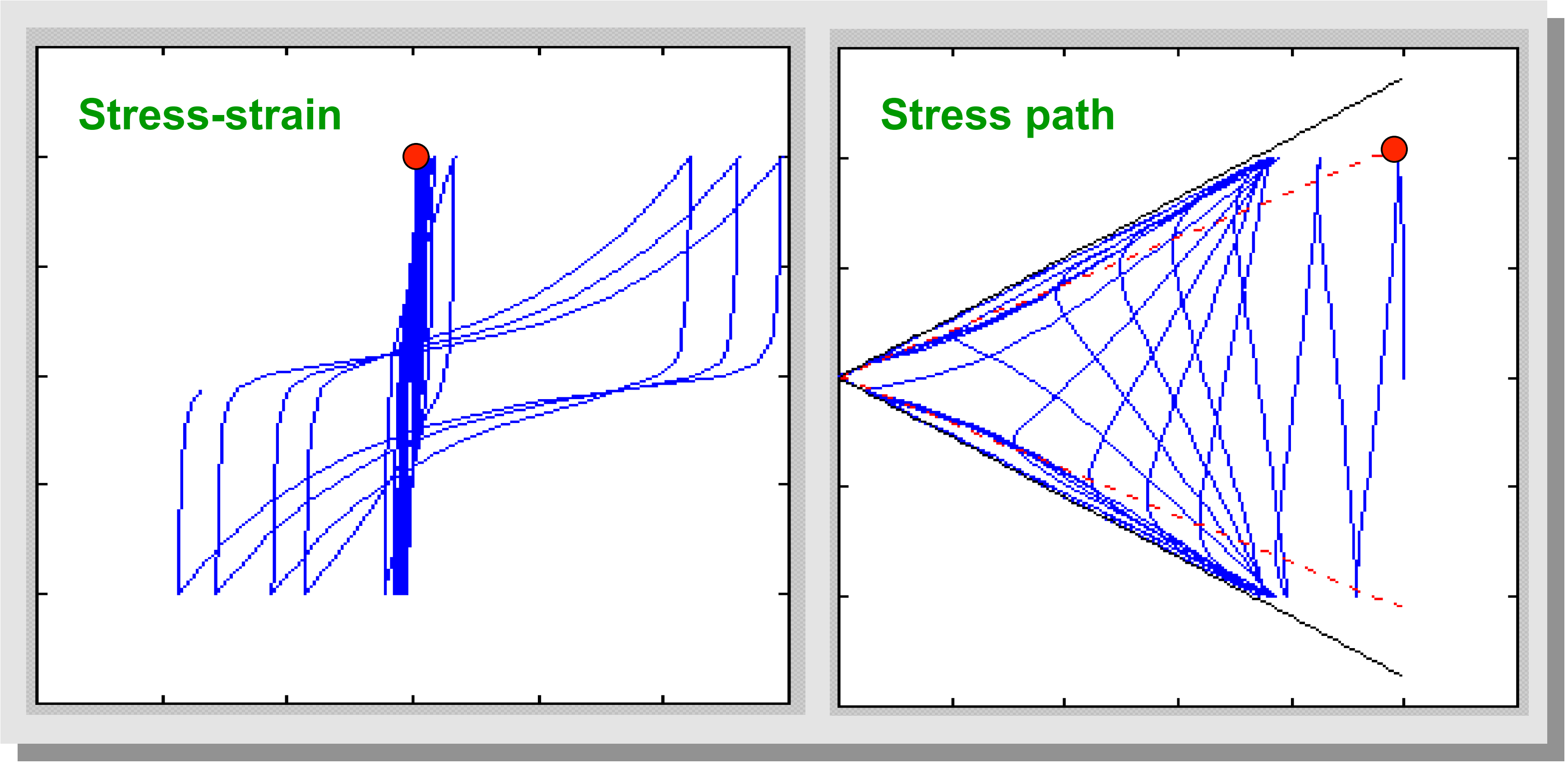

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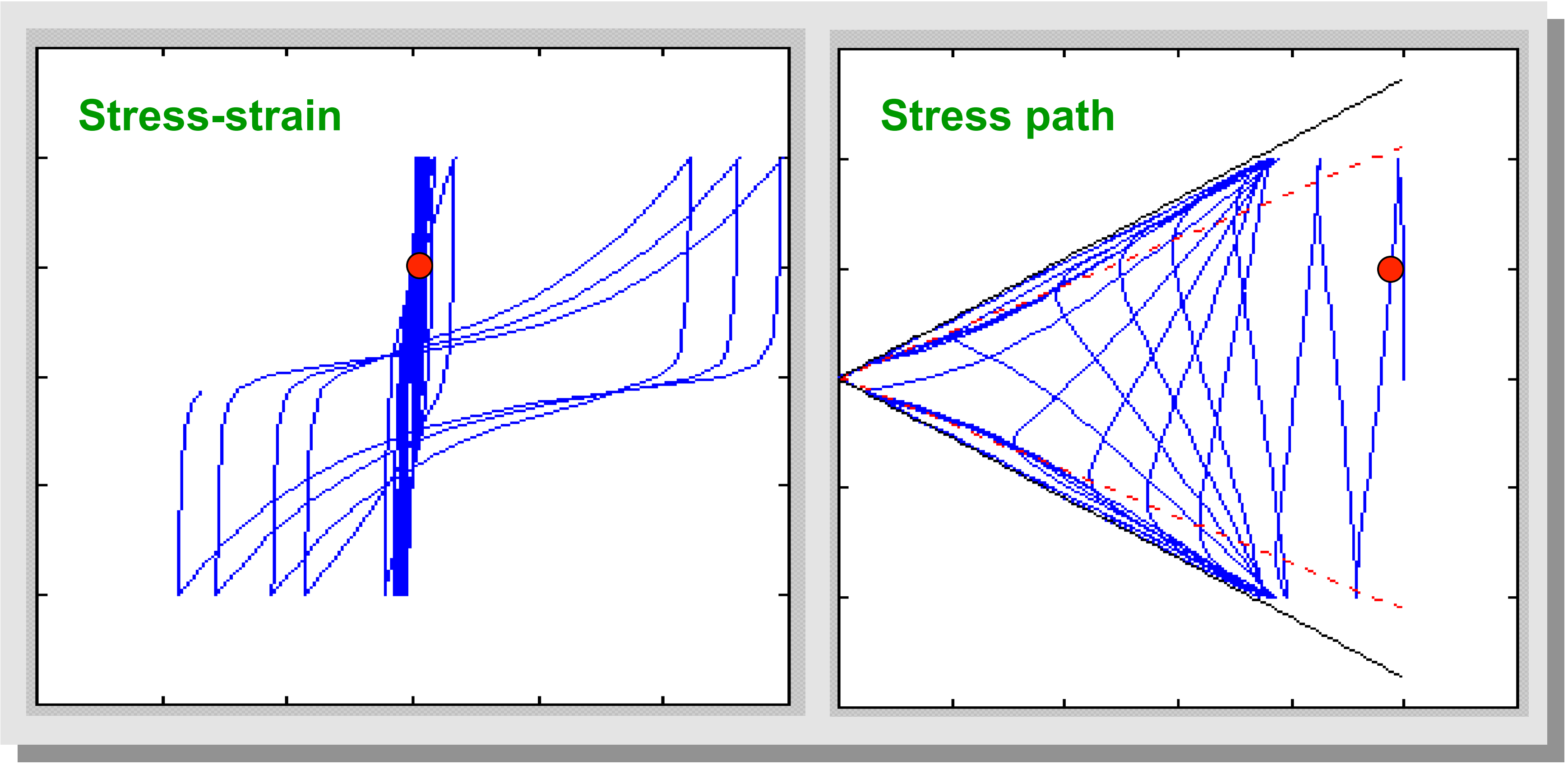

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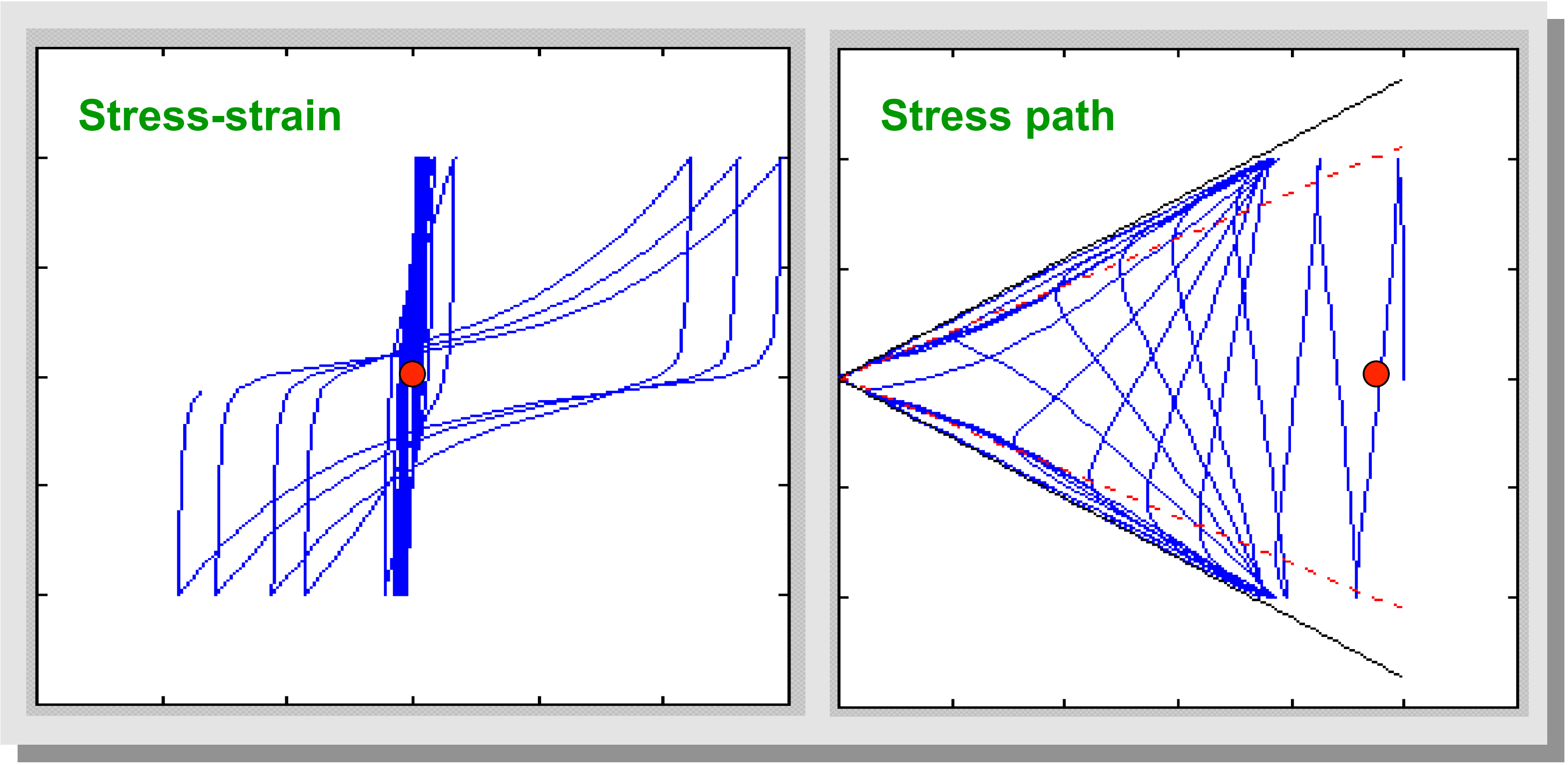

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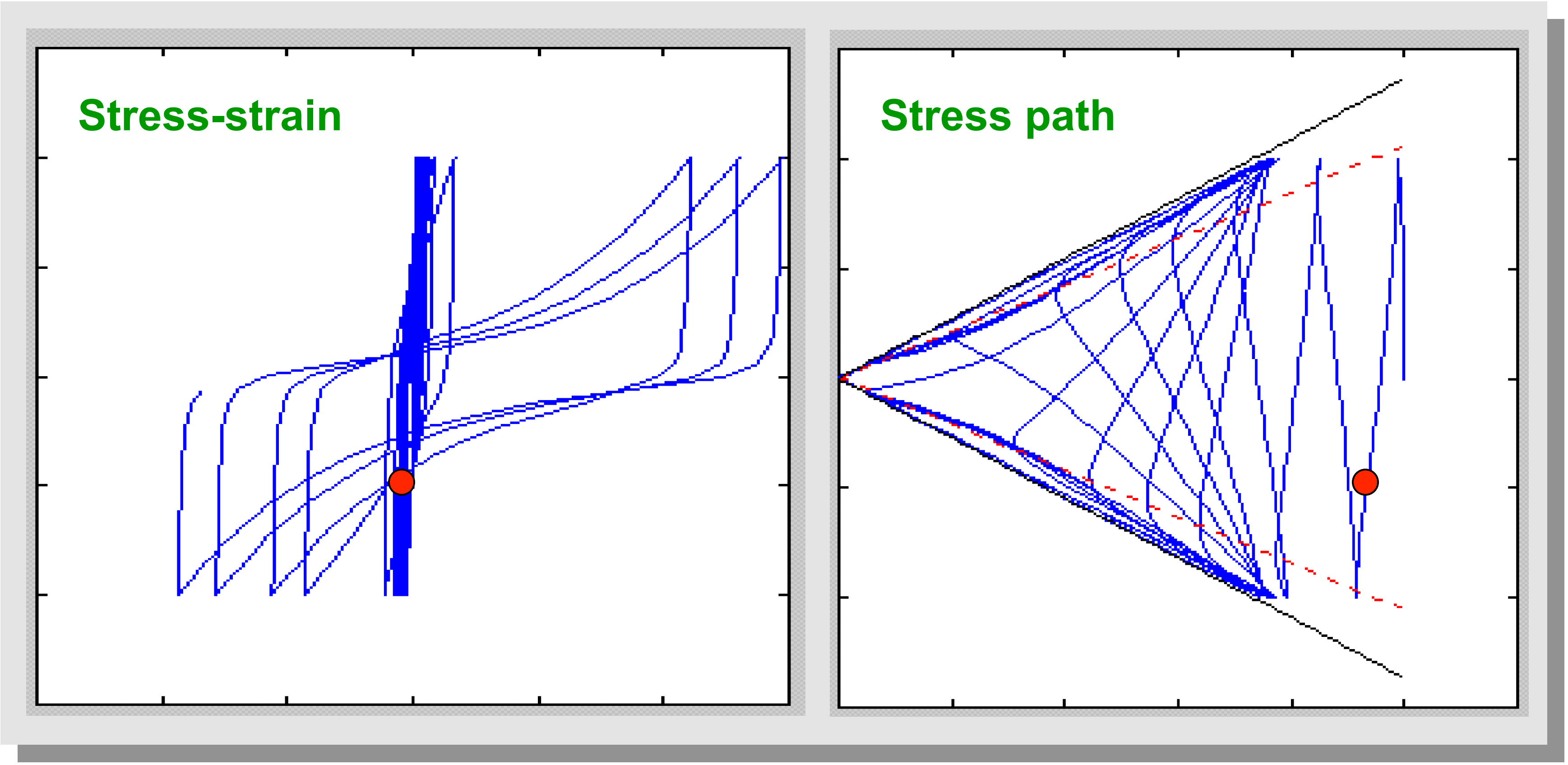

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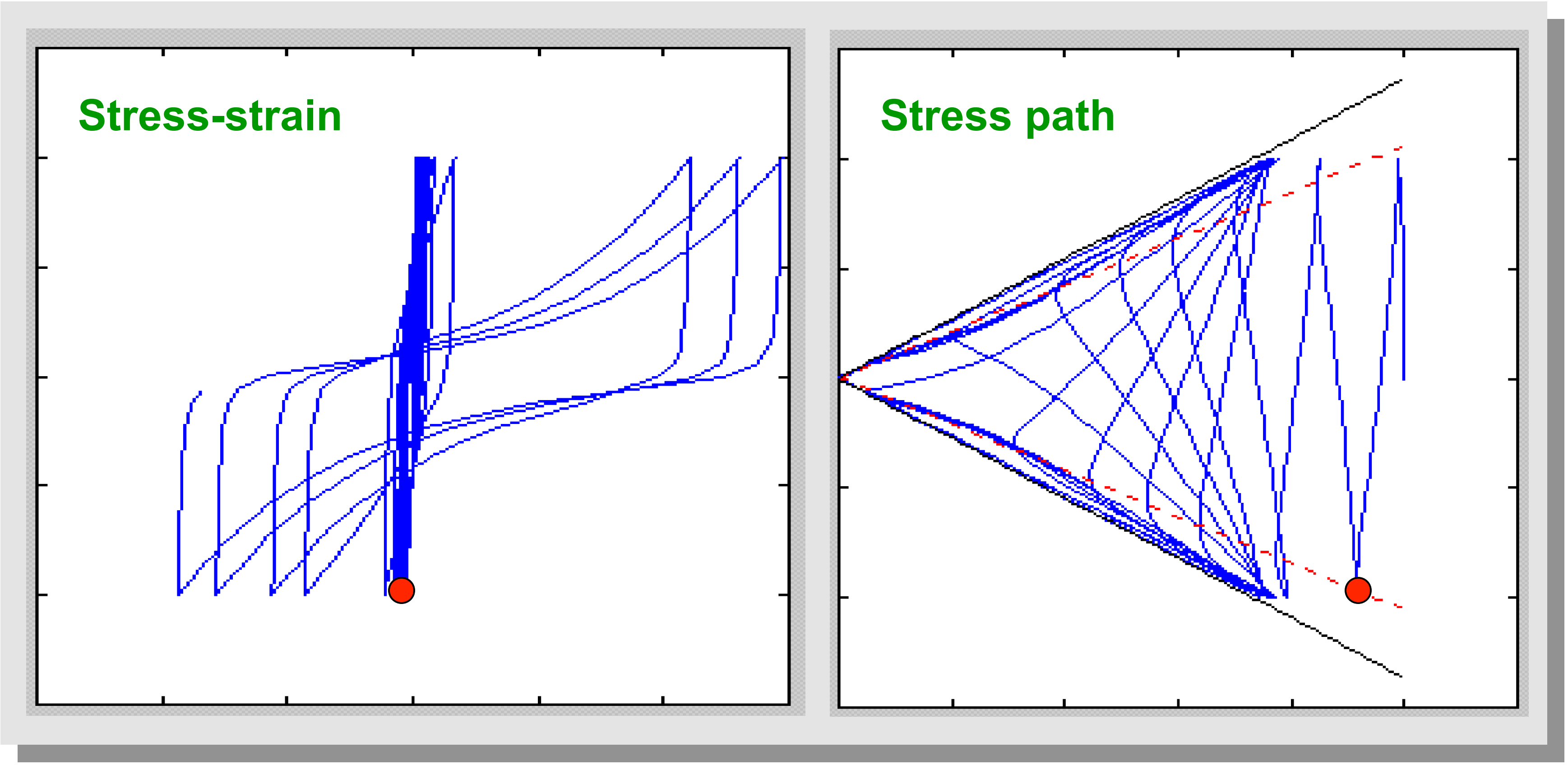

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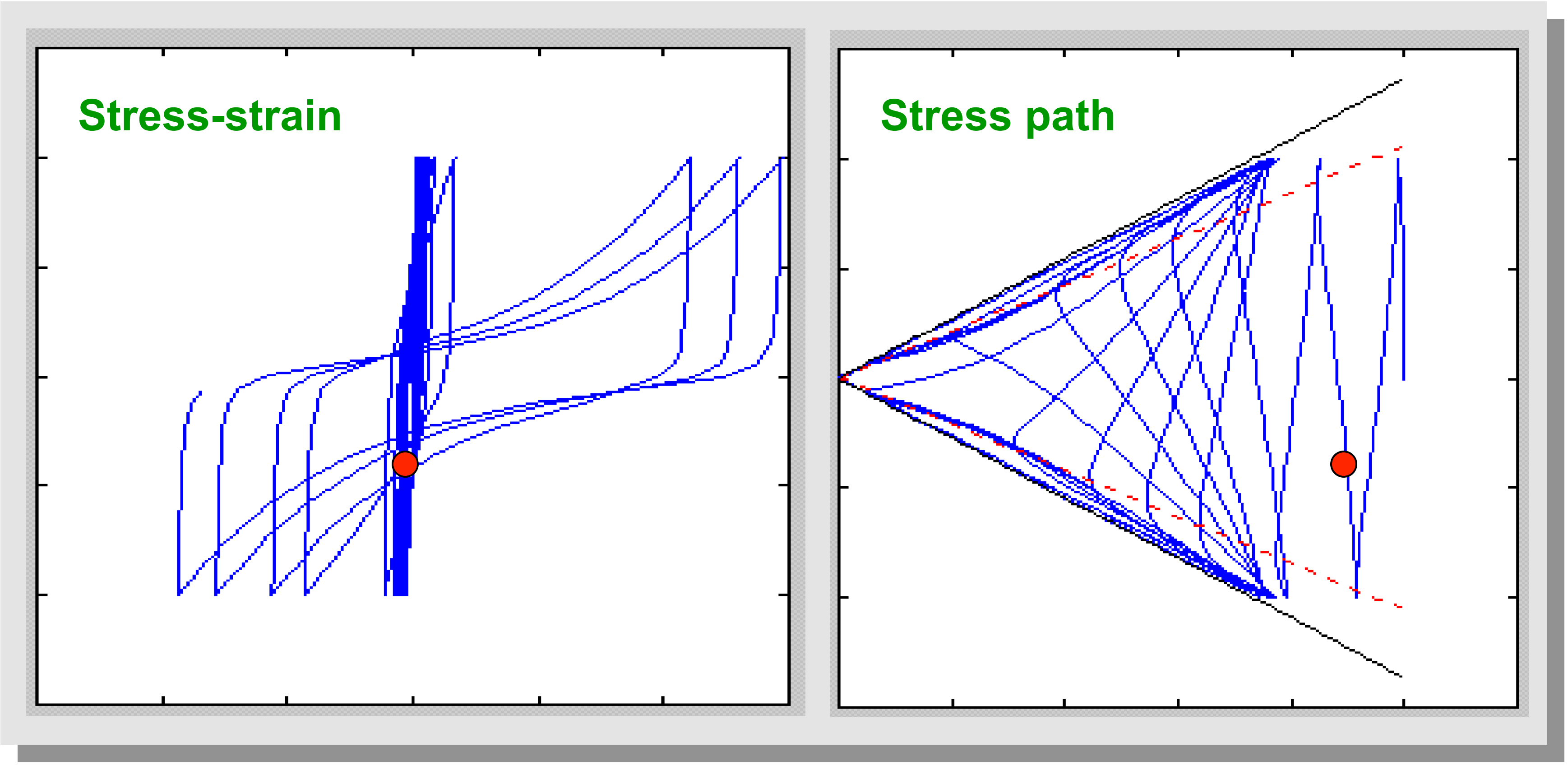

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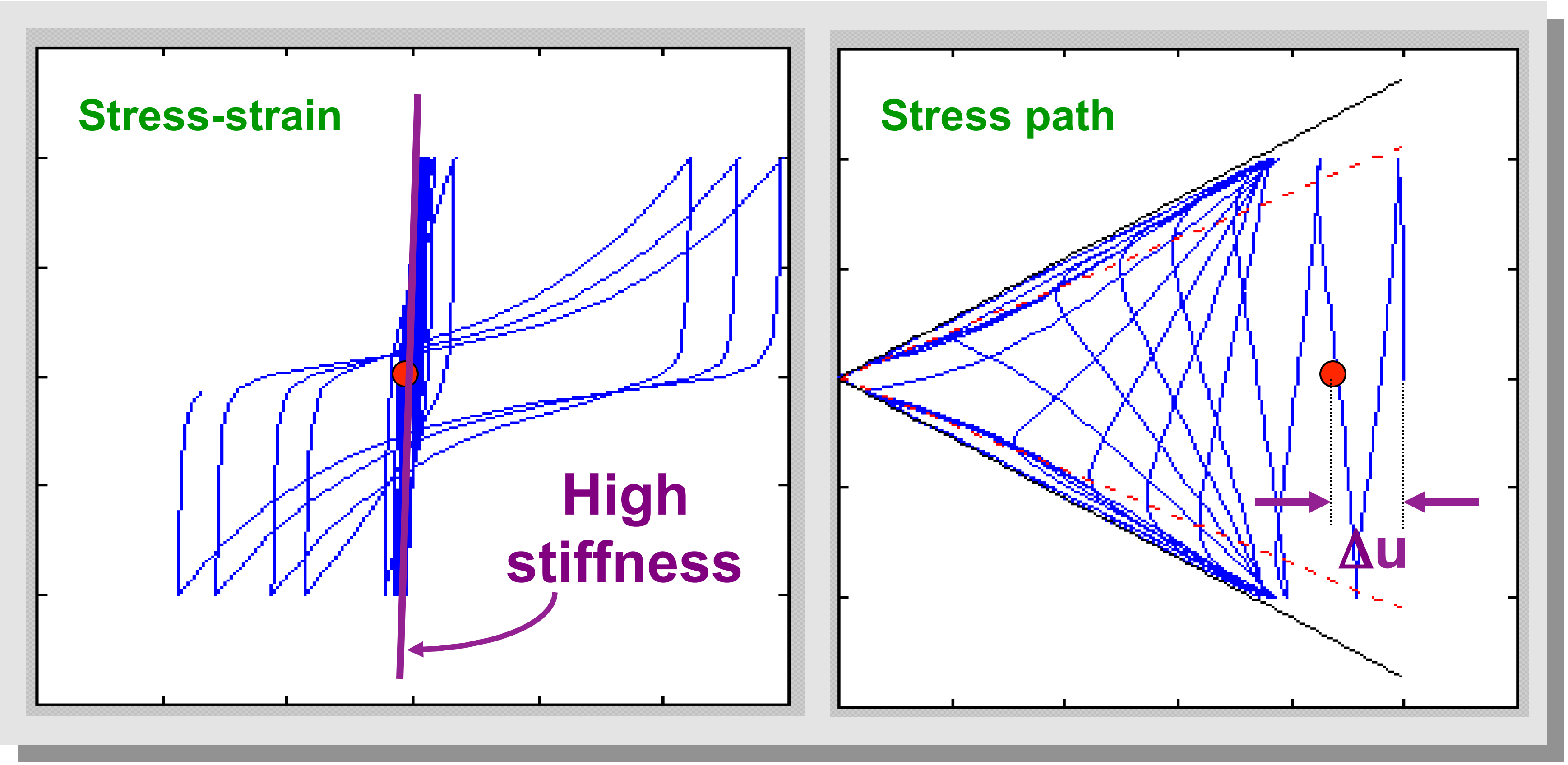

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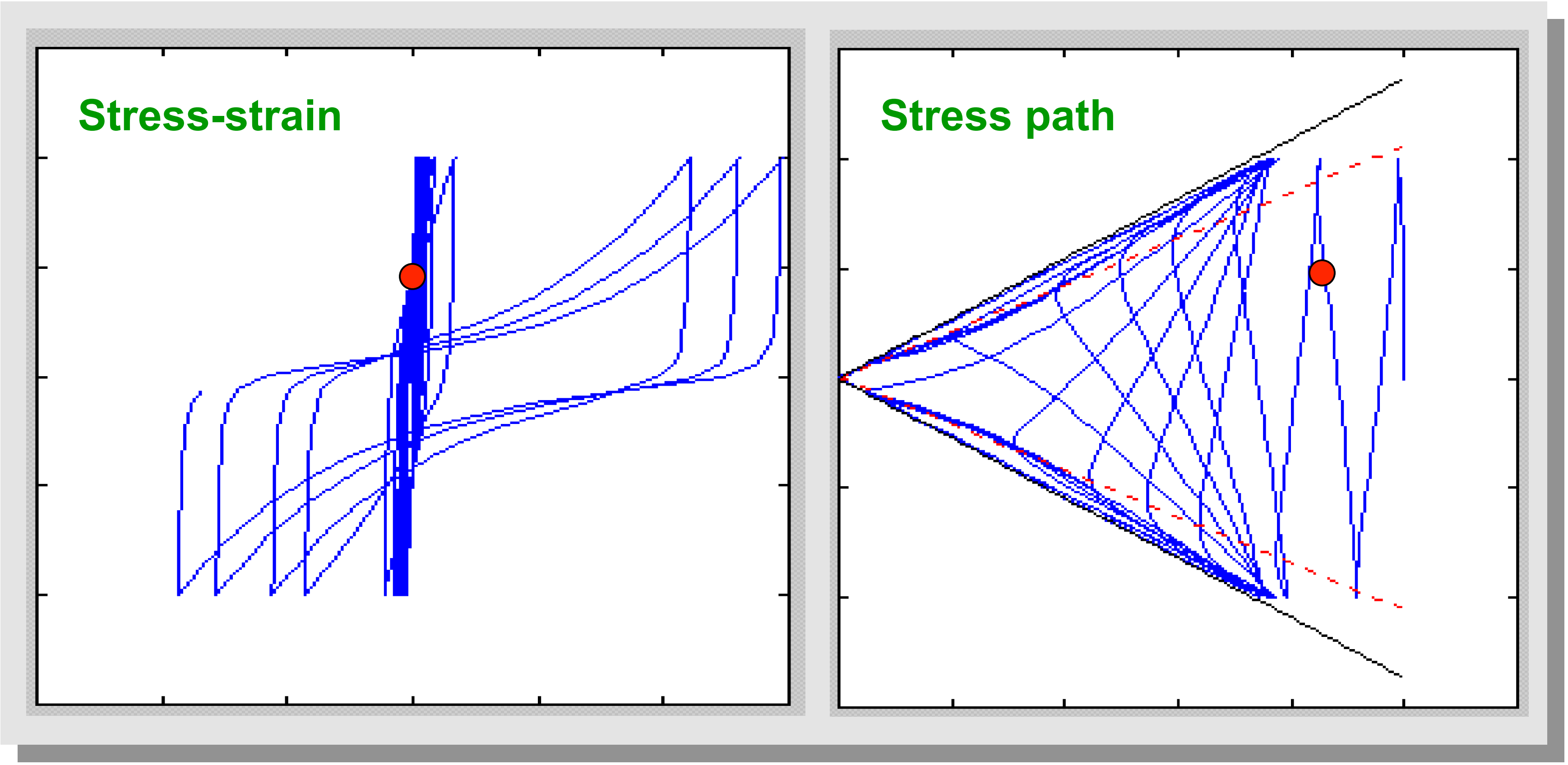

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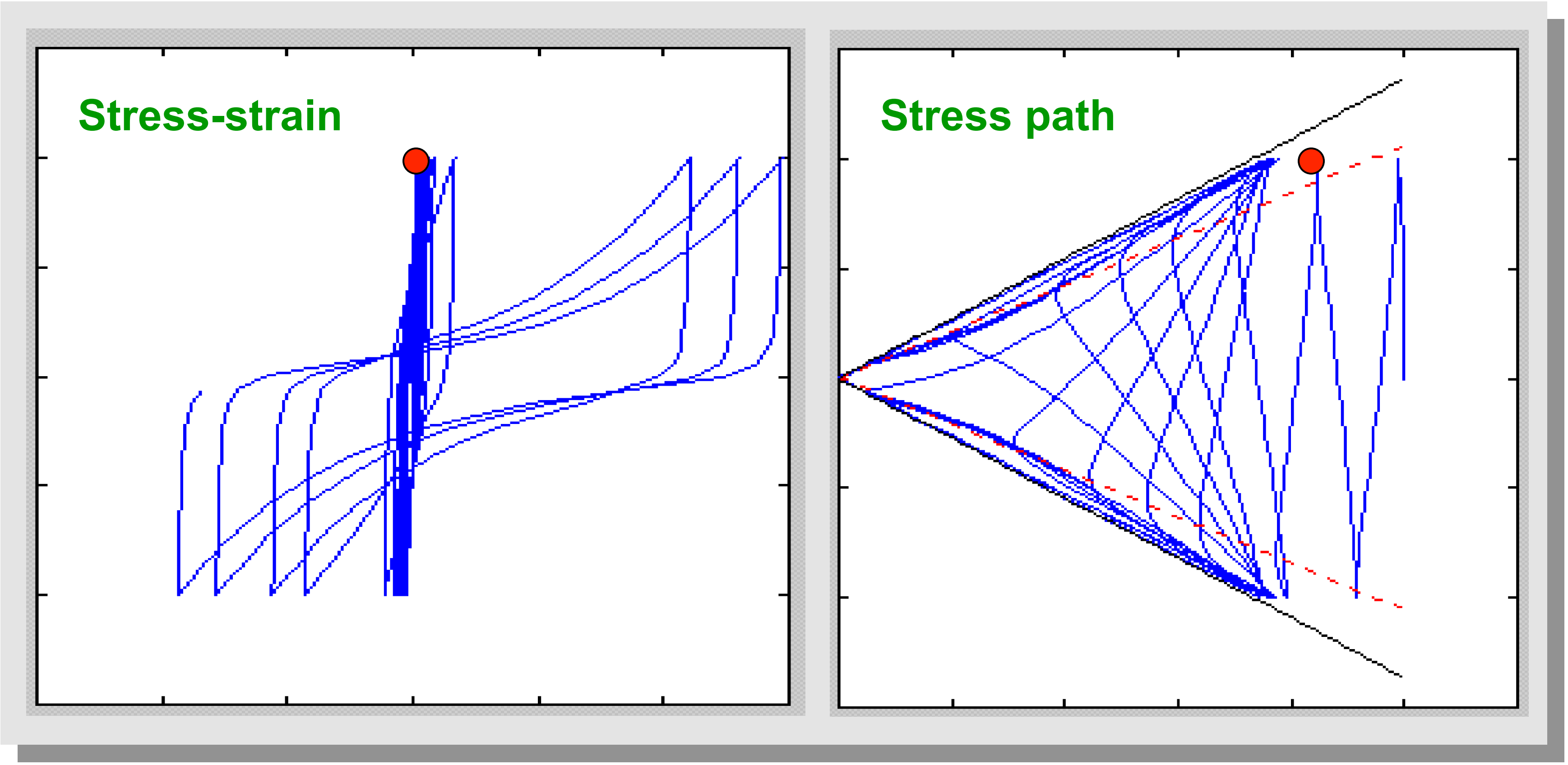

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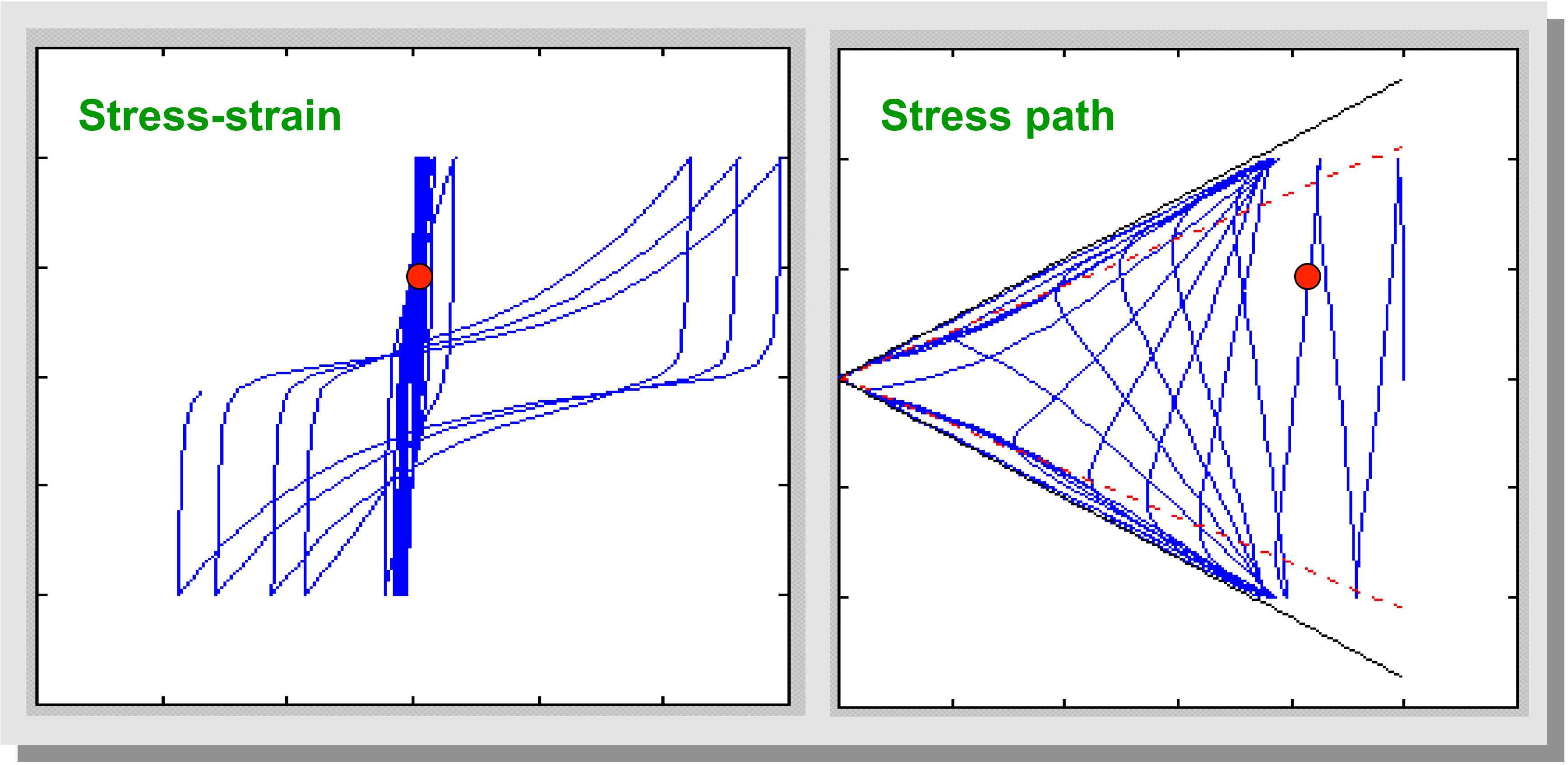

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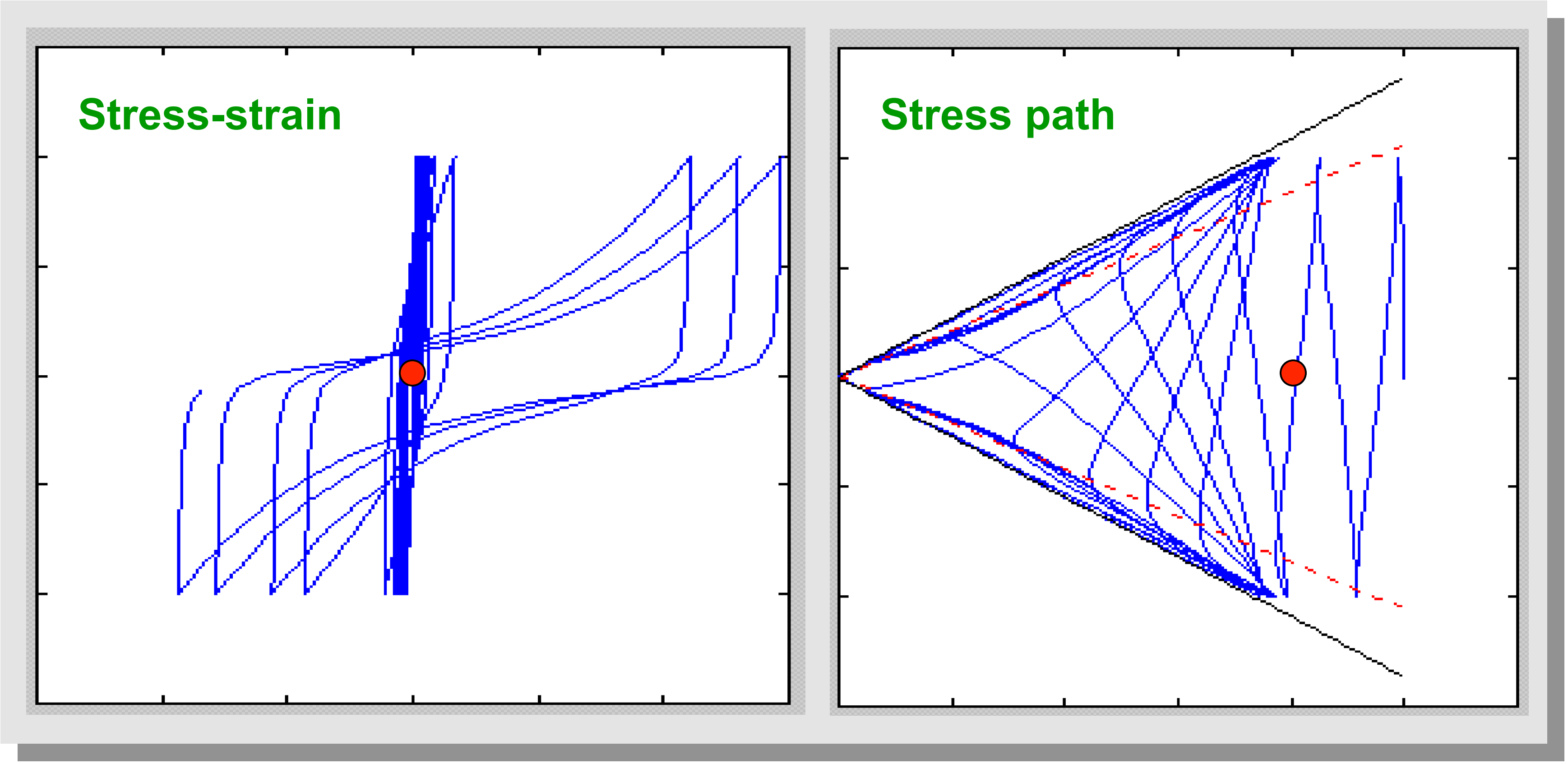

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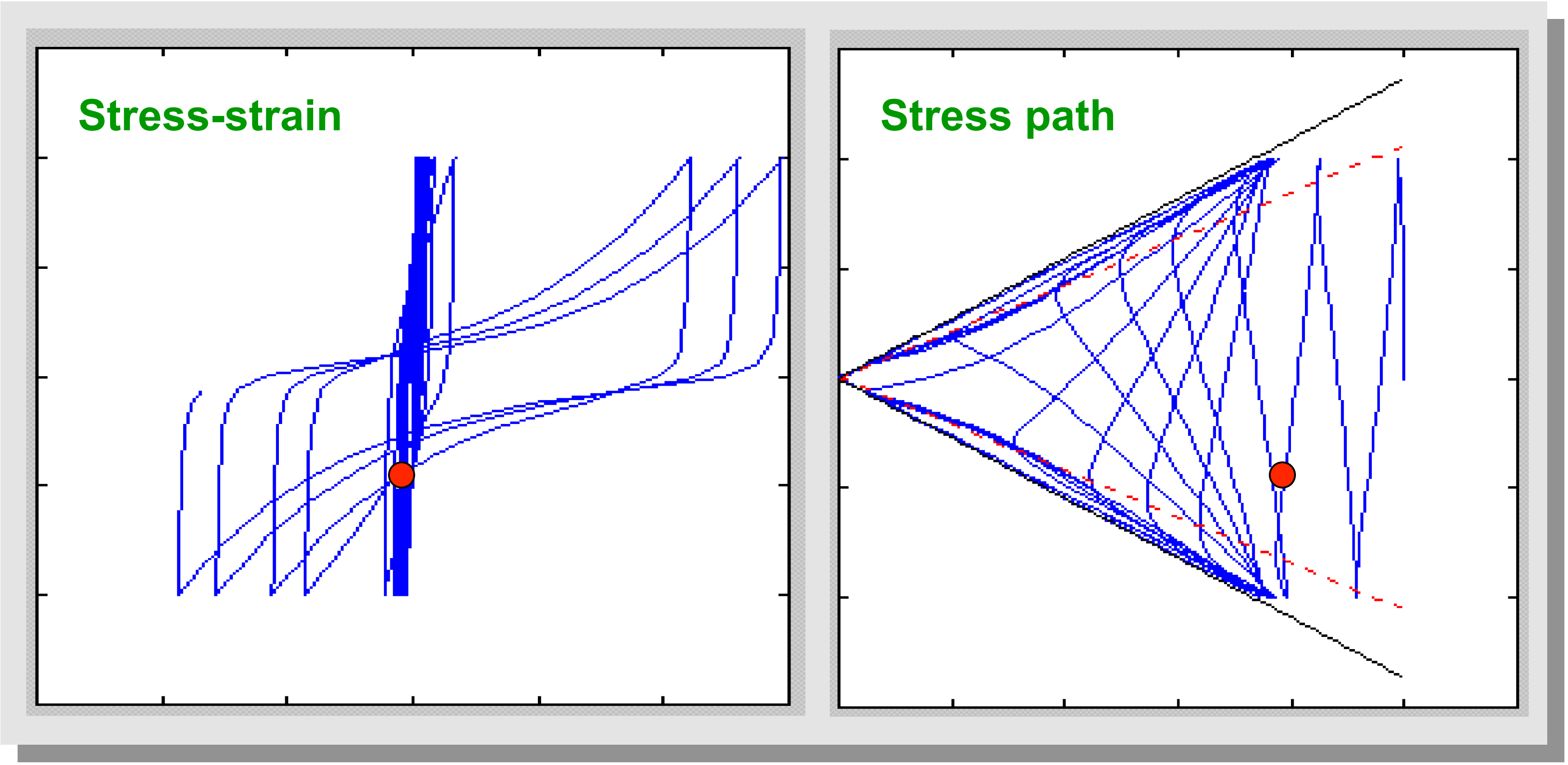

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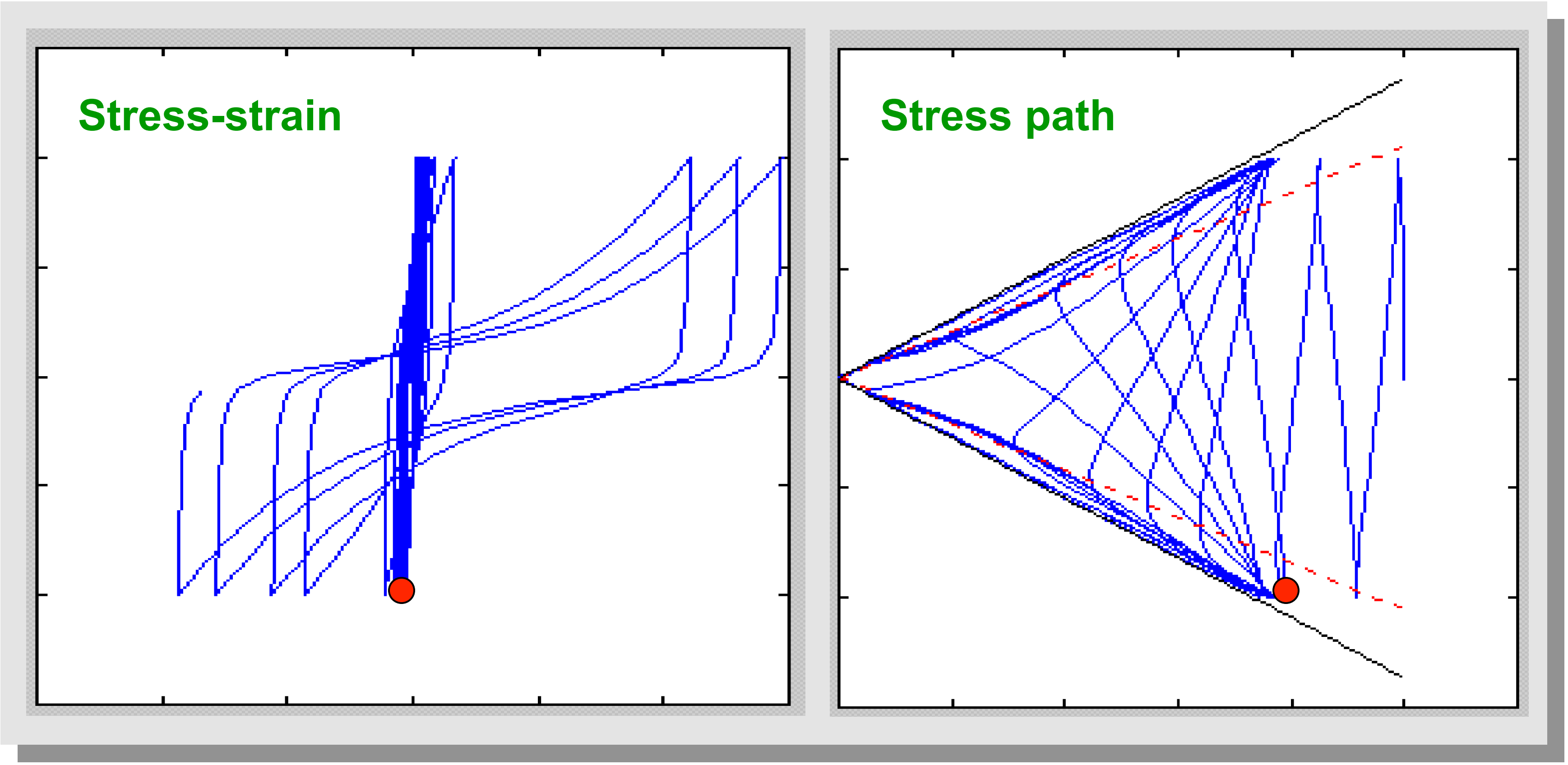

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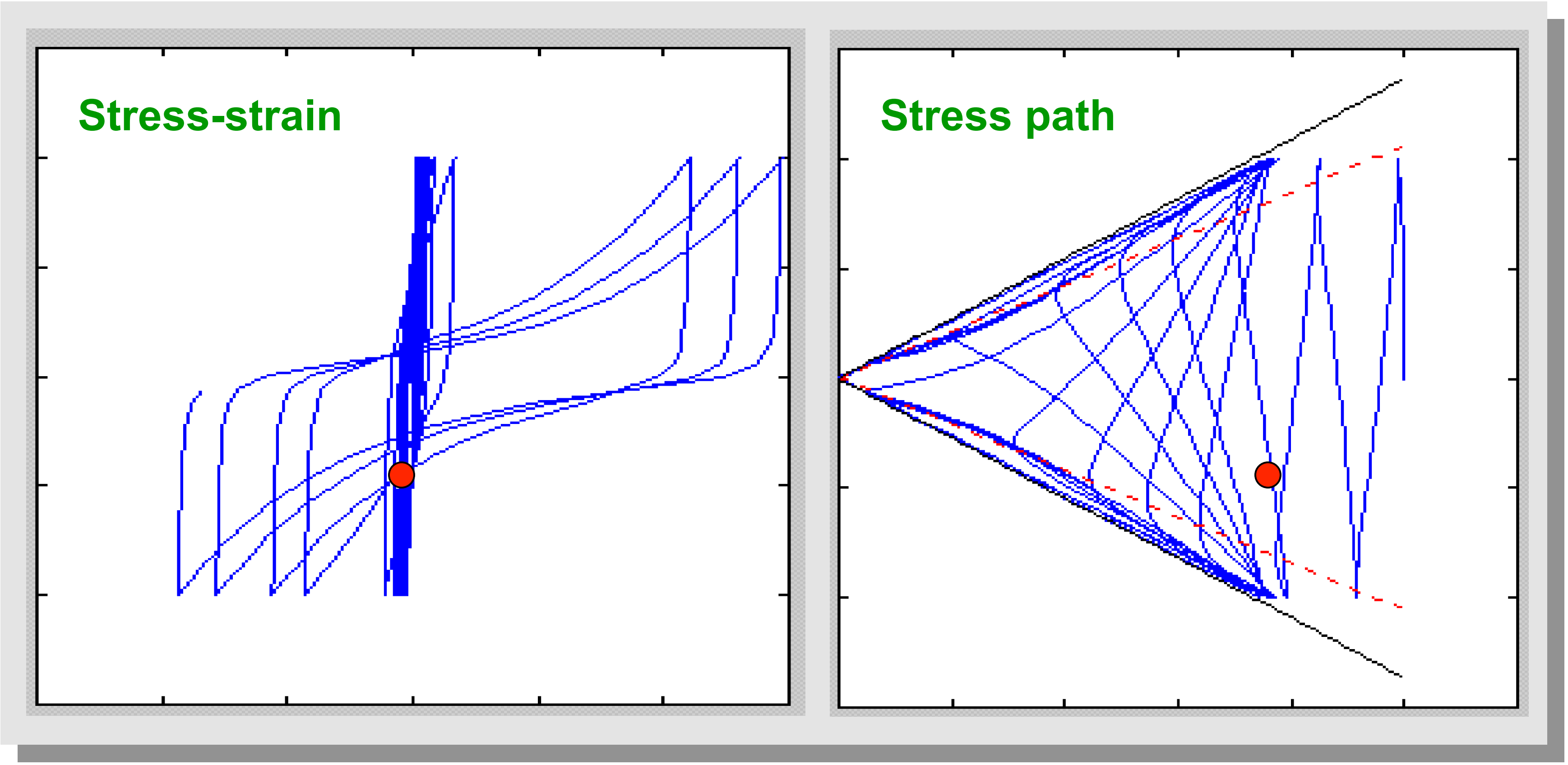

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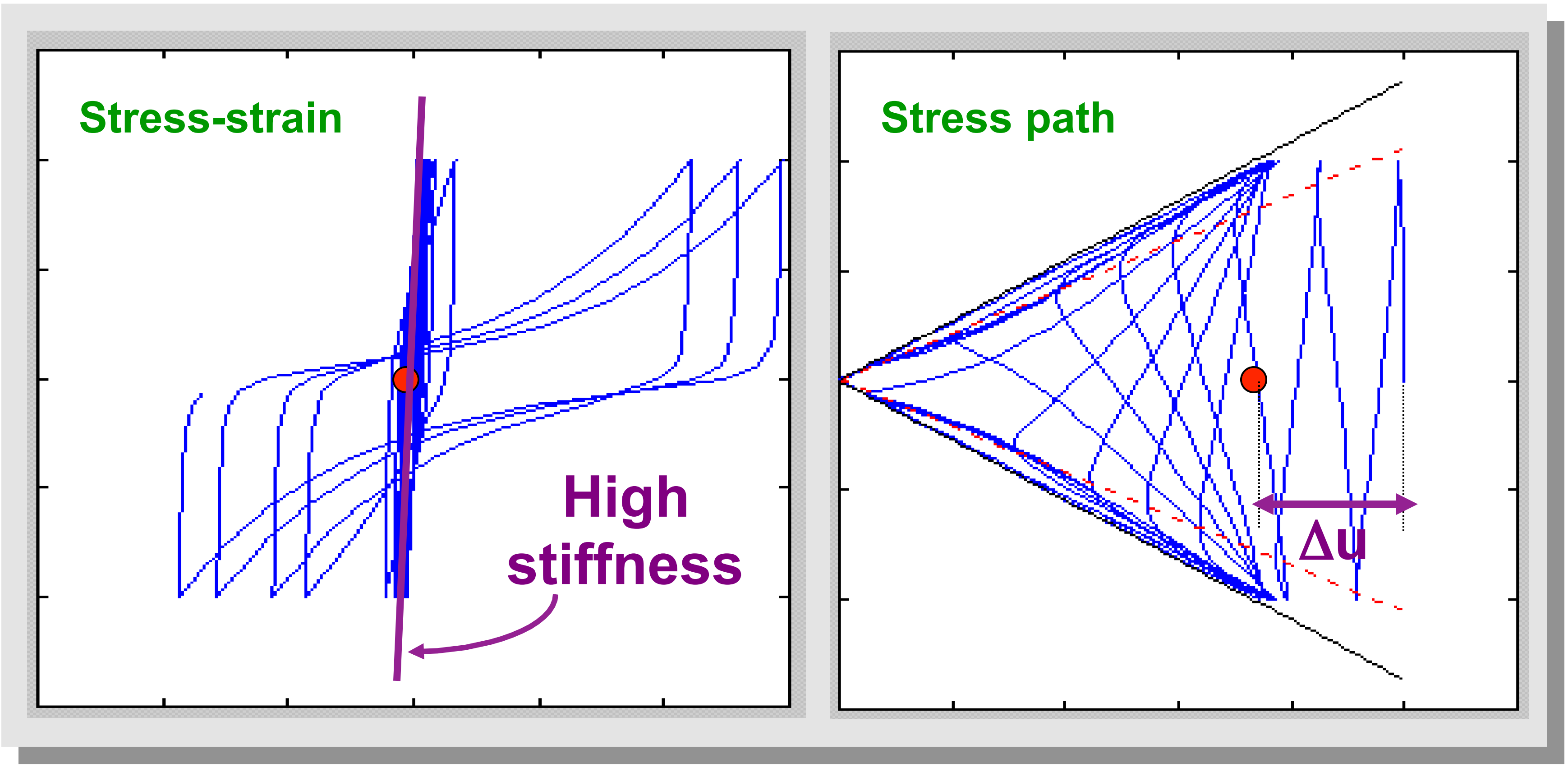

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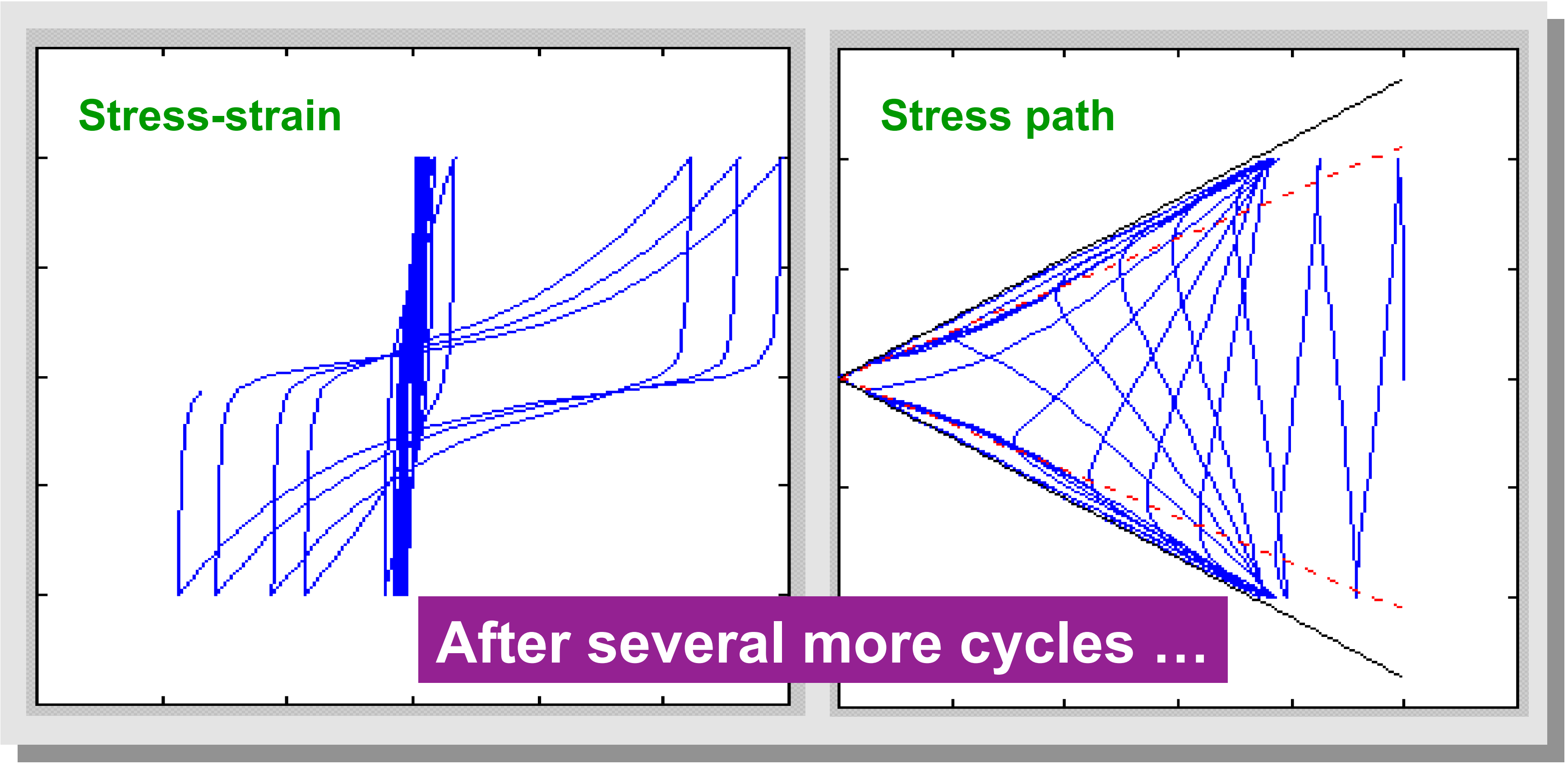

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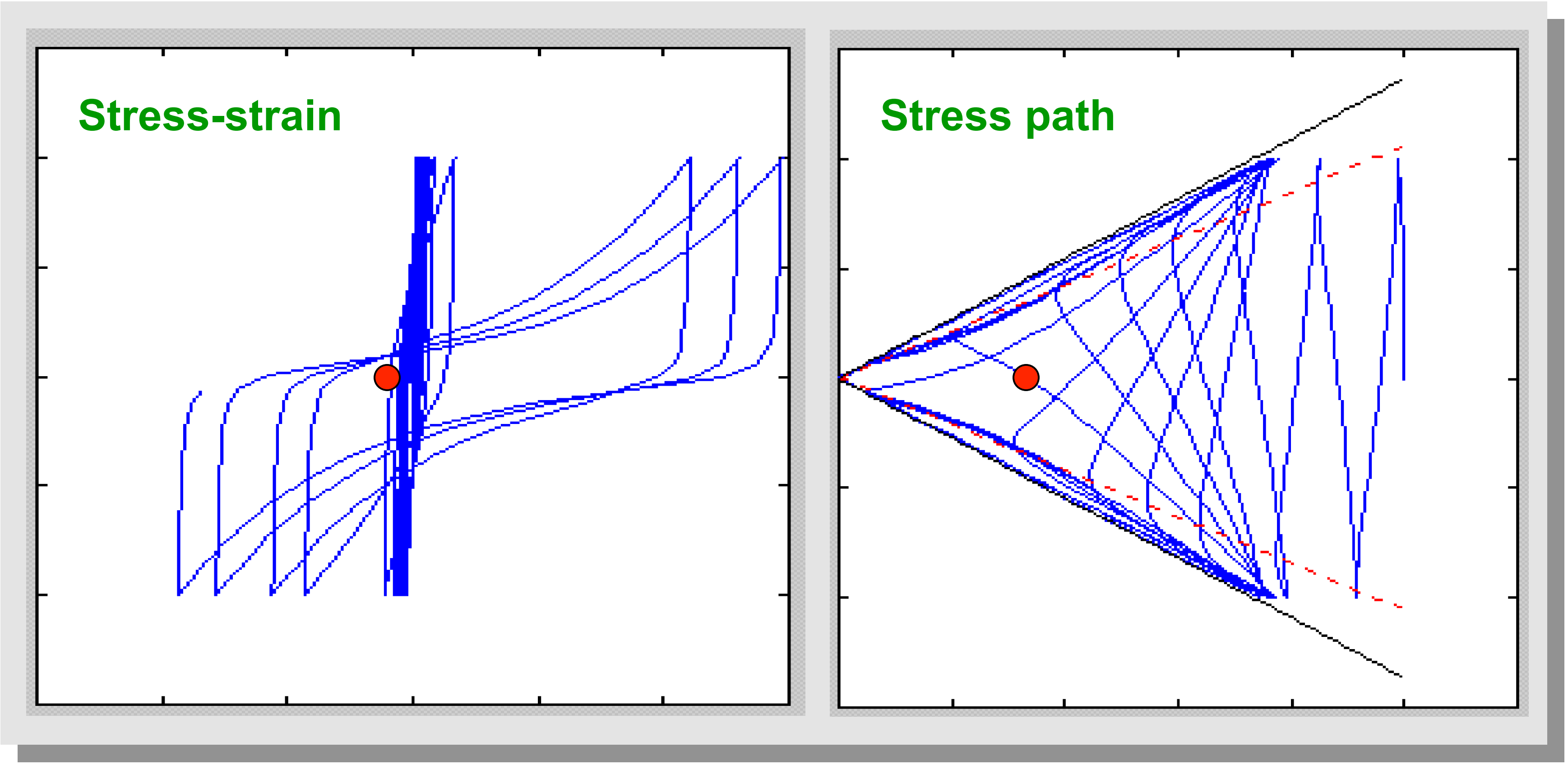

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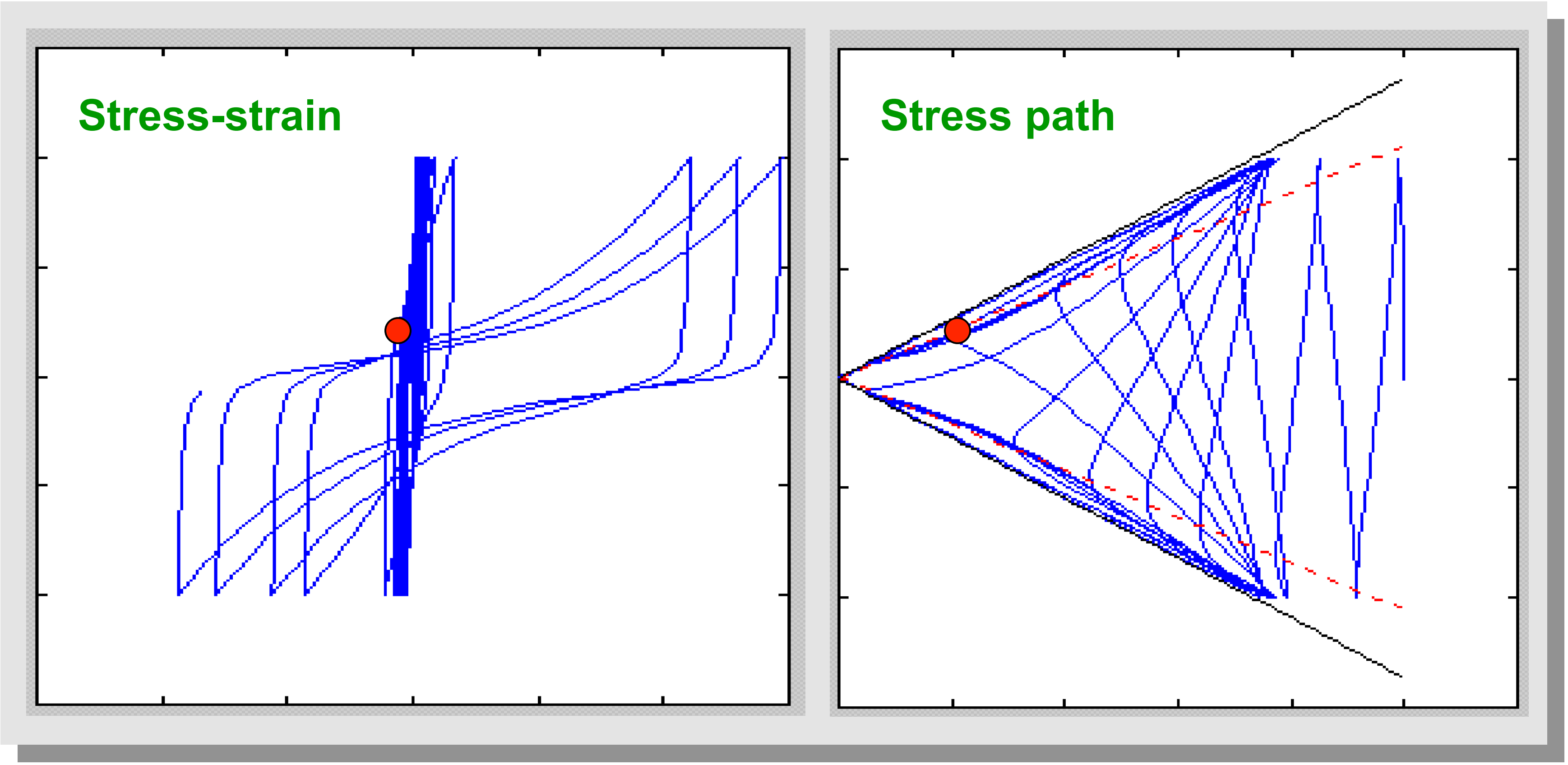

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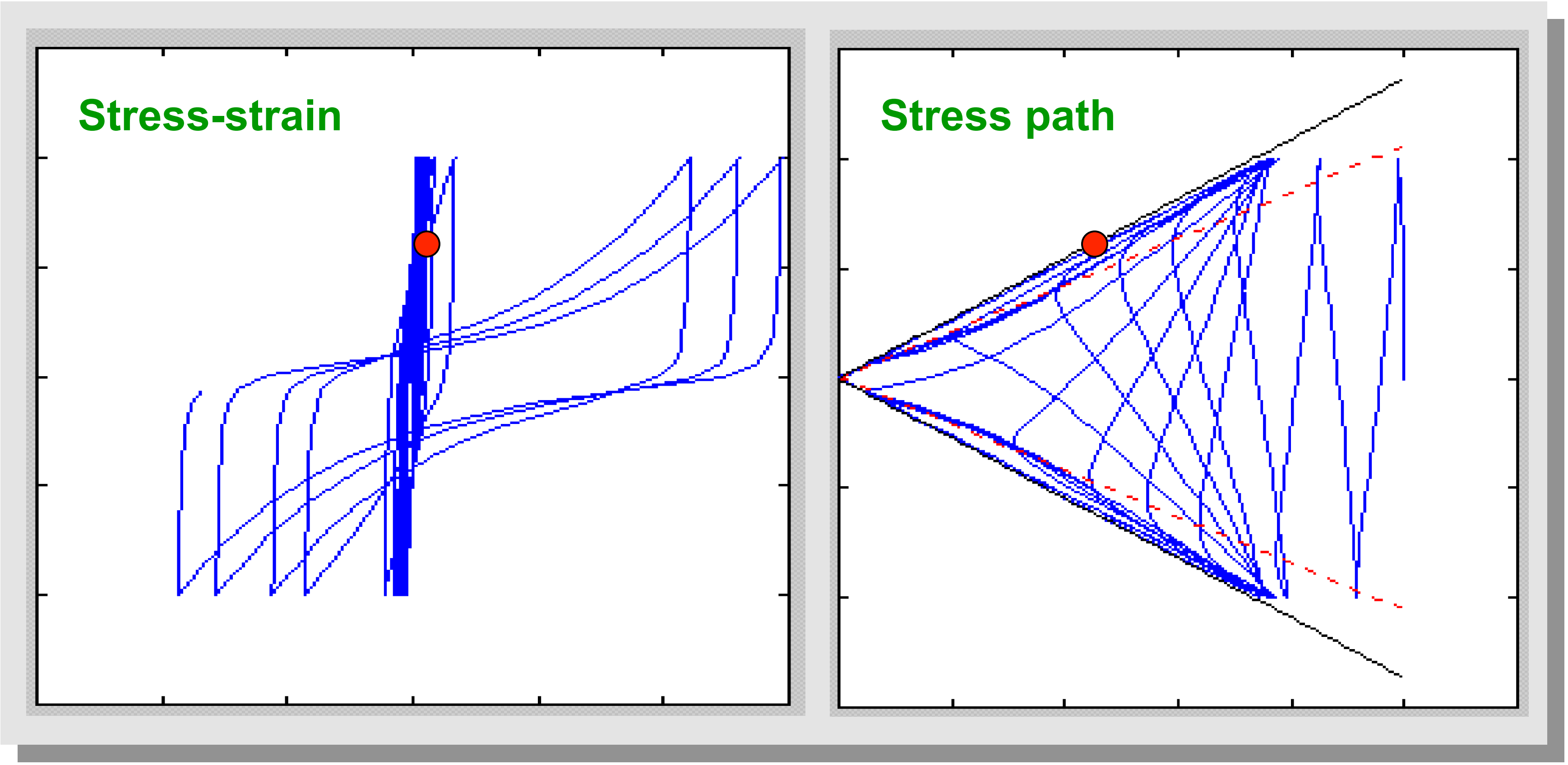

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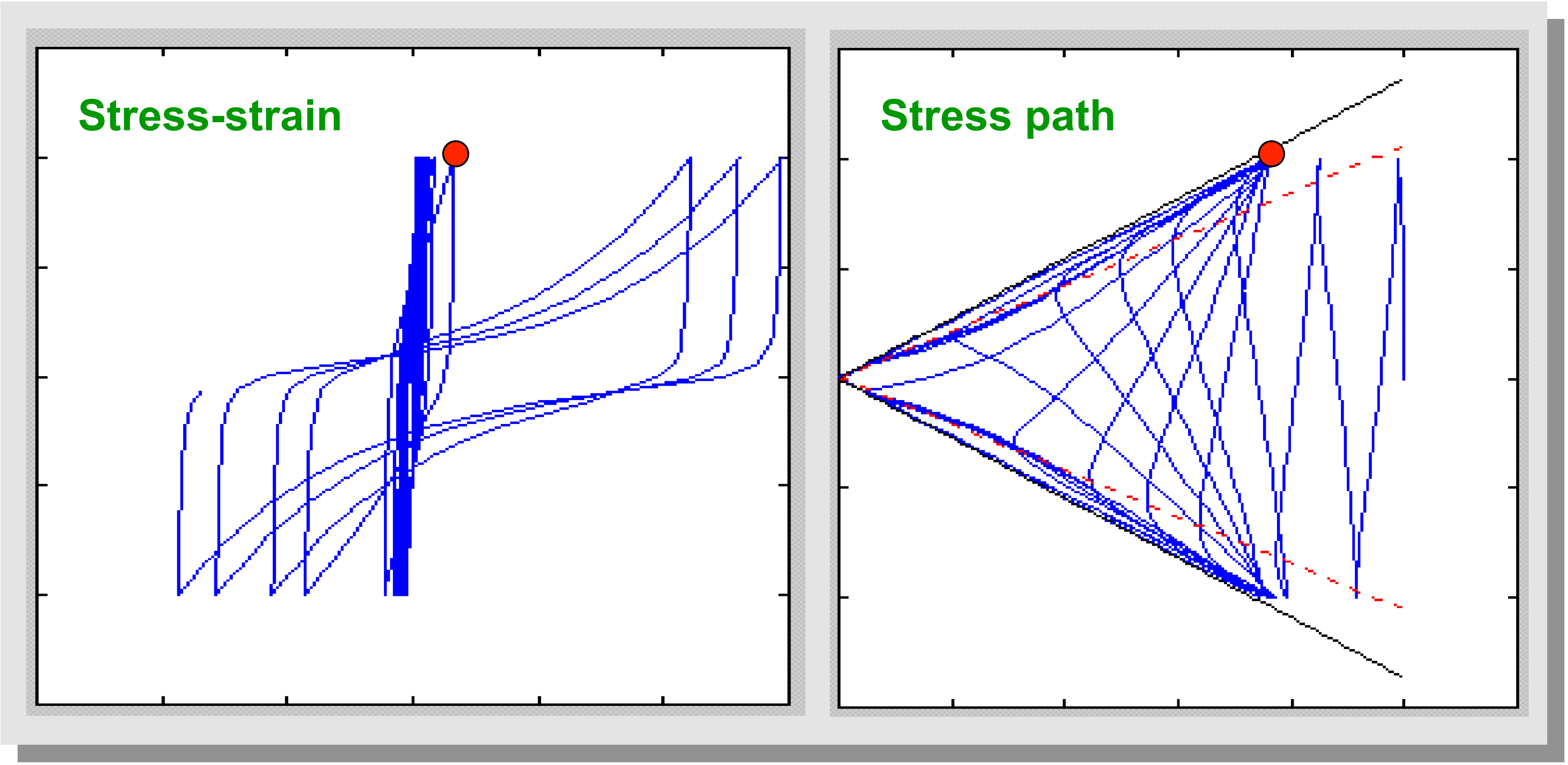

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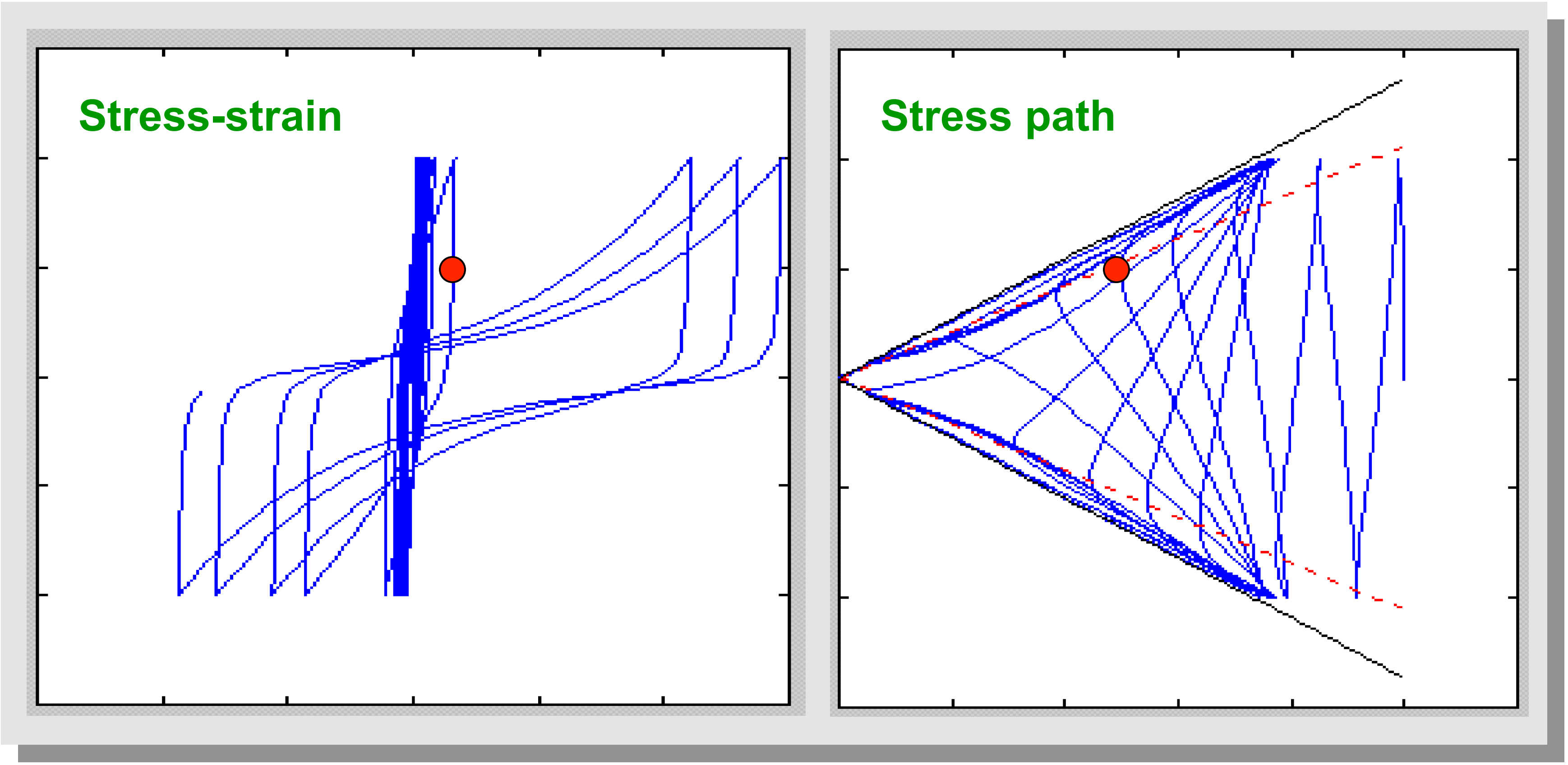

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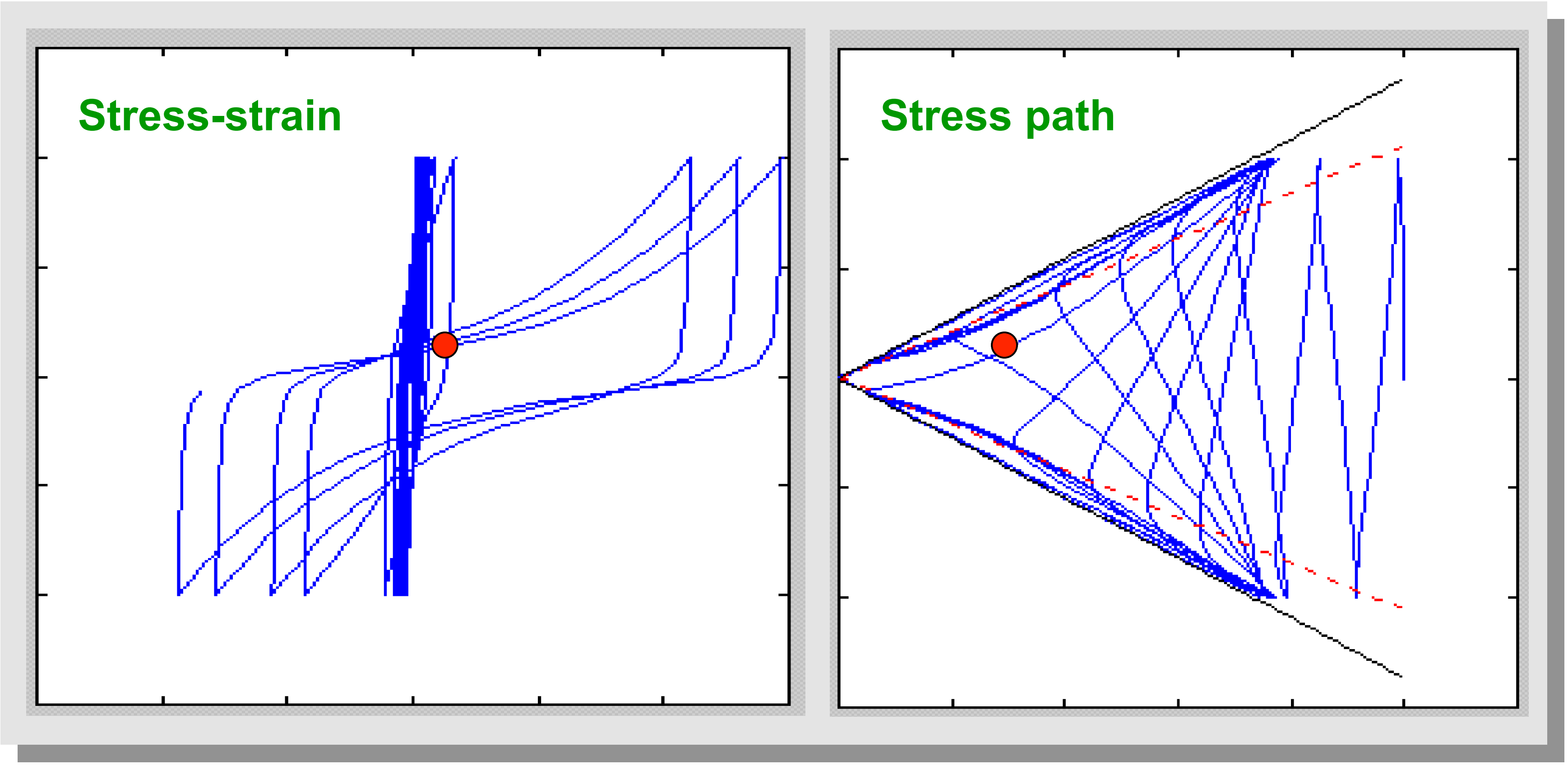

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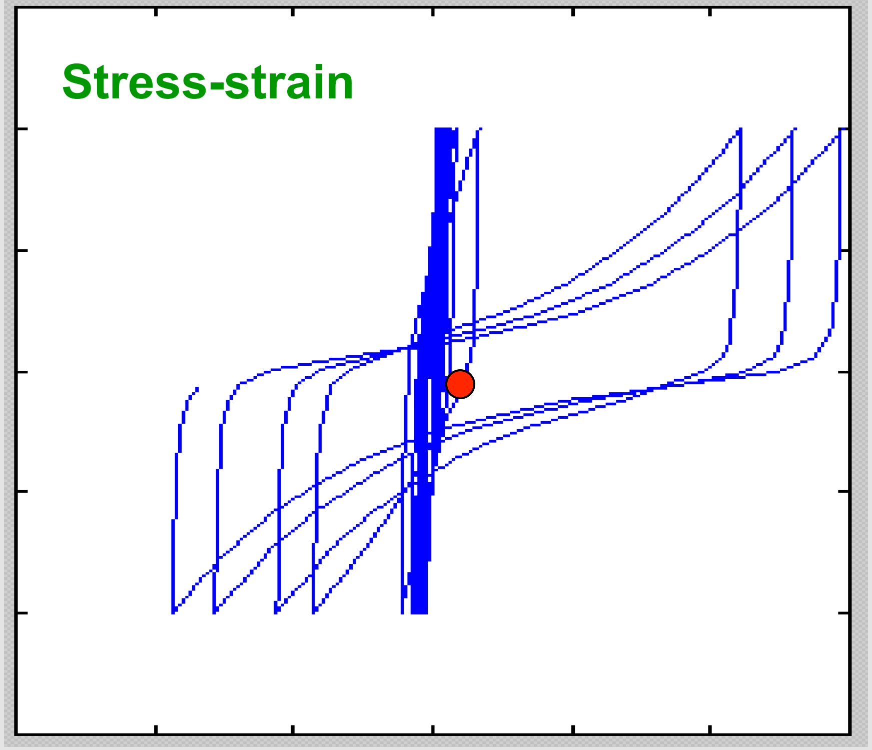

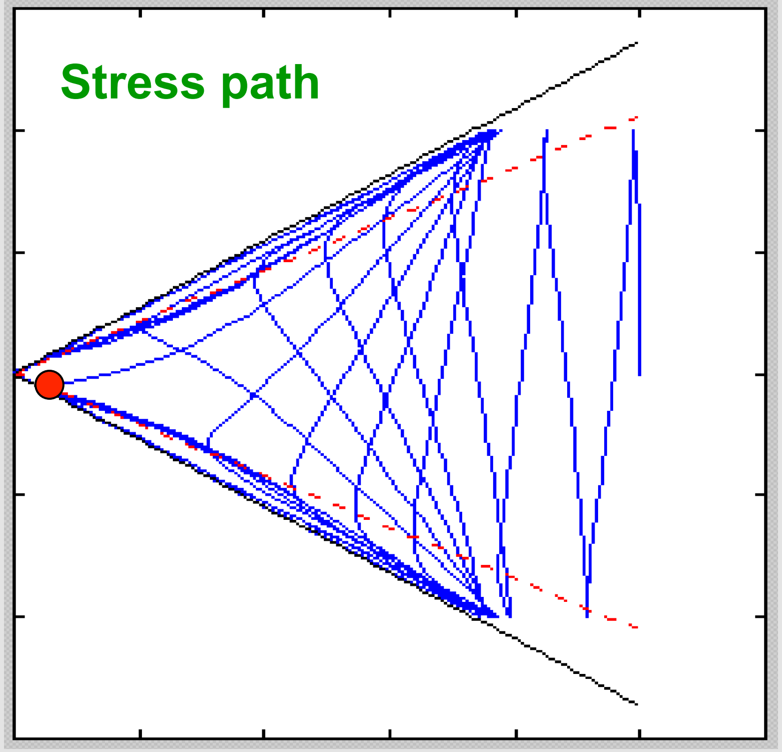

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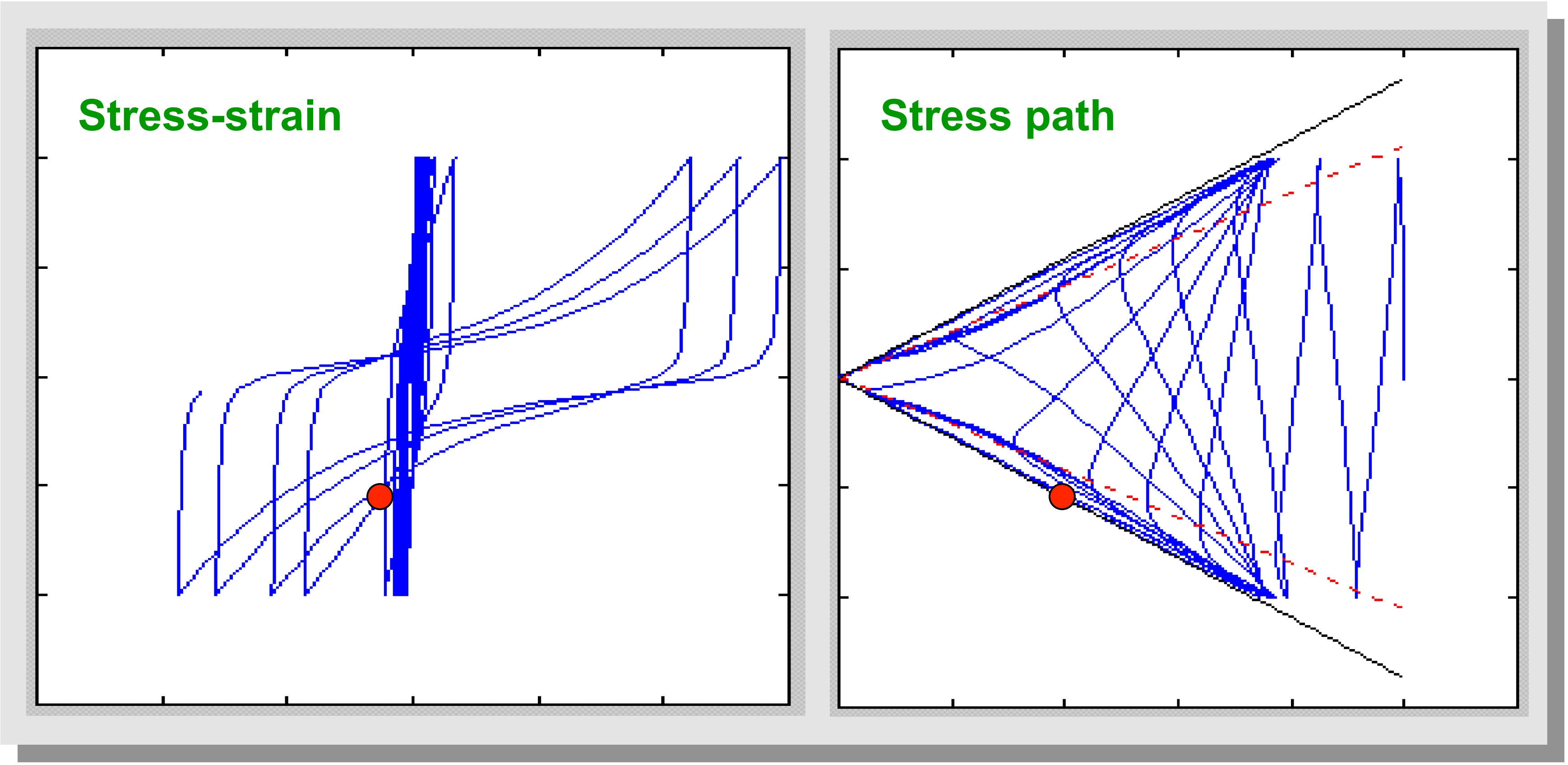

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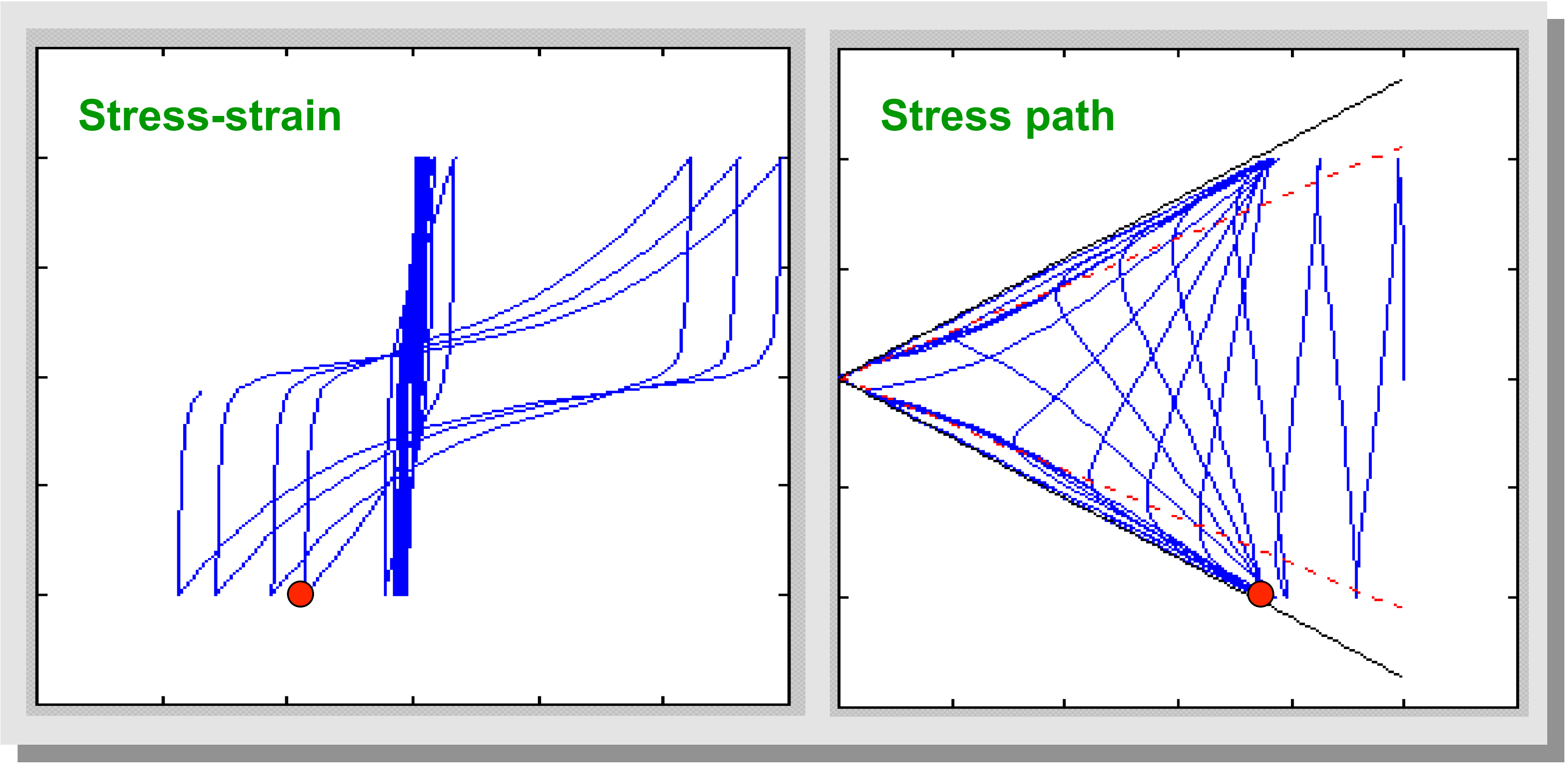

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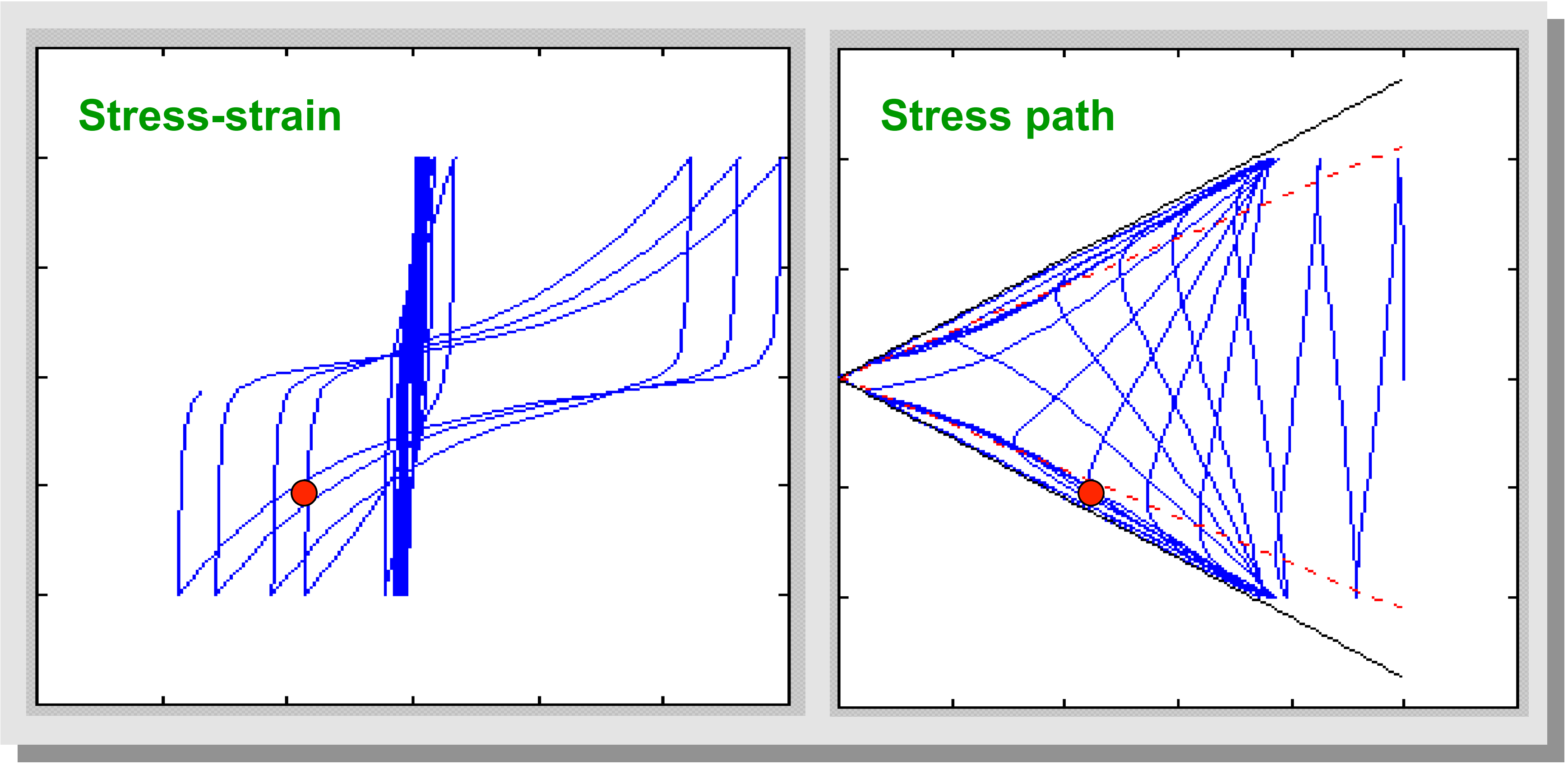

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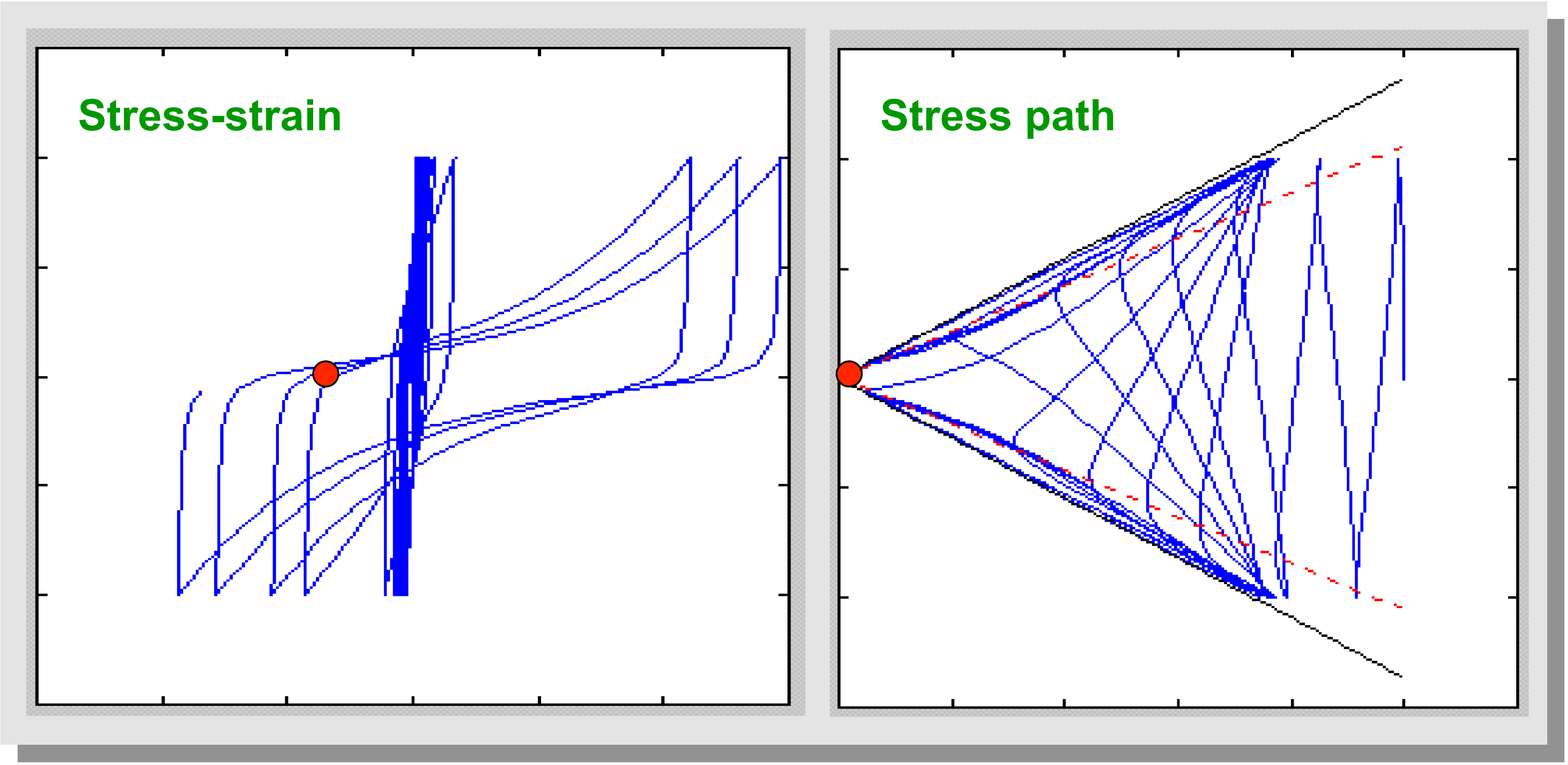

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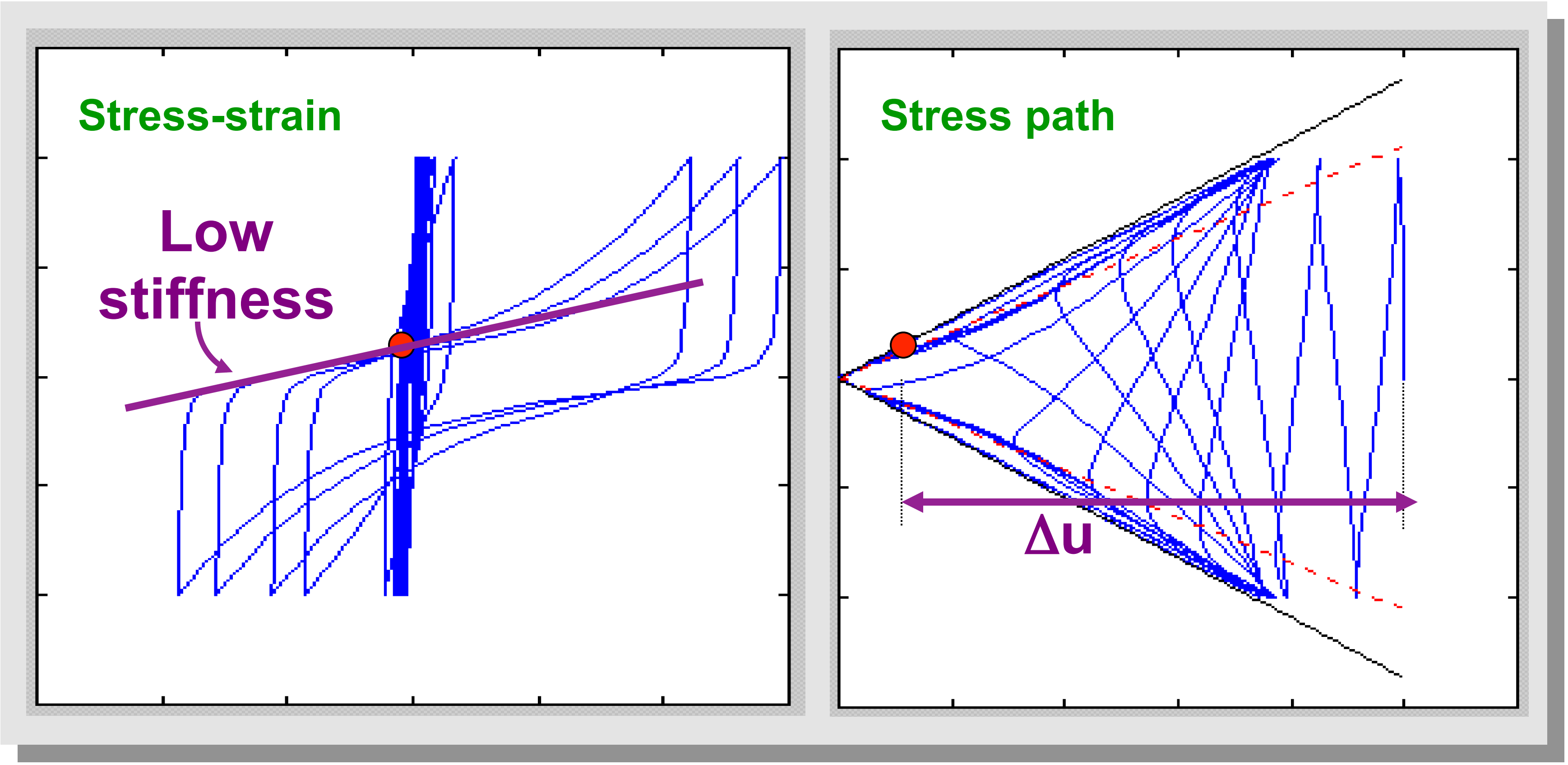

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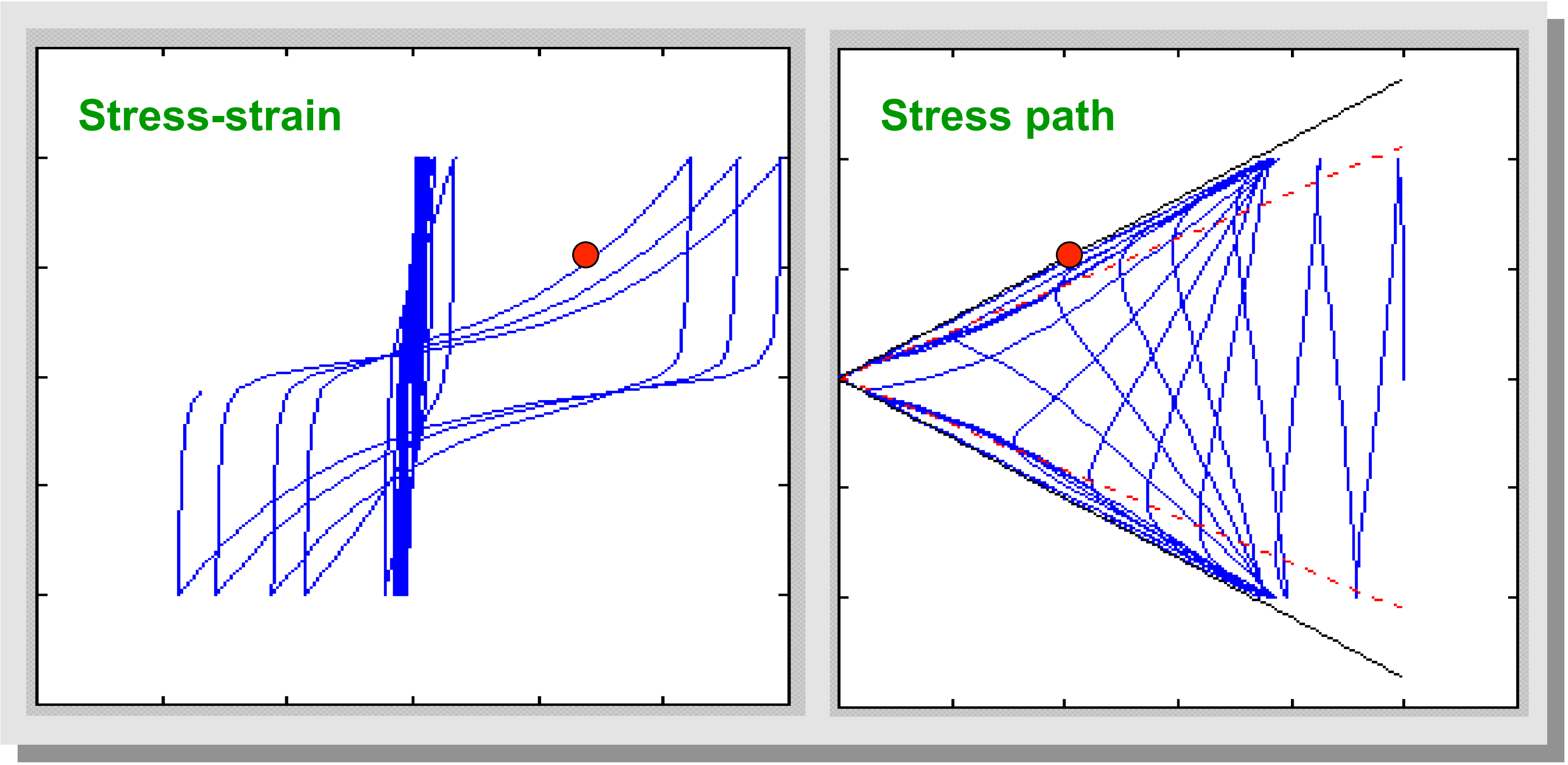

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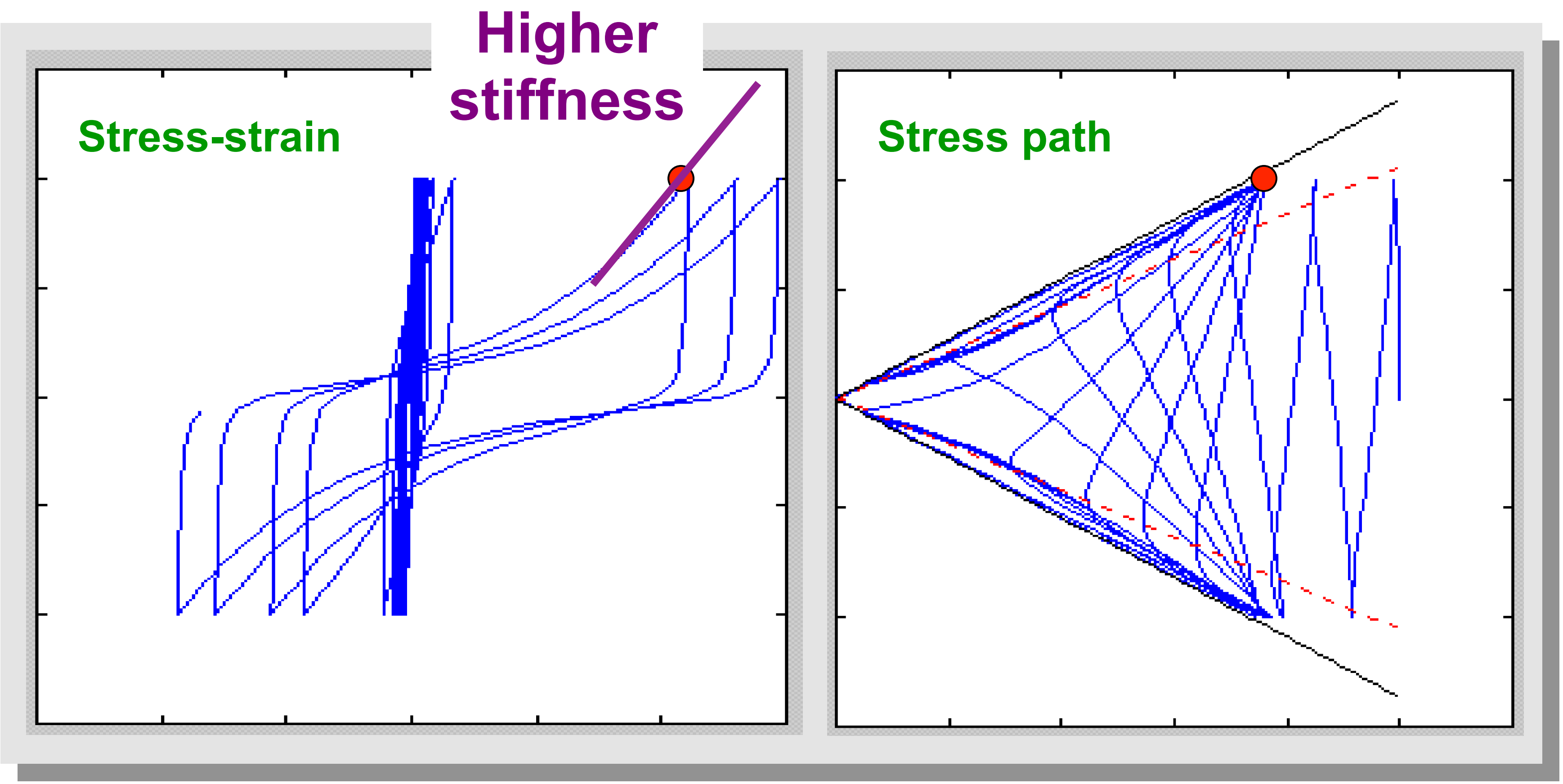

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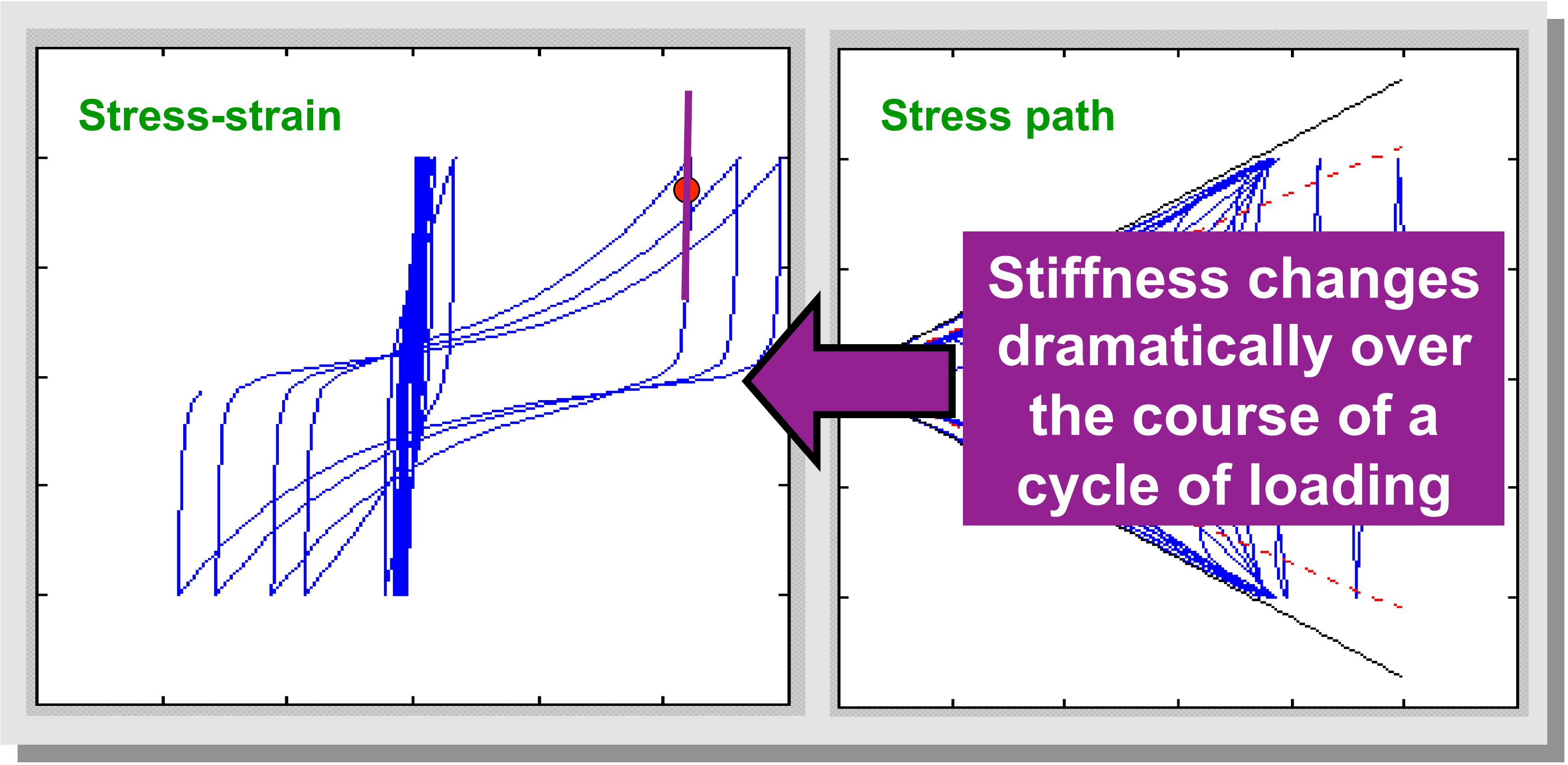

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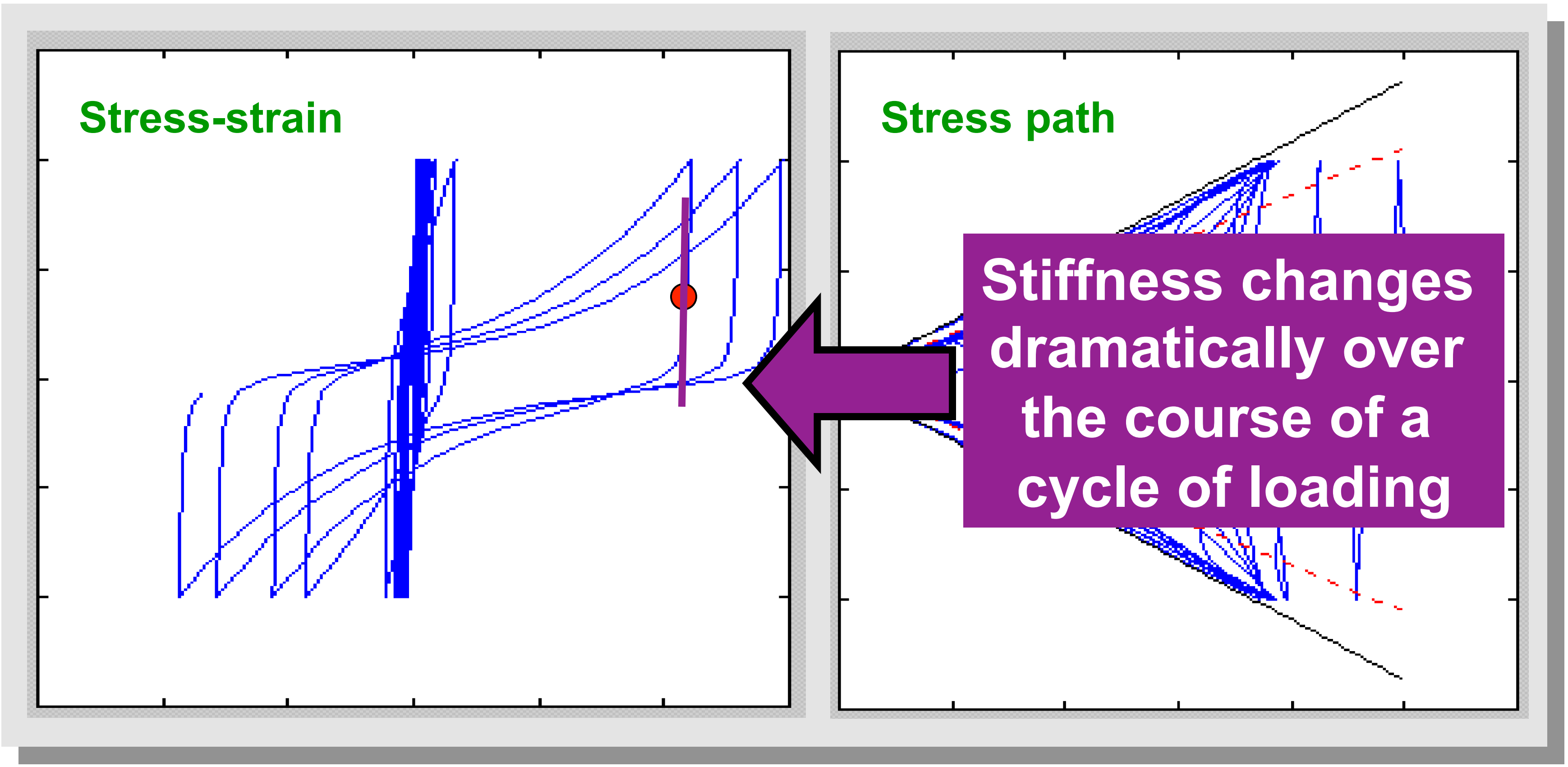

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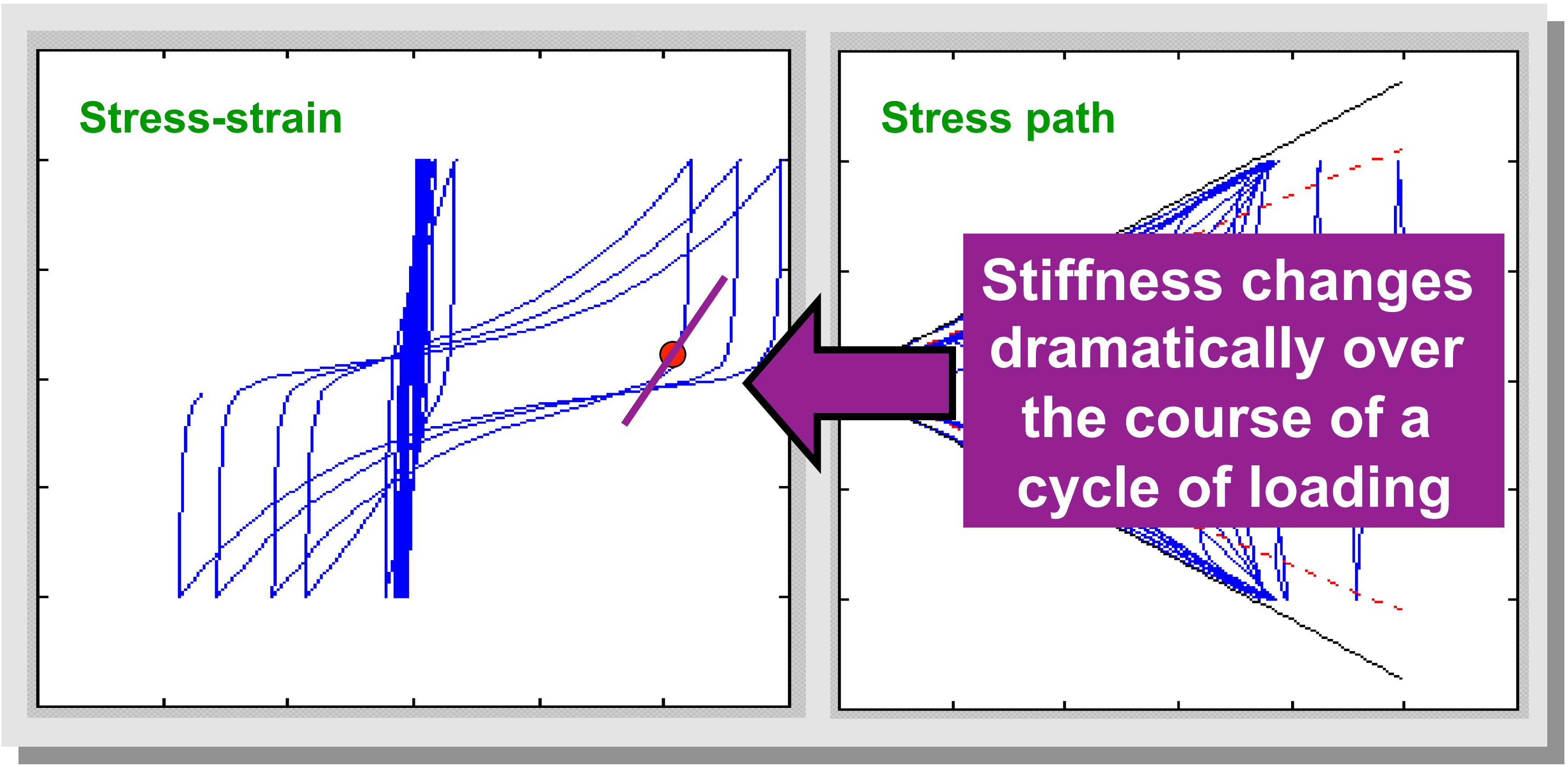

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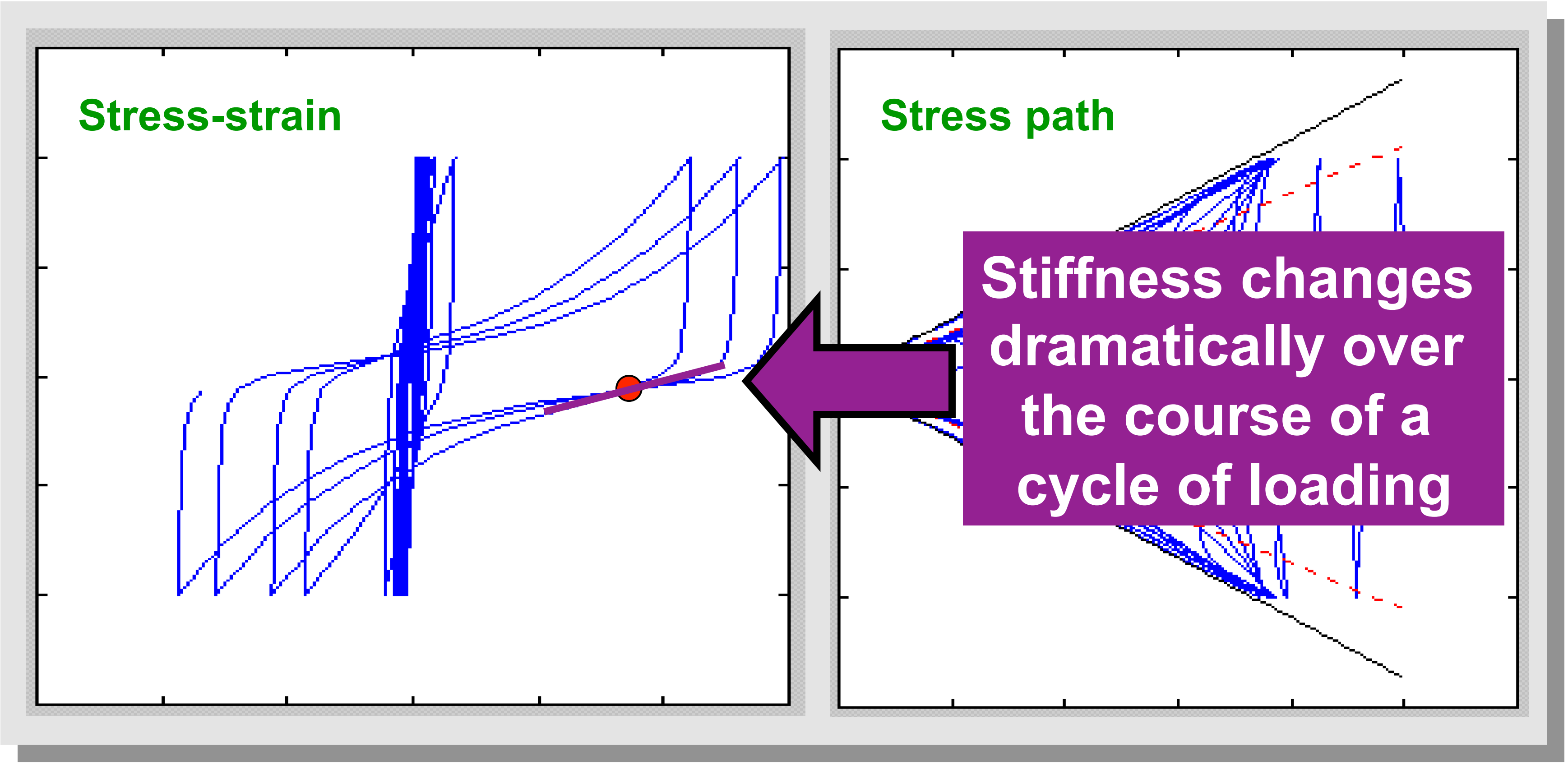

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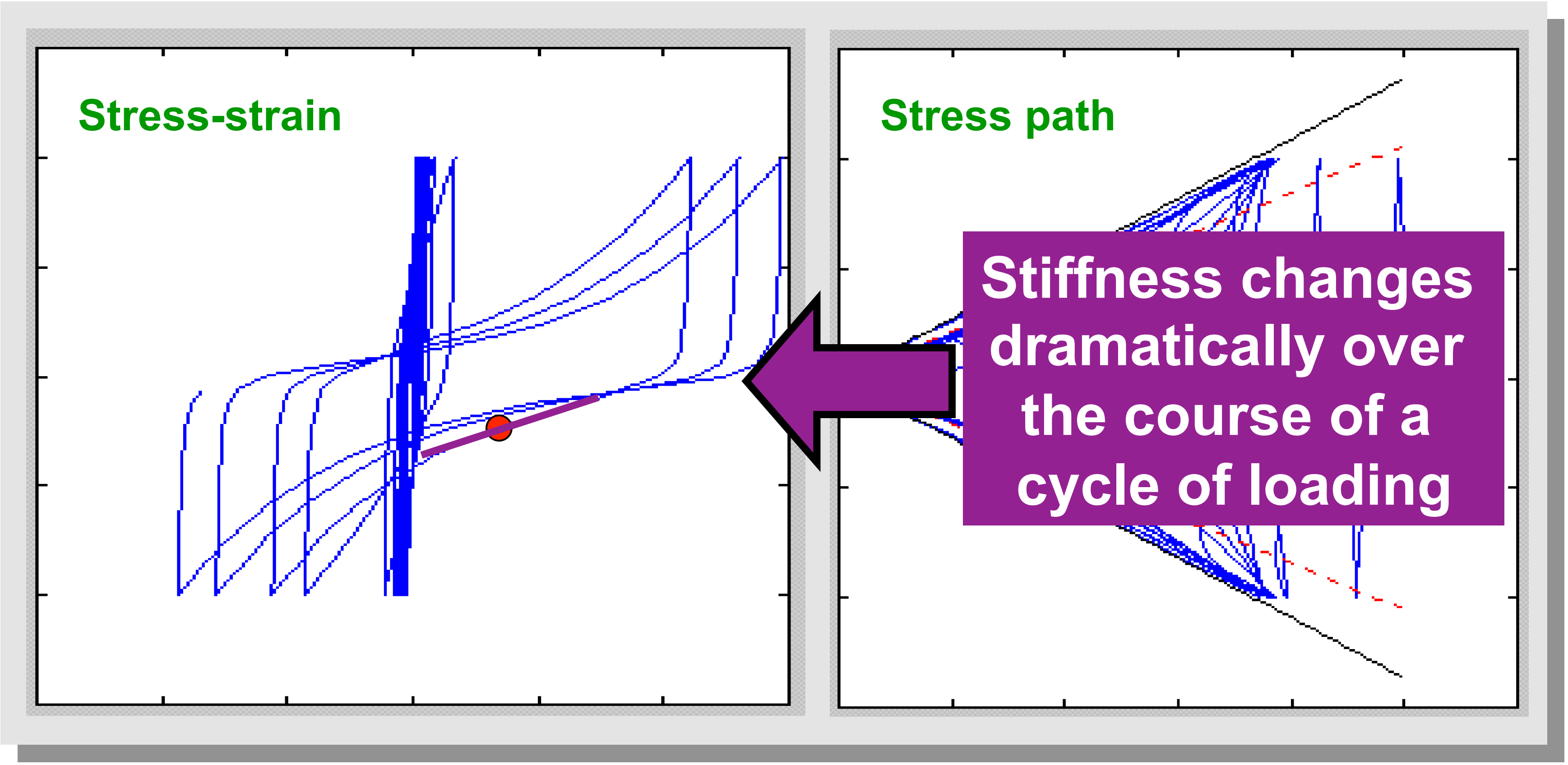

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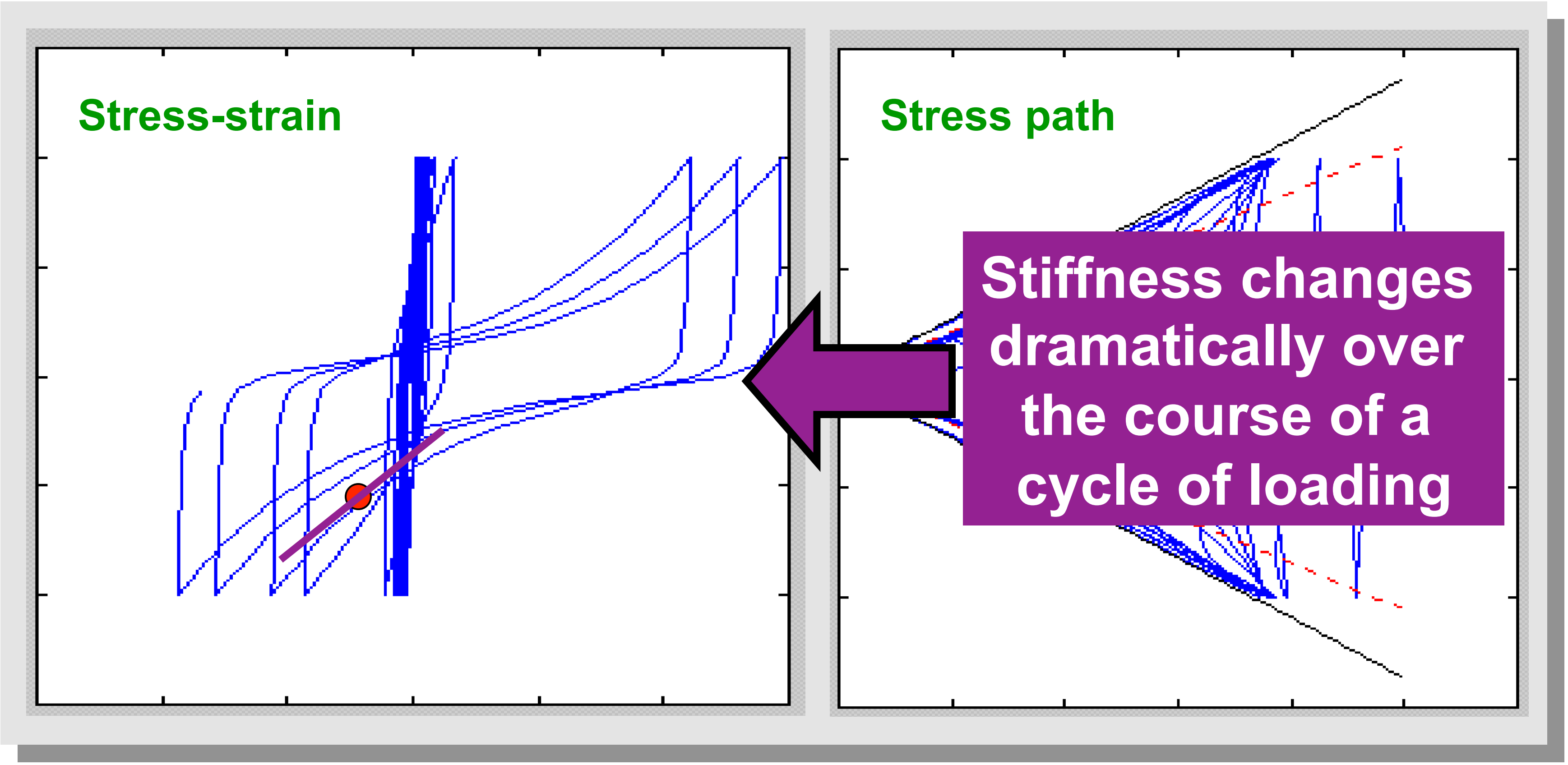

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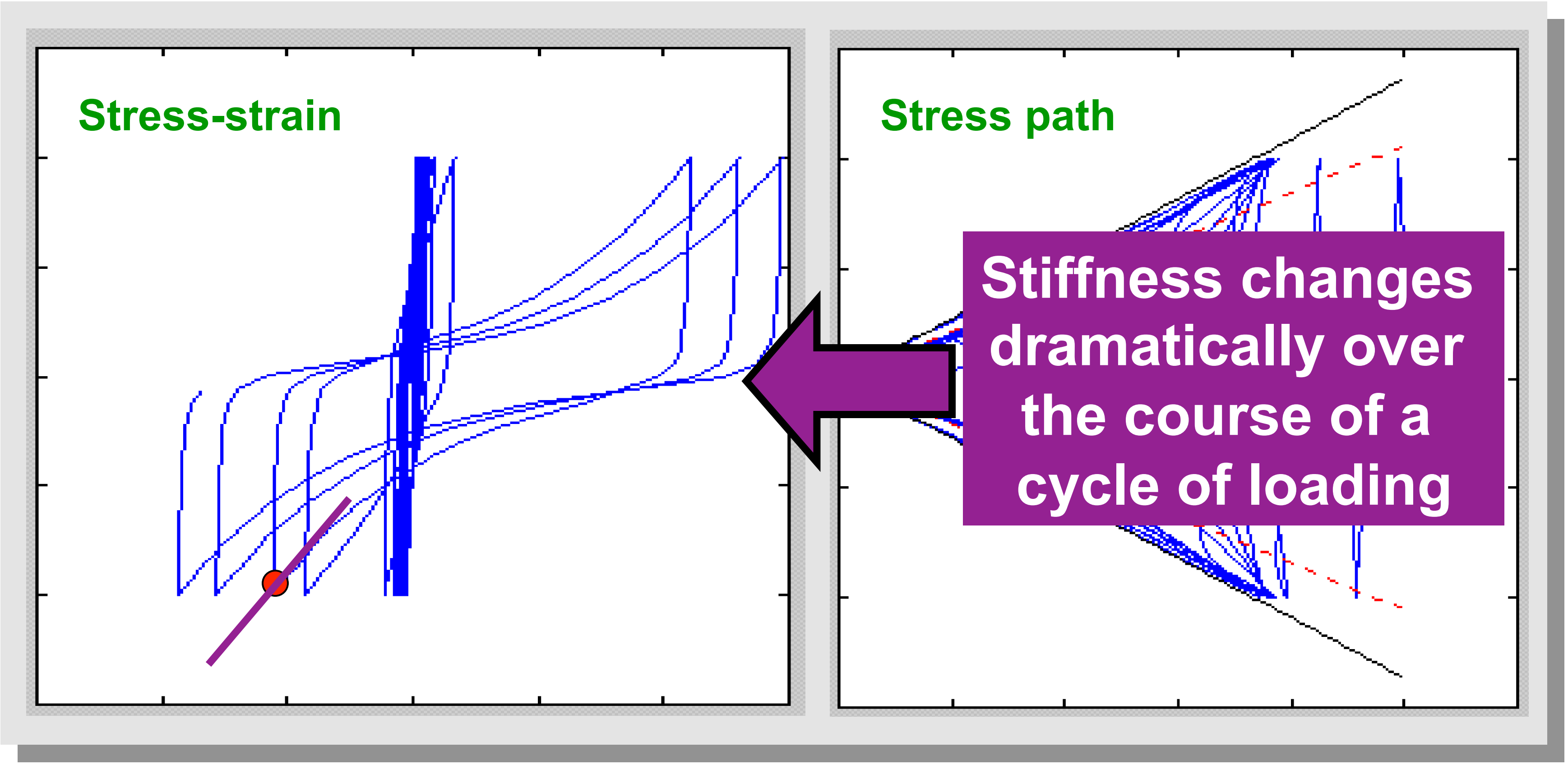

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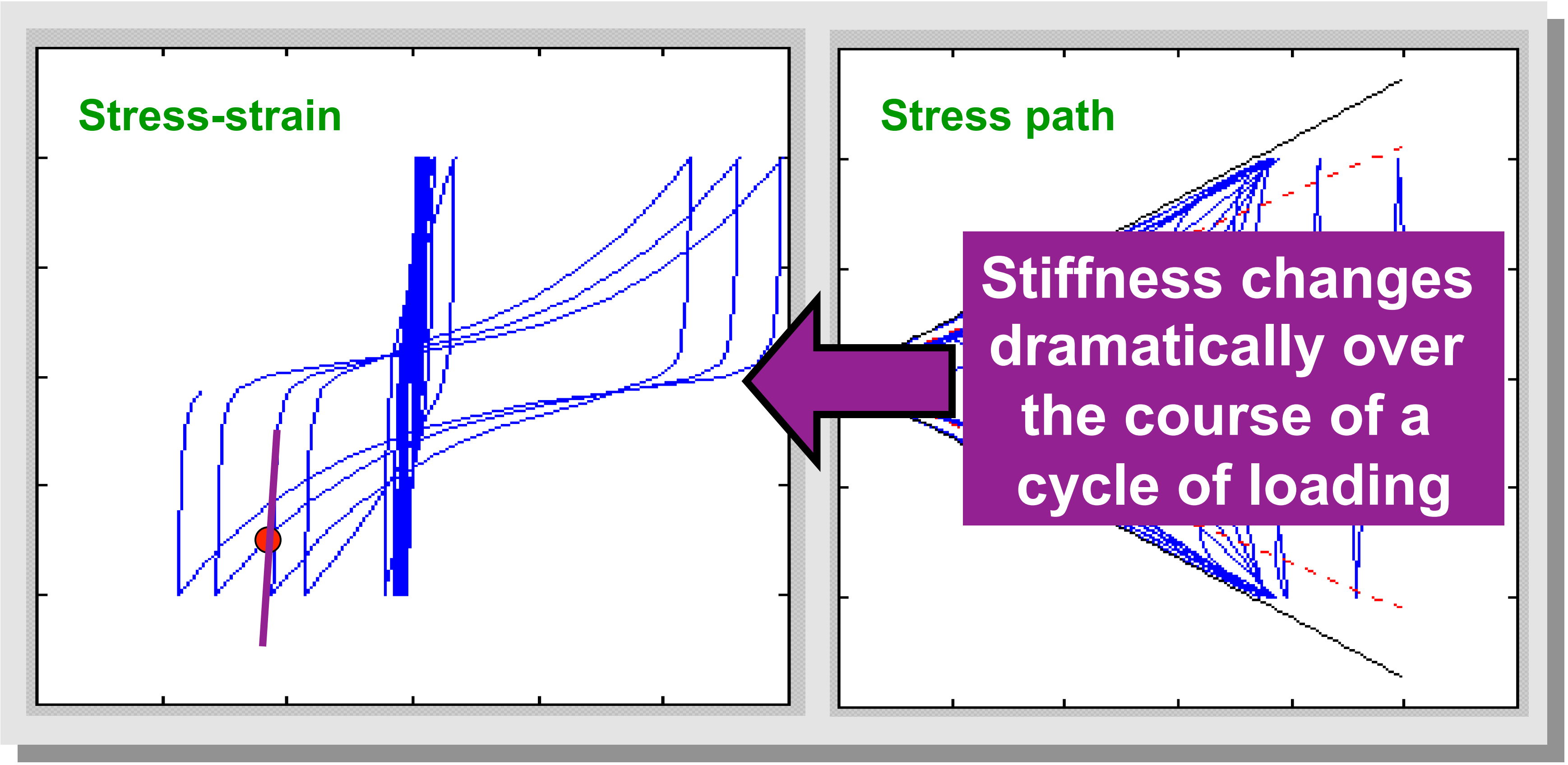

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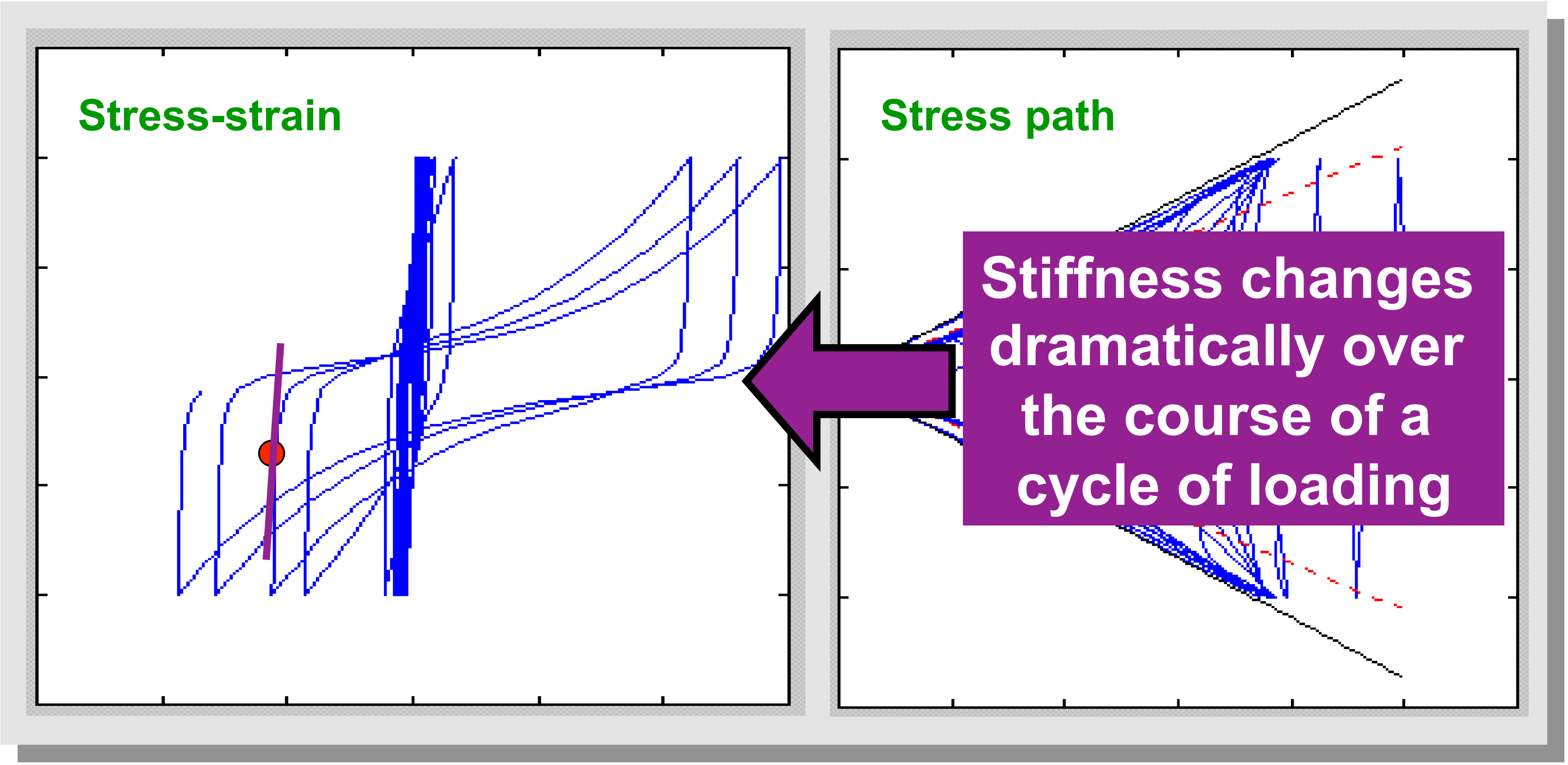

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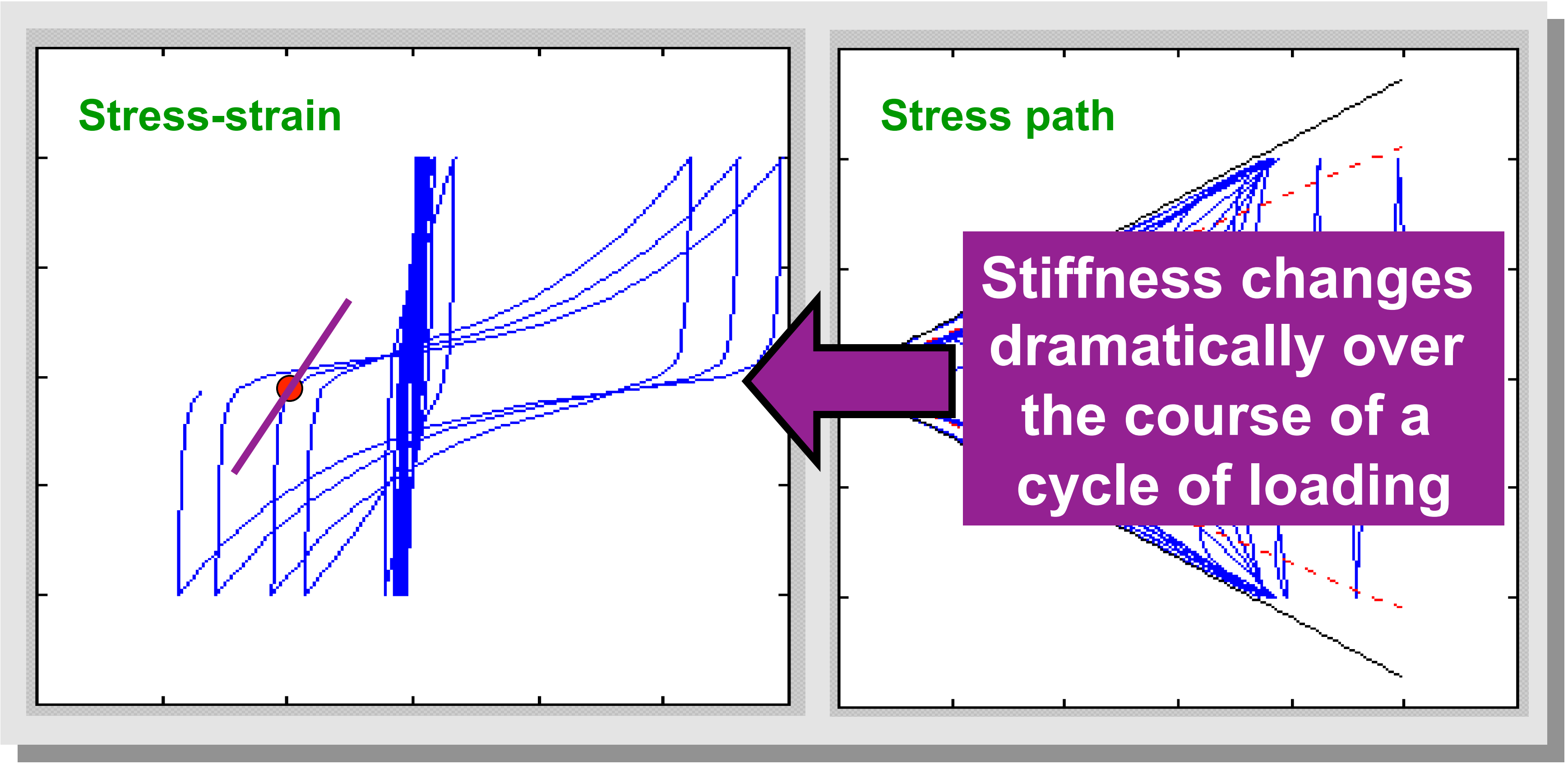

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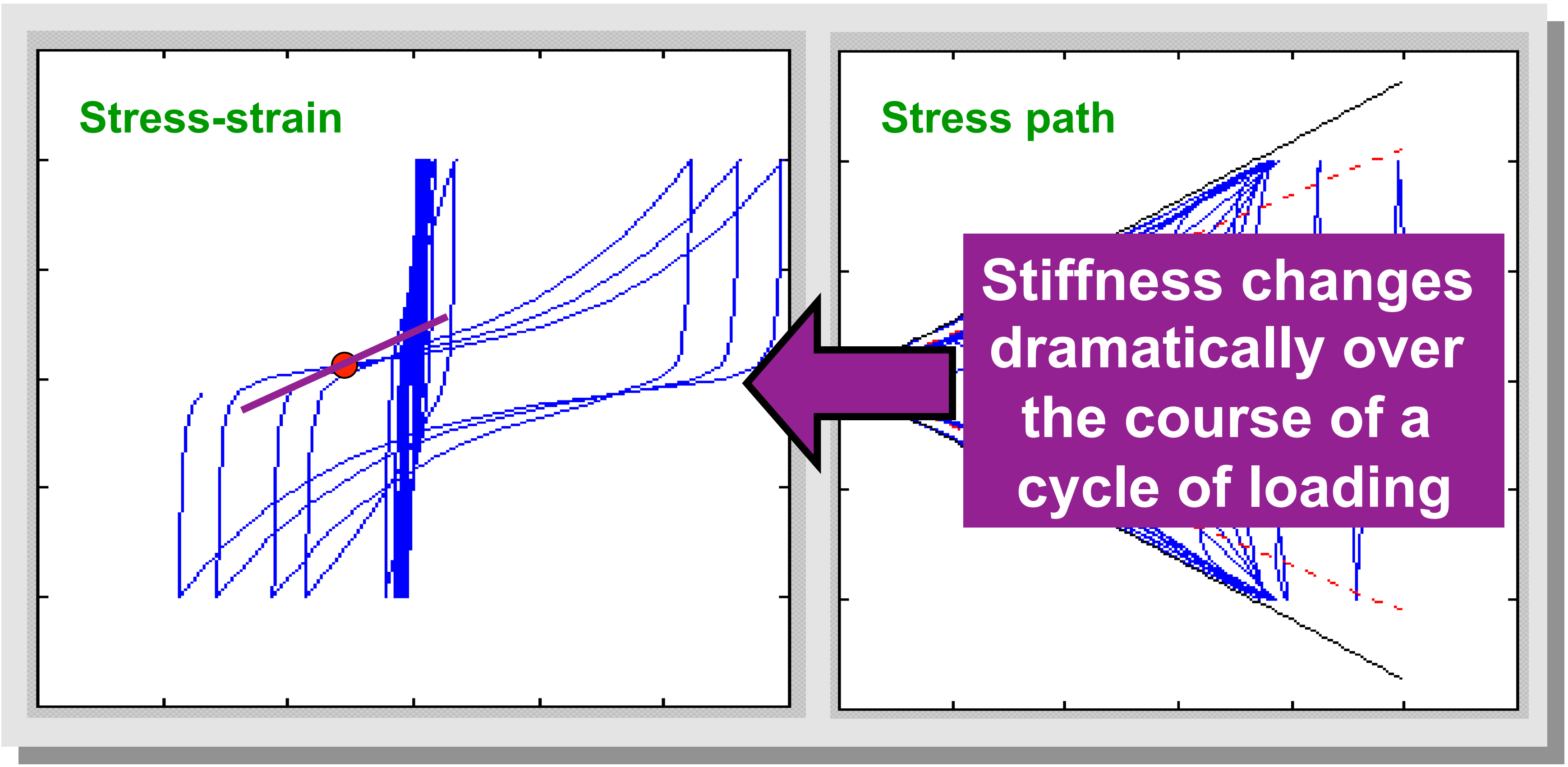

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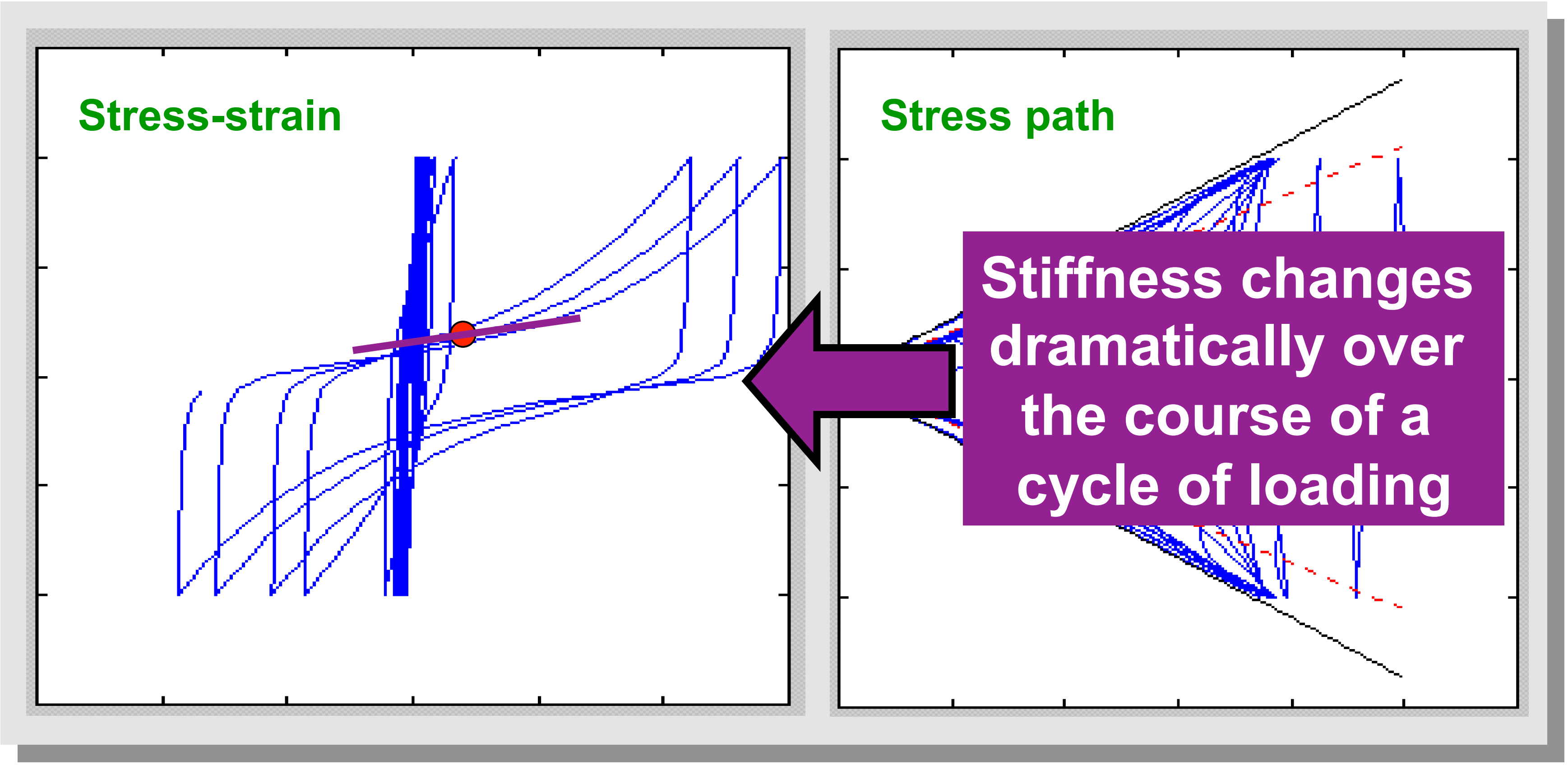

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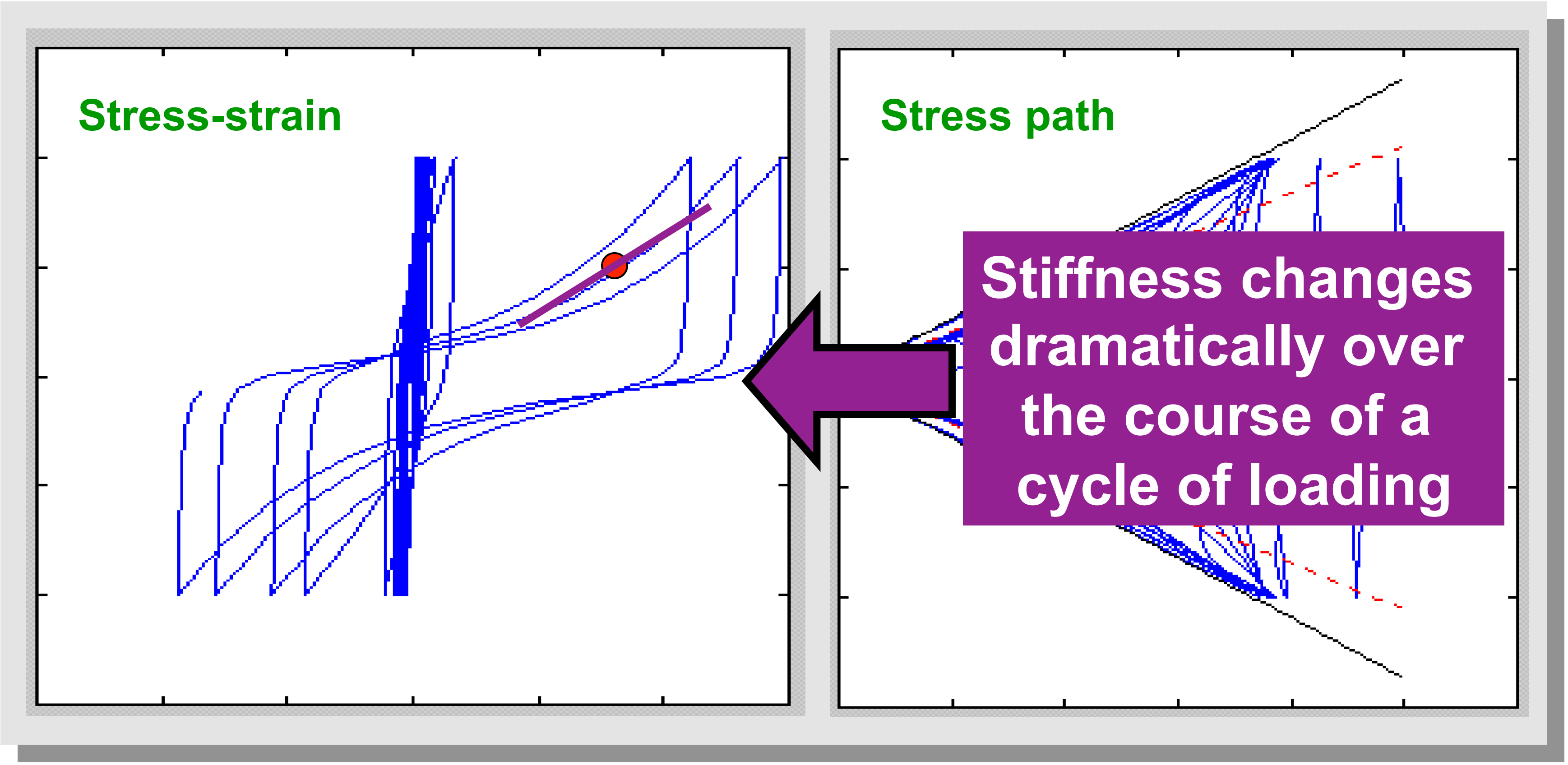

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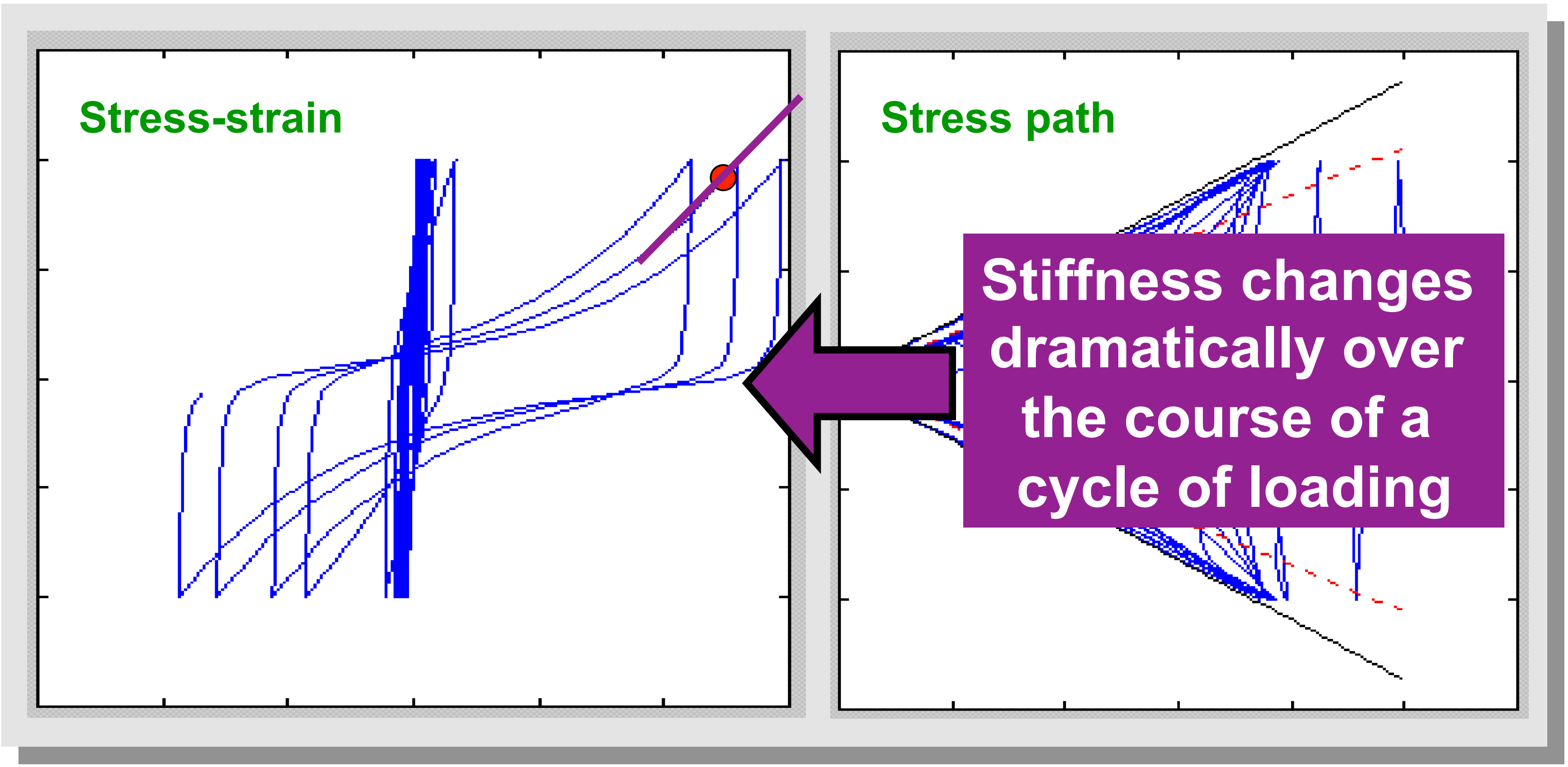
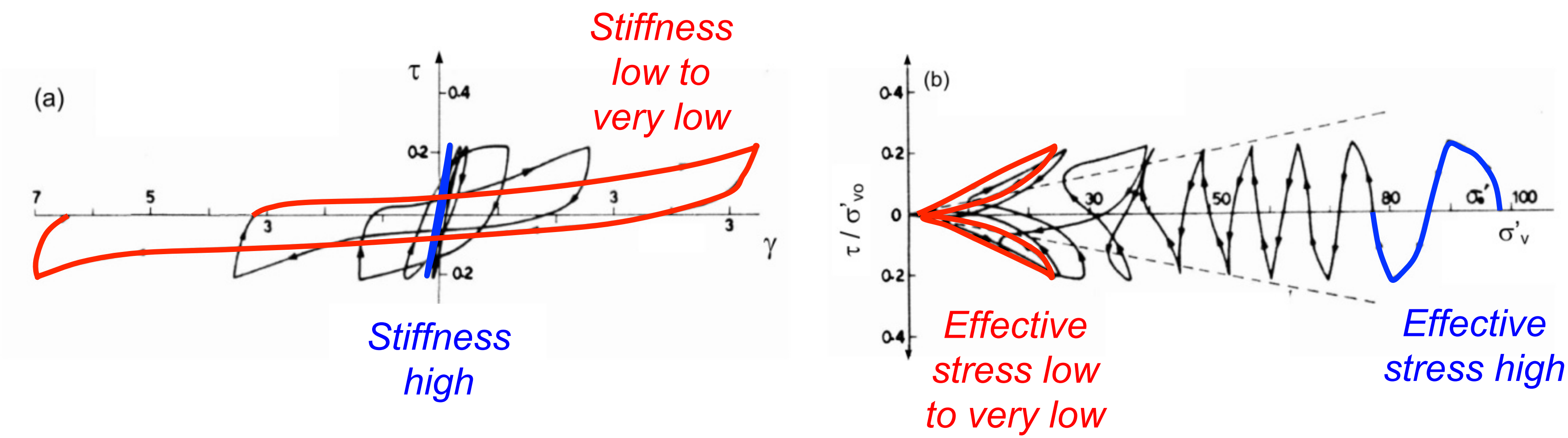


Effects of Liquefaction

Ishihara (1985) – Cyclic simple shear test



Phase transformation behavior well established by laboratory tests

Effects of Liquefaction

Site Response

- Stiffness generally decreases
- Longer period motion
- Lower acceleration amplitudes
- Higher displacement amplitudes

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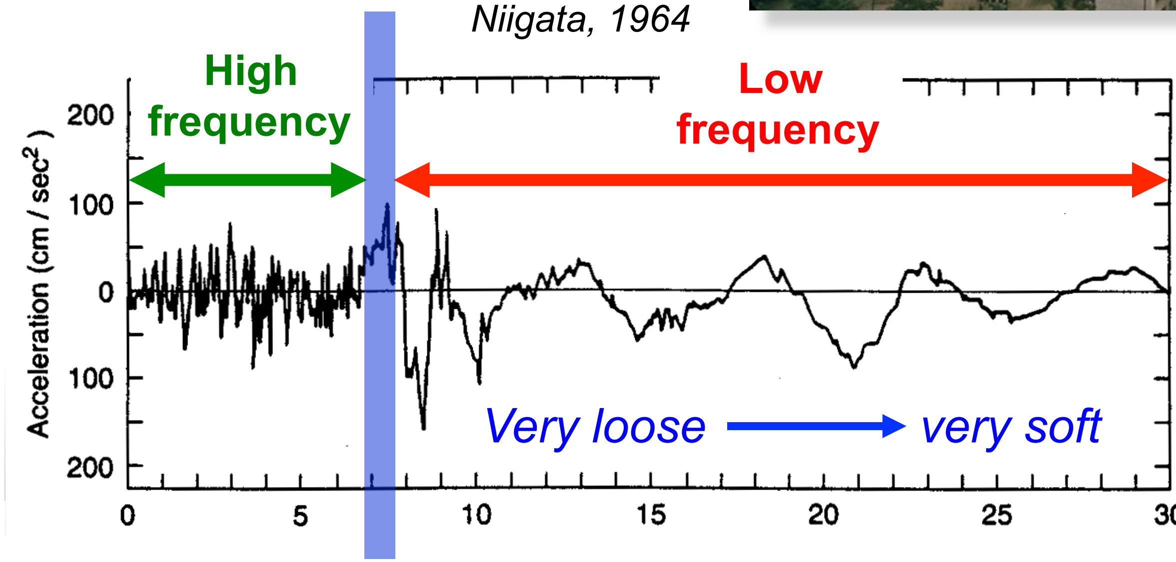
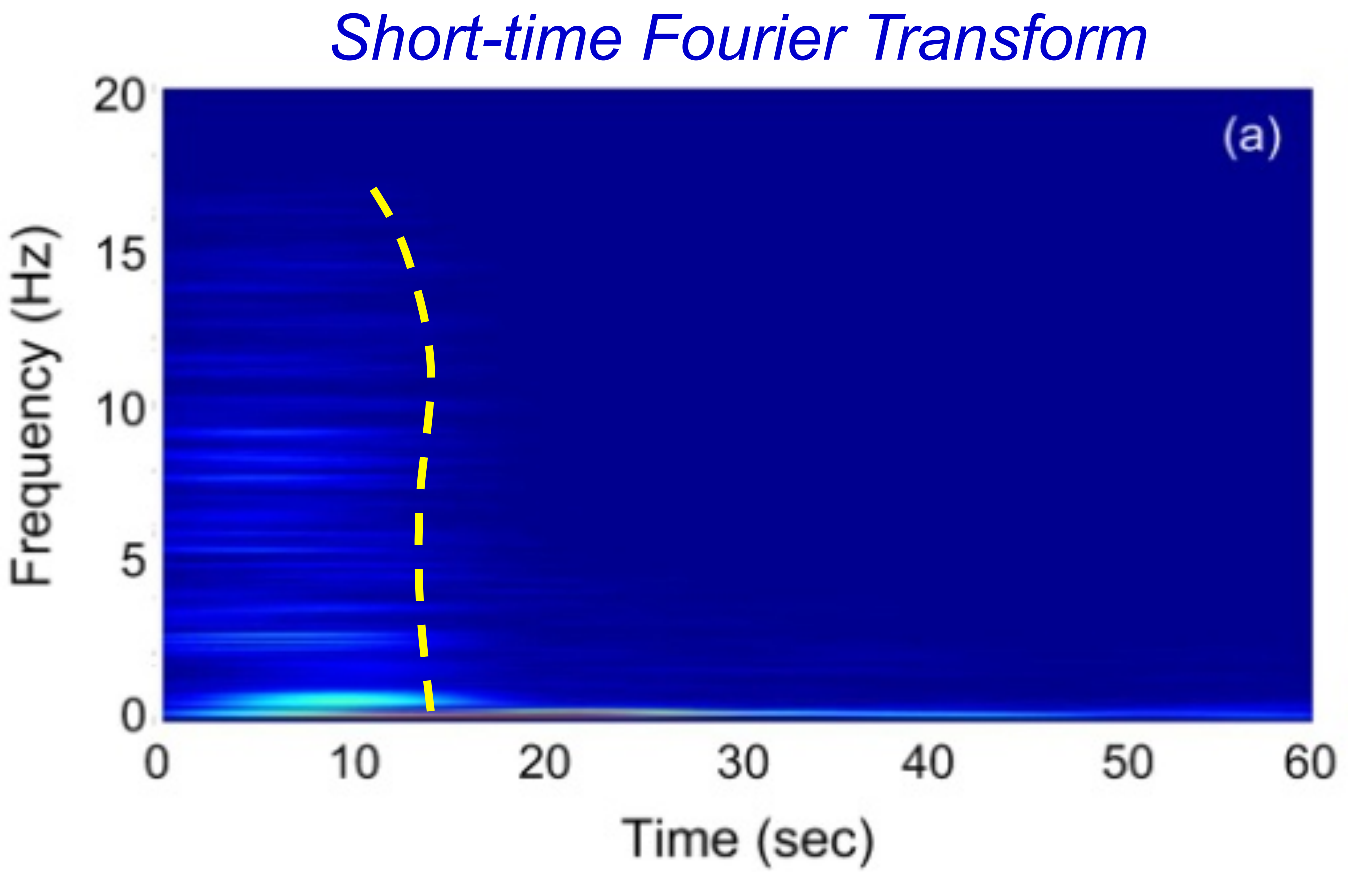
Kawagishi-cho apartment buildings
Niigata, 1964



Effects of Liquefaction

Time-frequency response



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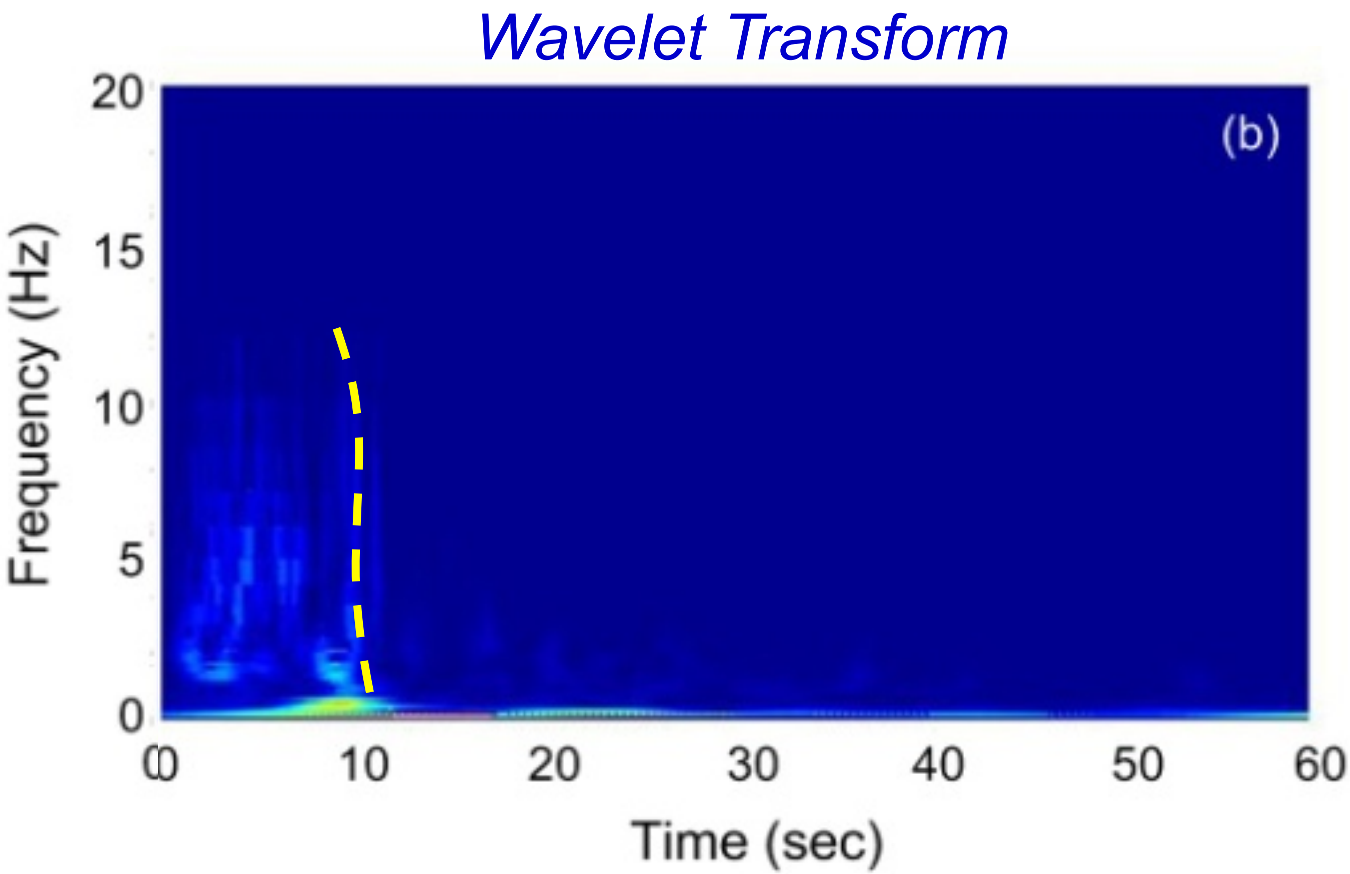

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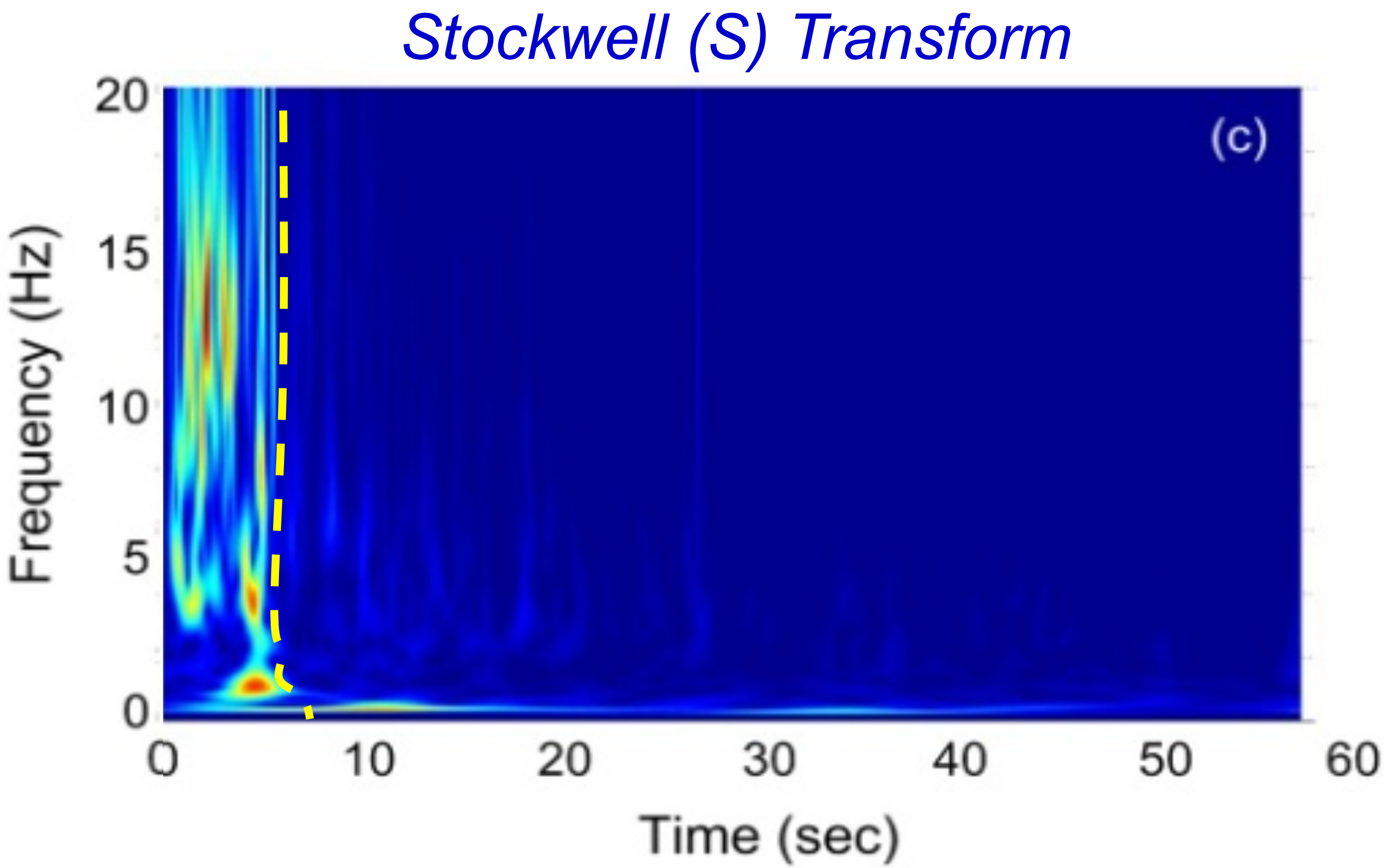
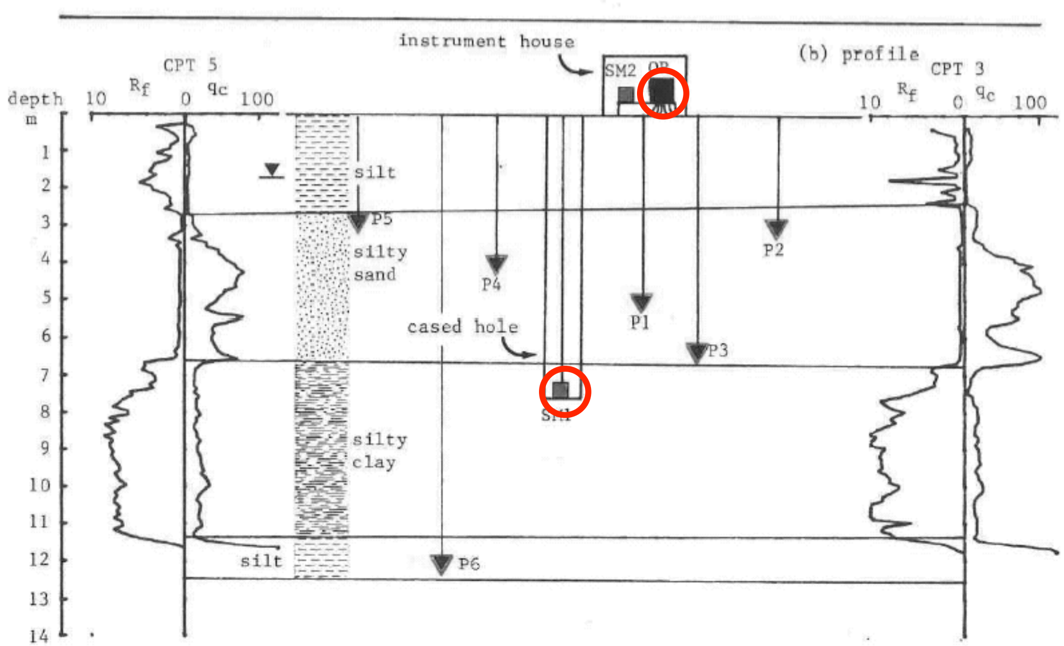


Site Response

Wildlife Array

- Located west side of Alamo River, Imperial county, CA
- Instrumented in 1982 by the USGS
- Non-liquefaction event – 1987 Elmore Ranch (M = 6.2)
- Liquefaction event – 1987 Superstition Hills (M = 6.6)



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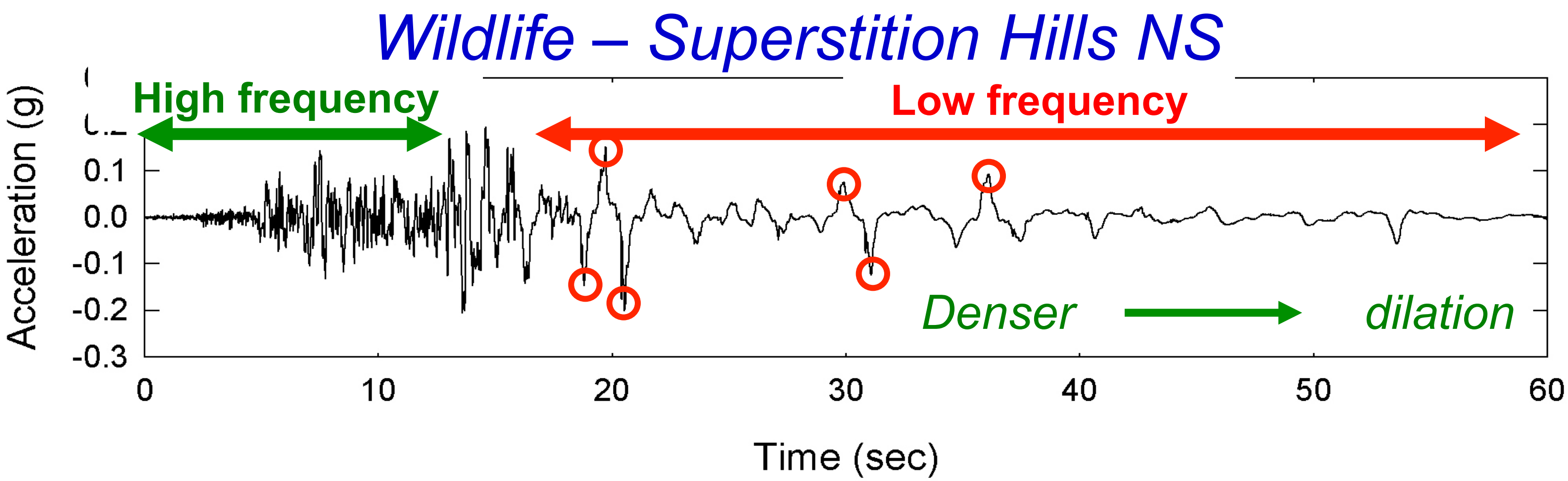

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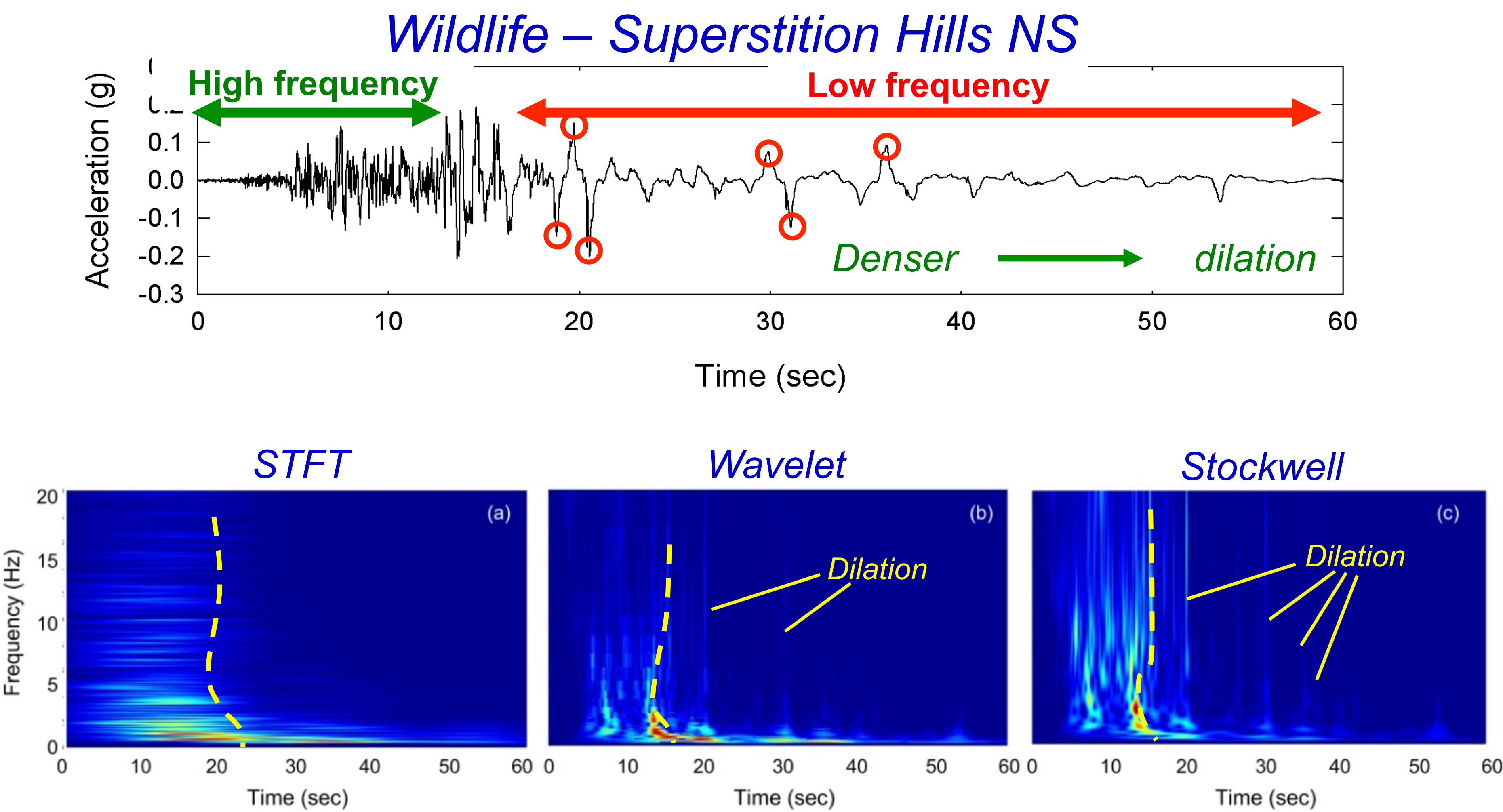

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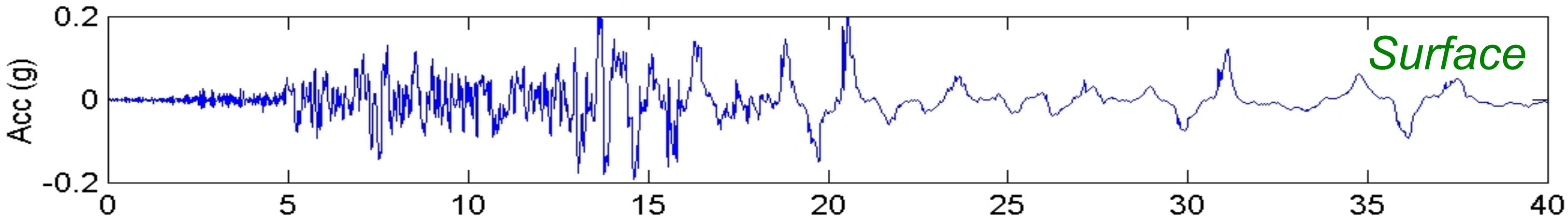
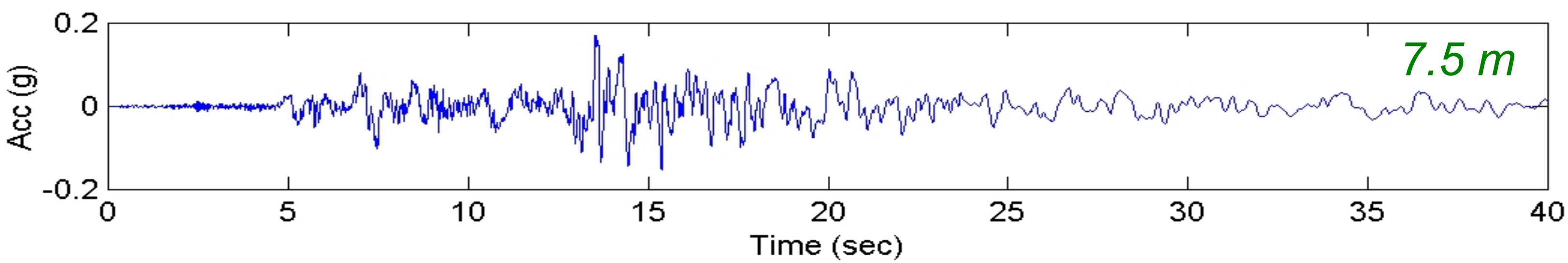
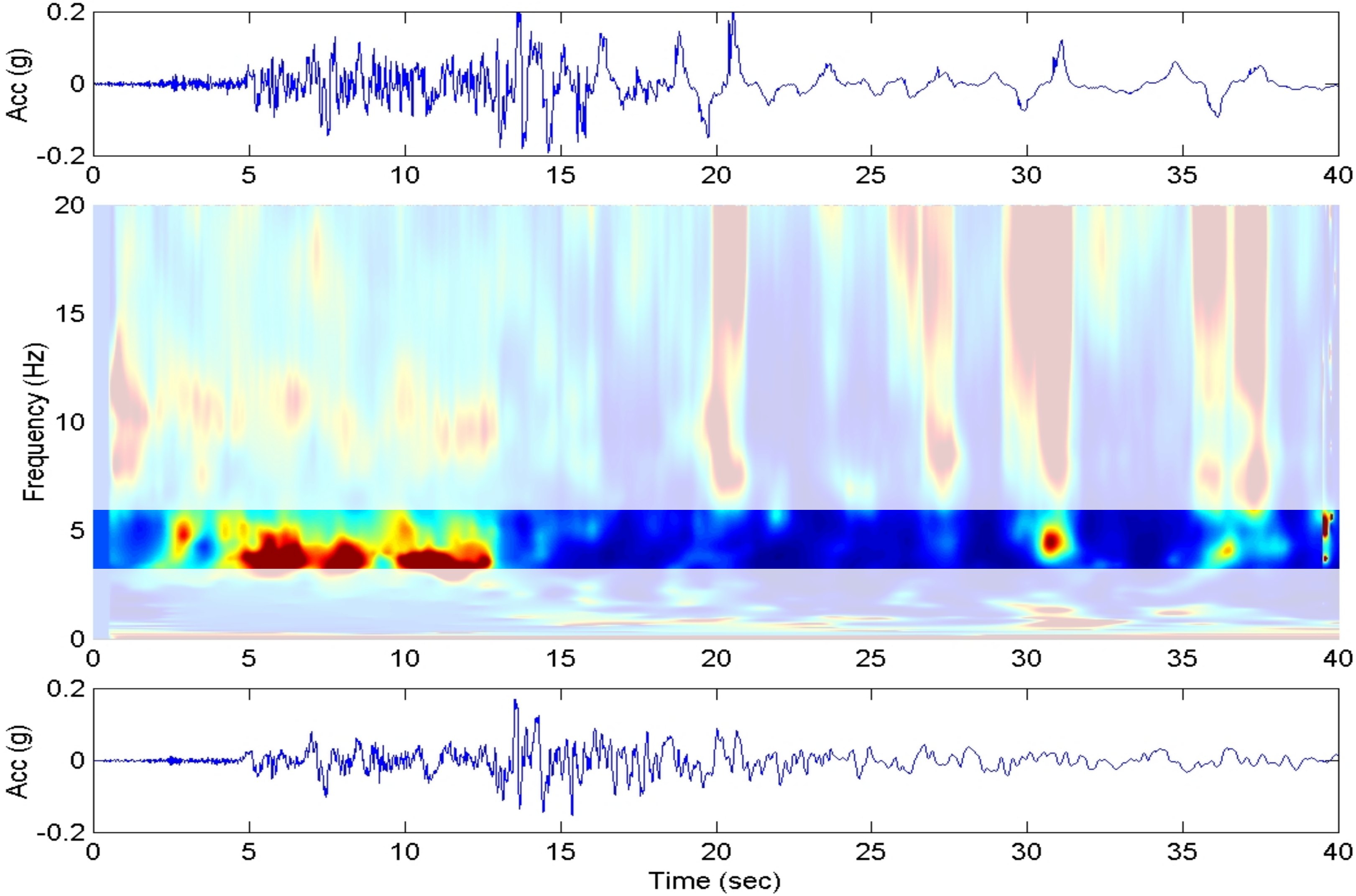


Frequency content of surface motion is influenced by frequency content of underlying motion



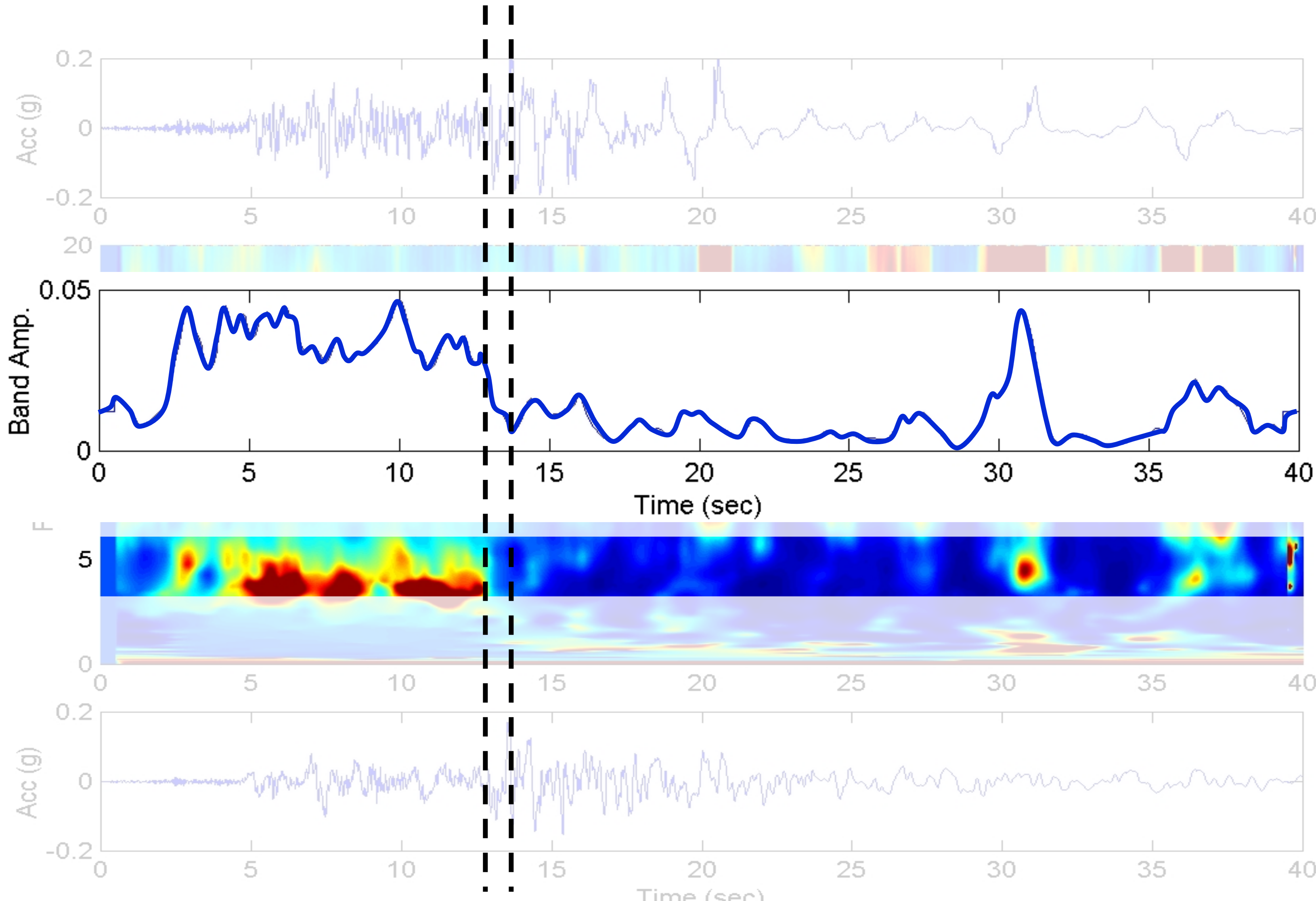
Effects of Liquefaction

Time-frequency response



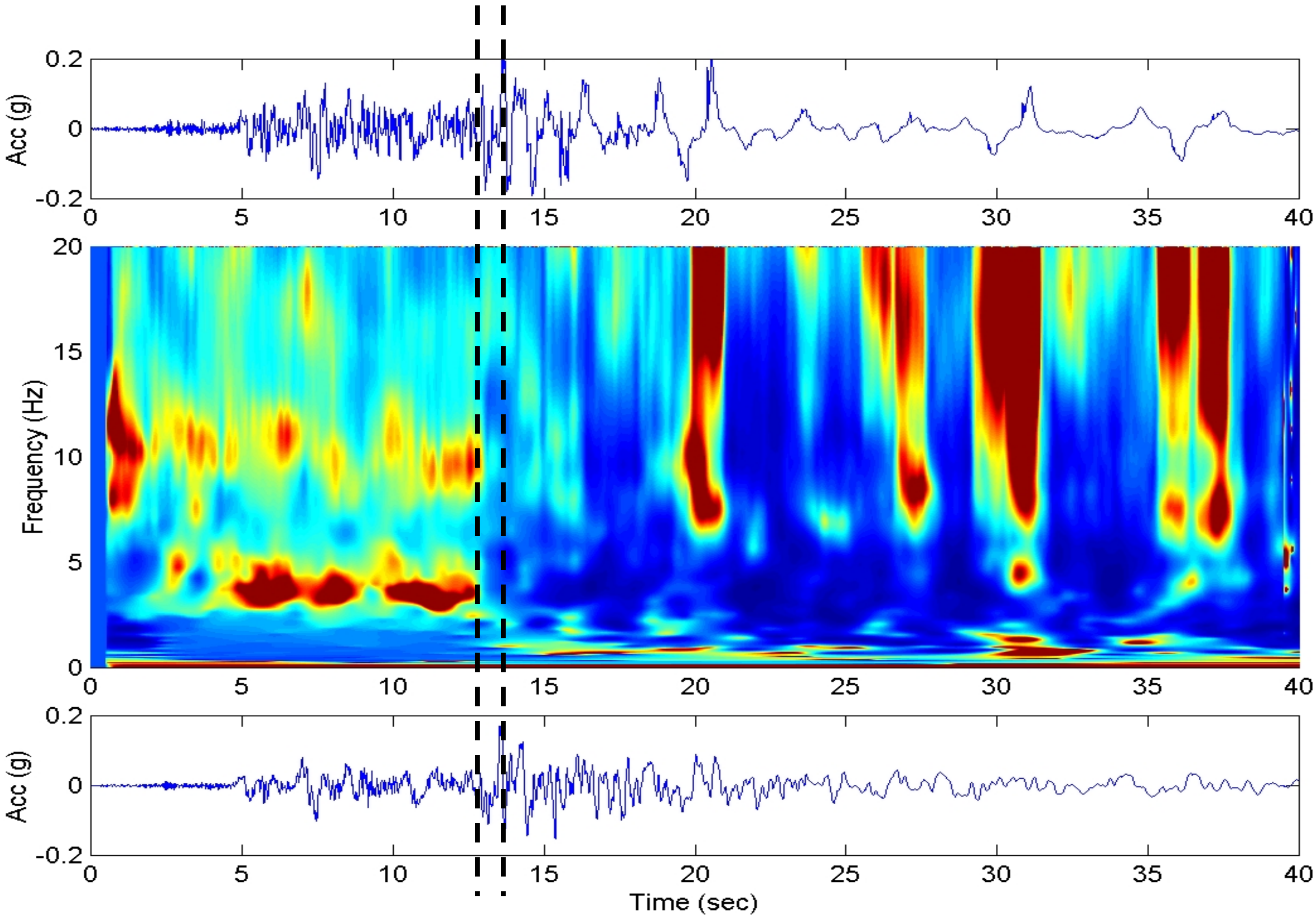
Effects of Liquefaction

Time-frequency response



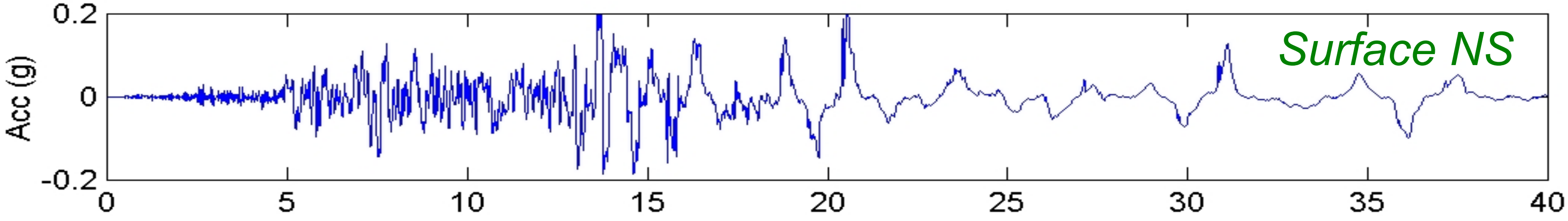
Effects of Liquefaction

Time-frequency response



Effects of Liquefaction

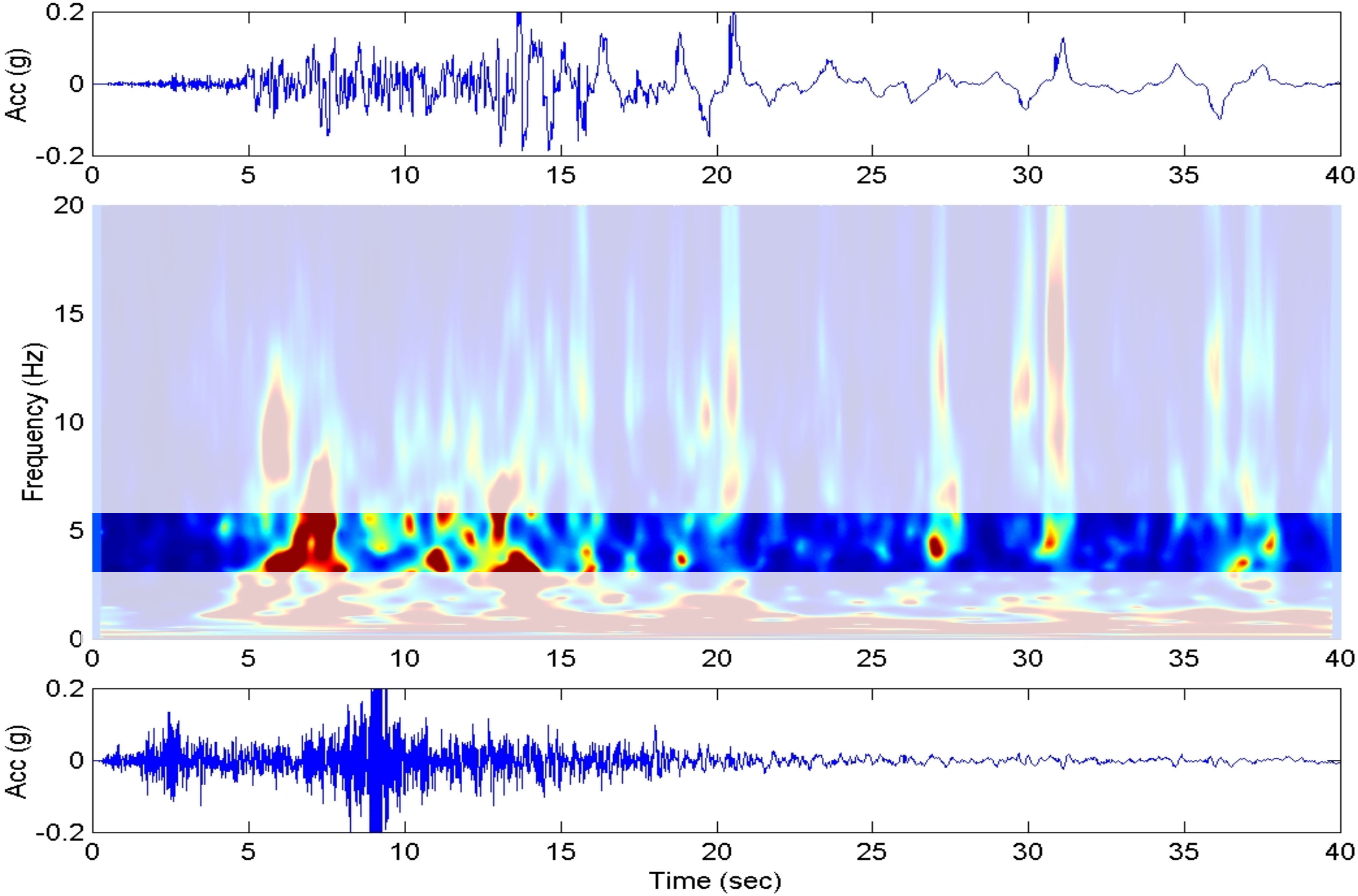
Time-frequency response



What if we don't have a useful downhole record?

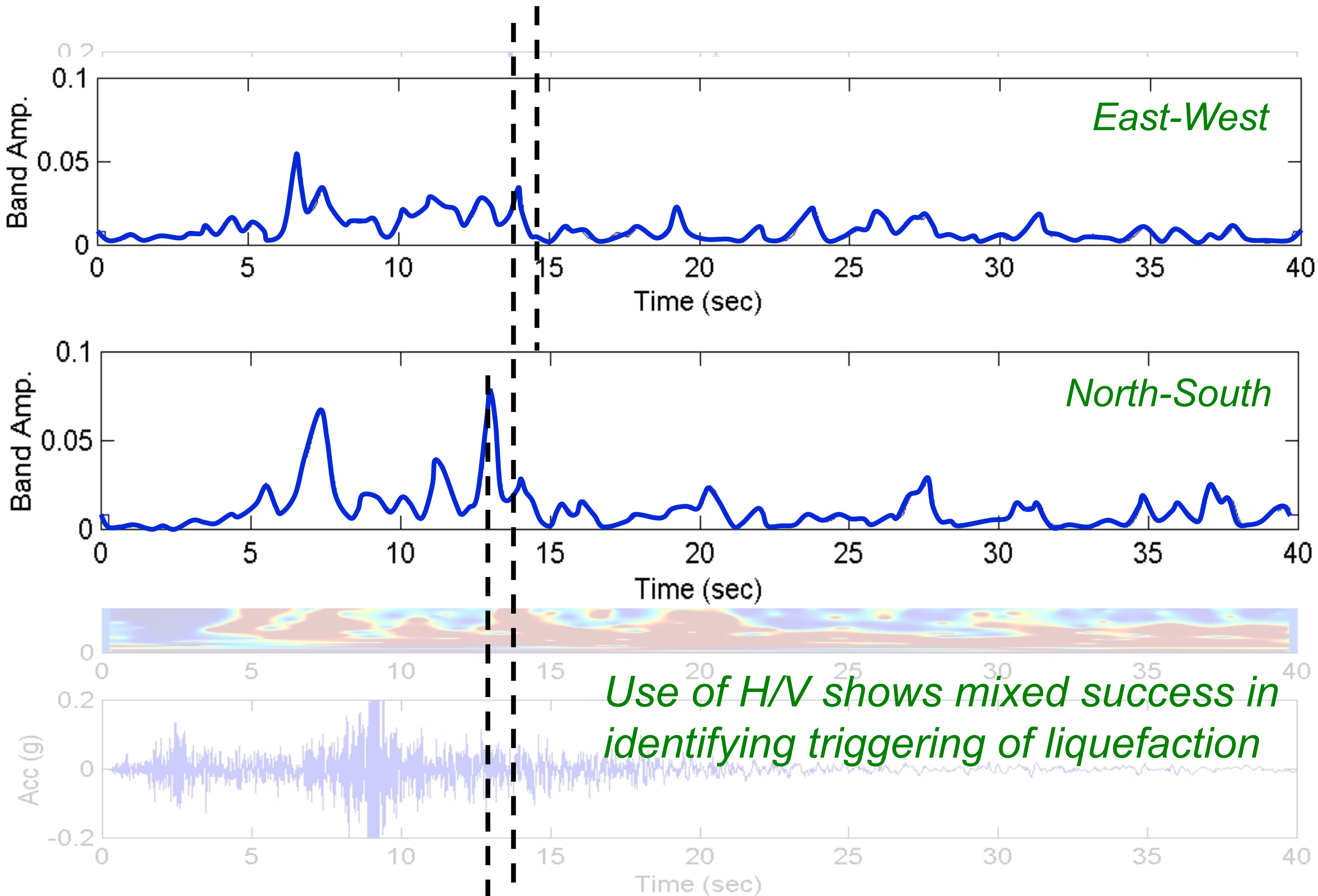
Effects of Liquefaction

Time-frequency response



Effects of Liquefaction

Time-frequency response



Use of H/V shows mixed success in identifying triggering of liquefaction

Effects of Liquefaction

Can we predict this type of behavior?

- Nonlinear, effective stress-based analysis
- Reasonable constitutive model
  - Must allow pore pressure generation
  - Should include phase transformation behavior
  - Must be calibratable

Nonlinear site response models

DMOD2000 (www.geomotions.com)

- Lumped mass MDOF system with Rayleigh damping
- Hyperbolic soil model with Masing rules
- Dobry-Vucetic strain-based pore pressure model (no PT behavior)
- Pore pressure models provided for Wildlife sands

WAVE (Horne, 1995)

- Approximately follows Seed-Idriss upper bound modulus reduction and lower bound damping curves for liquefiable layers
- Accounts for phase transformation behavior
- Calibrated to match empirical pore pressure generation and strain behavior – $(N_1)_{60\text{-}cs}$

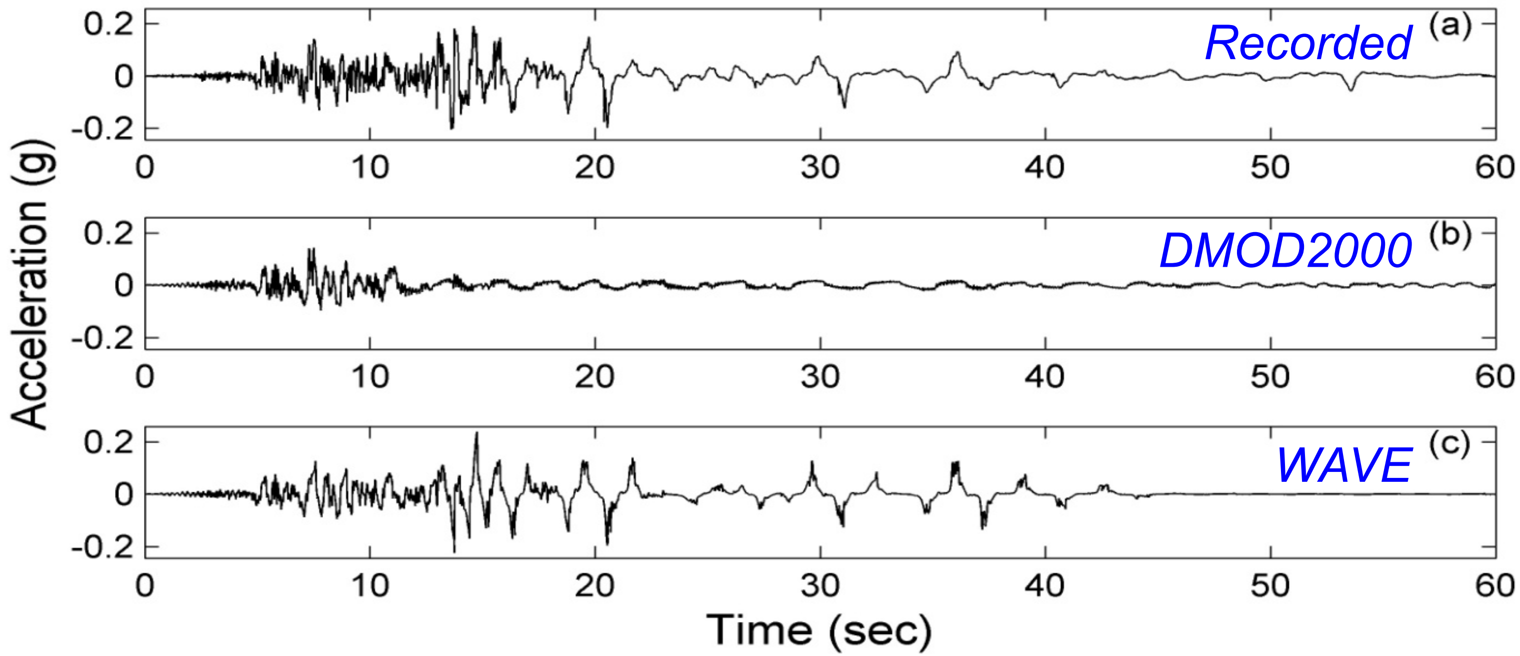
Nonlinear site response modeling challenges

- Site characterization – different models require different parameters
- Dimensionality – 1D misses surface wave, basin effects
- Directionality – nearly all codes deal with one horizontal component
- Repeatability – models should work for weak and strong shaking
- Crust behavior – crust will distort, break … not accounted for
- Soil-structure interaction – may affect recorded motions
- Sloping ground effects – asymmetric response

Lots of possible ~~excuses~~ reasons for inexact predictions

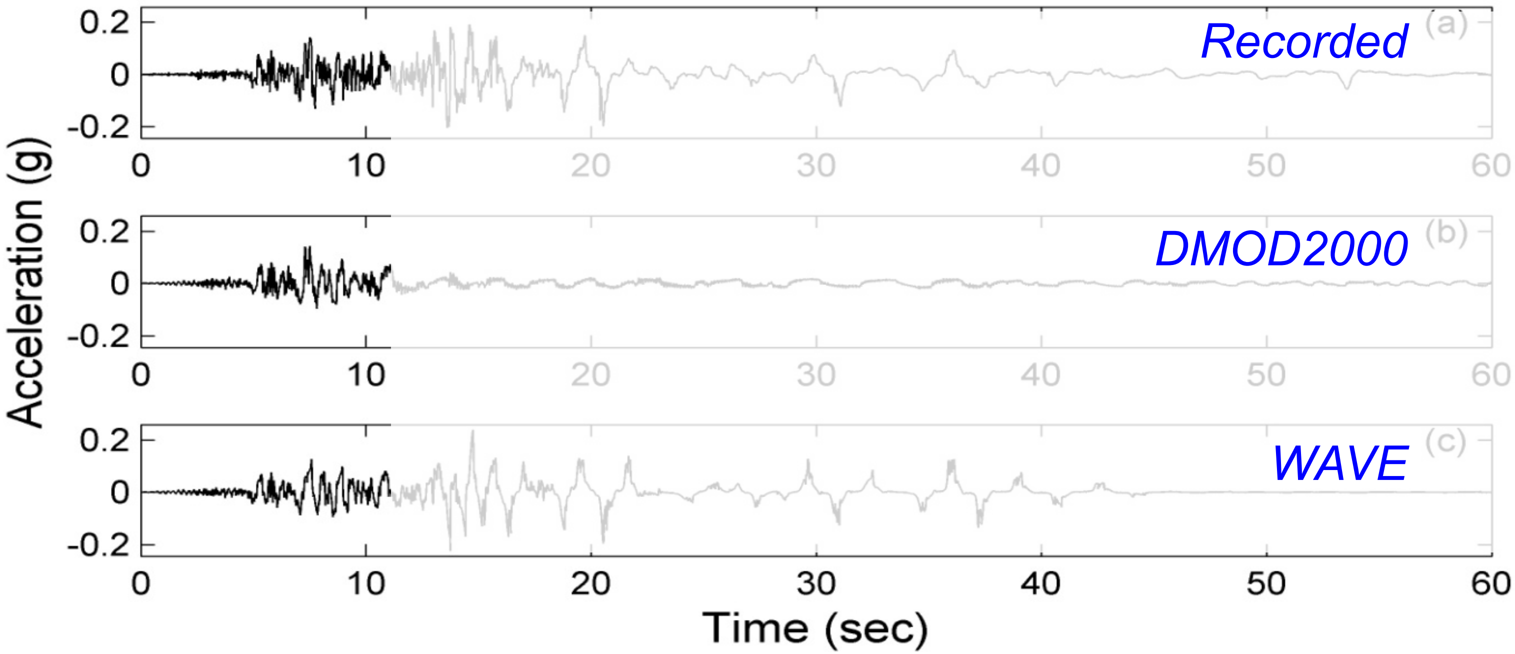
Nonlinear site response

Superstition Hills NS surface motion



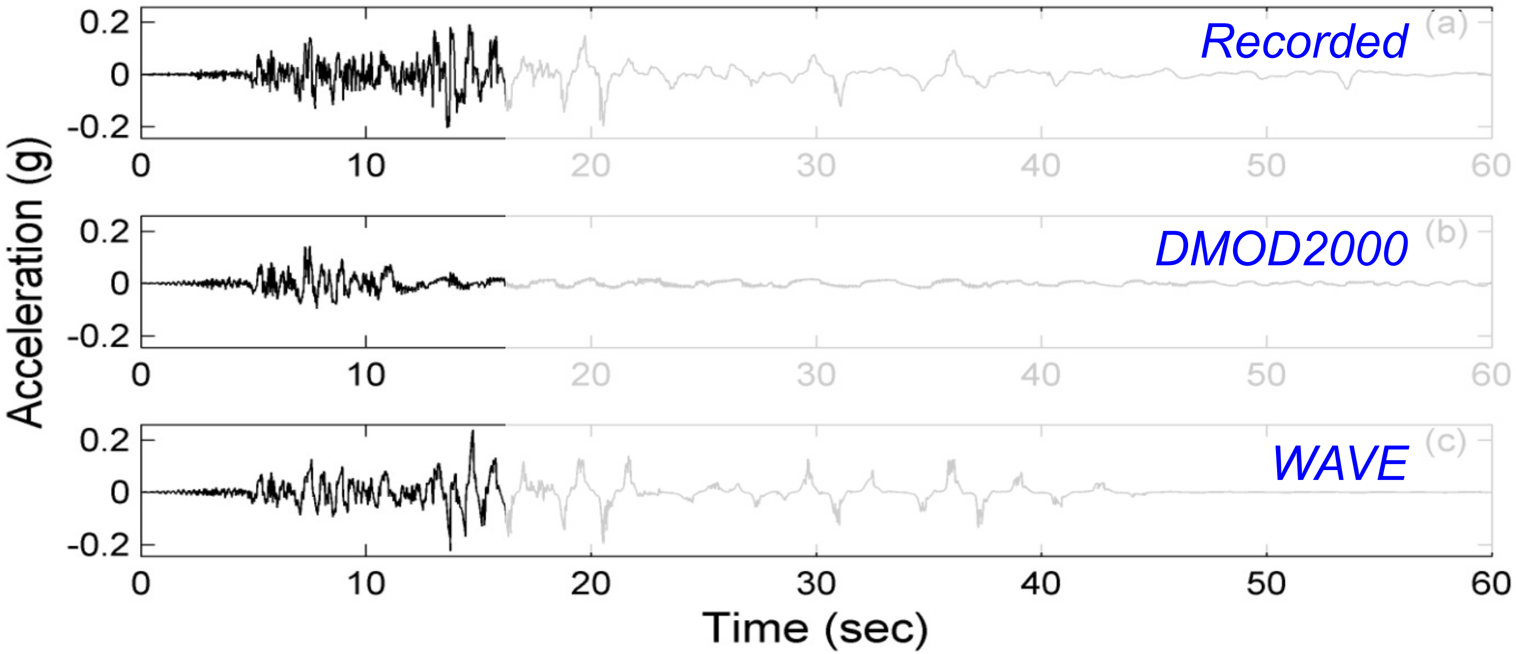
Nonlinear site response

Superstition Hills NS surface motion



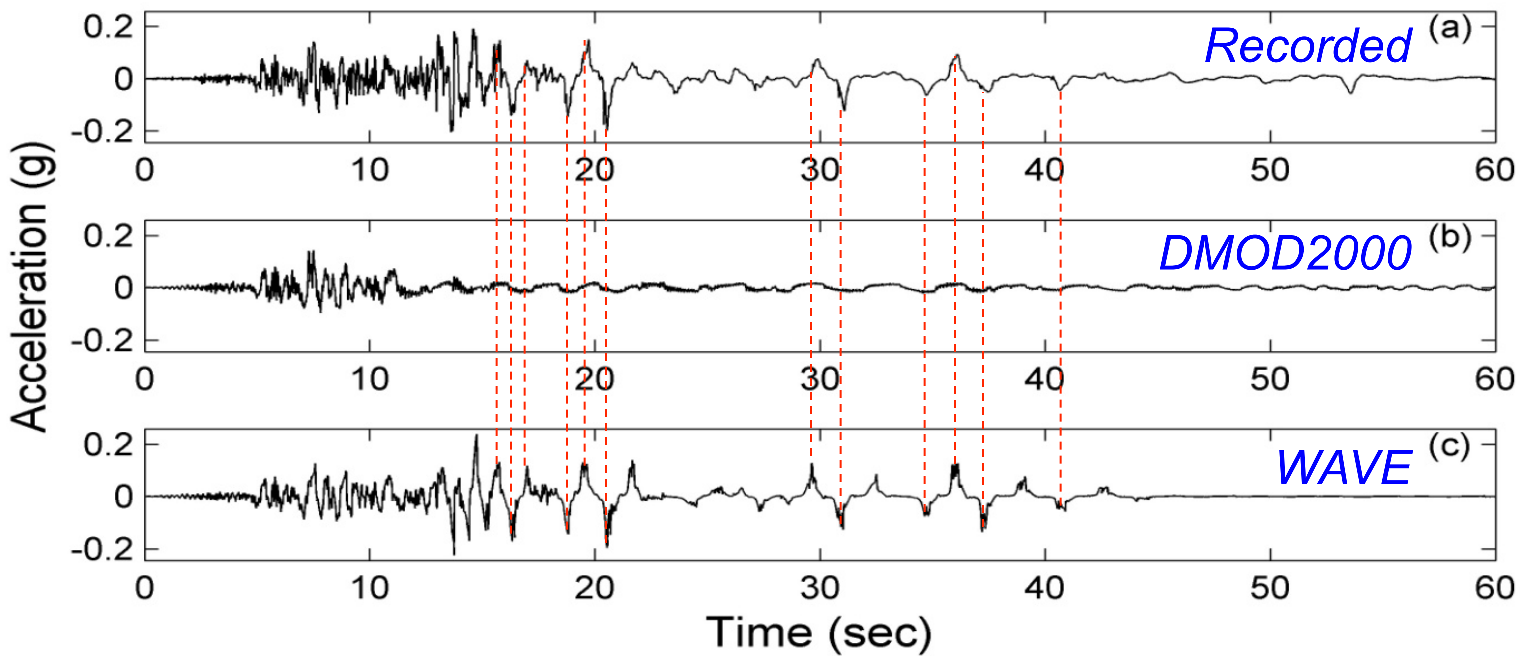
Nonlinear site response

Superstition Hills NS surface motion



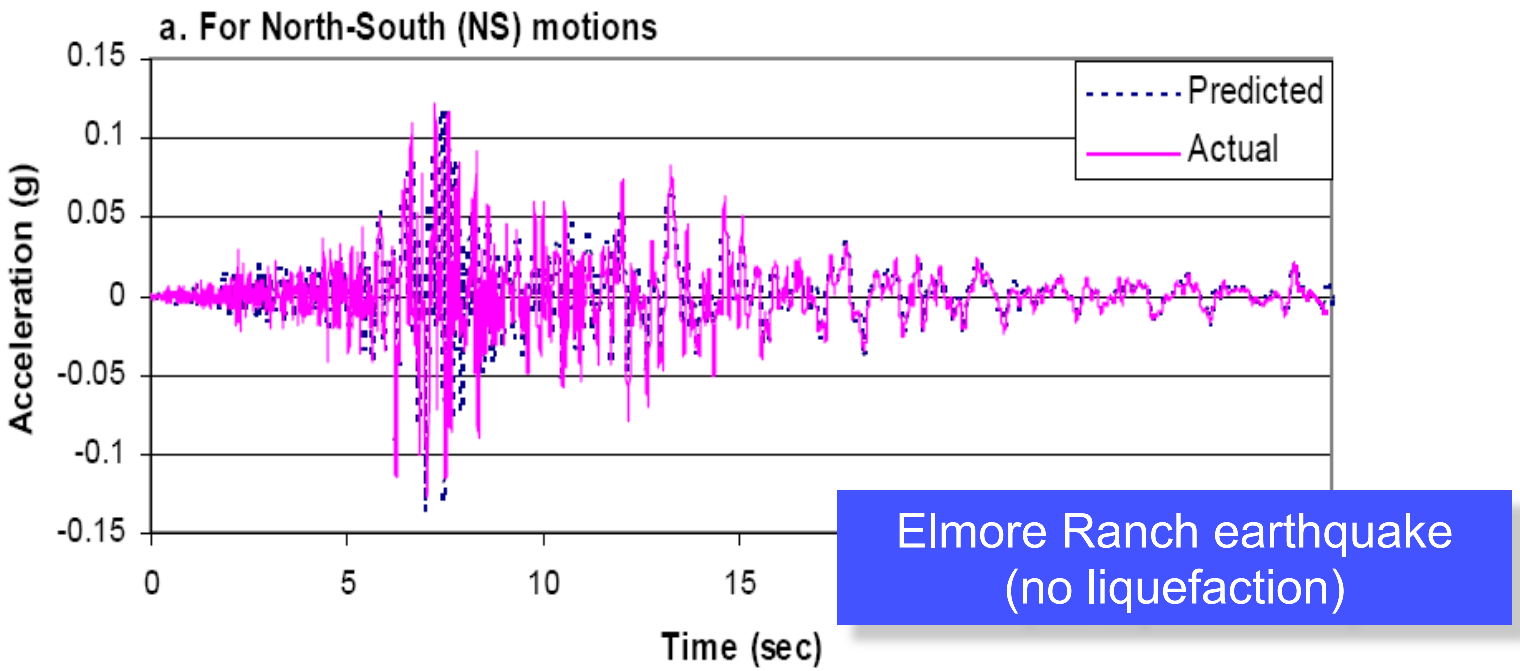
Nonlinear site response

Superstition Hills NS surface motion



Effects of Liquefaction on Ground Surface Motions

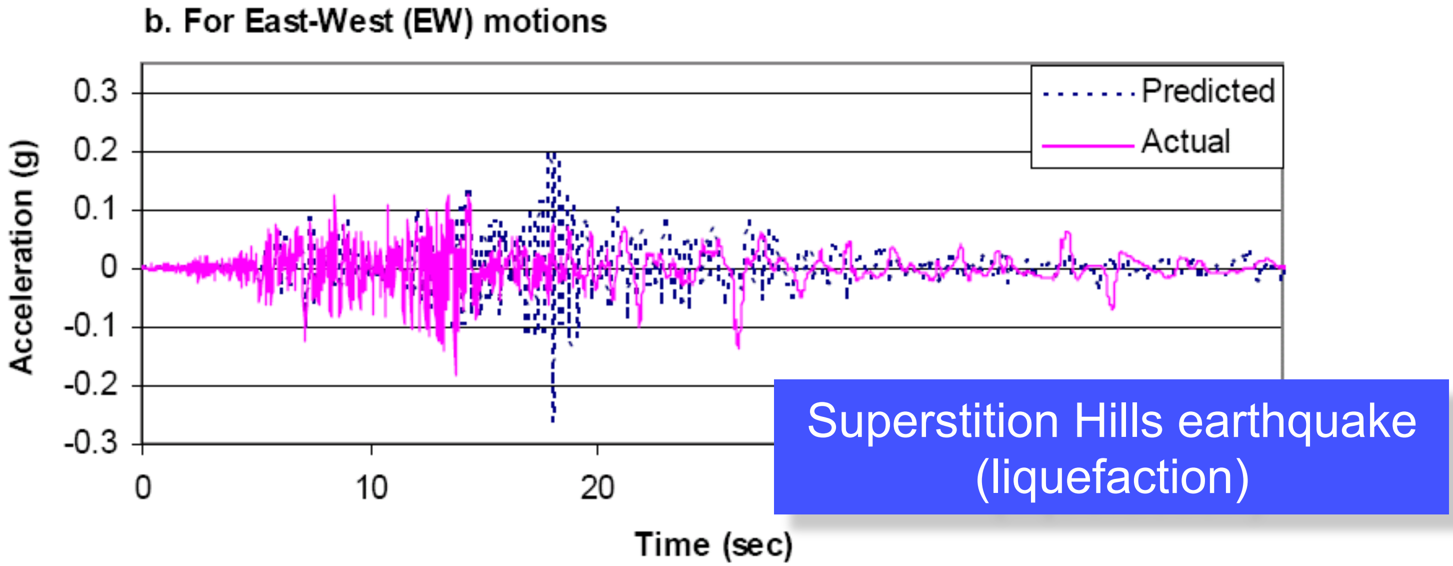
Youd and Carter (2005)



Validated equivalent linear model by comparing SHAKE time history to the actual recorded time history – good agreement

Effects of Liquefaction on Ground Surface Motions

Youd and Carter (2005)

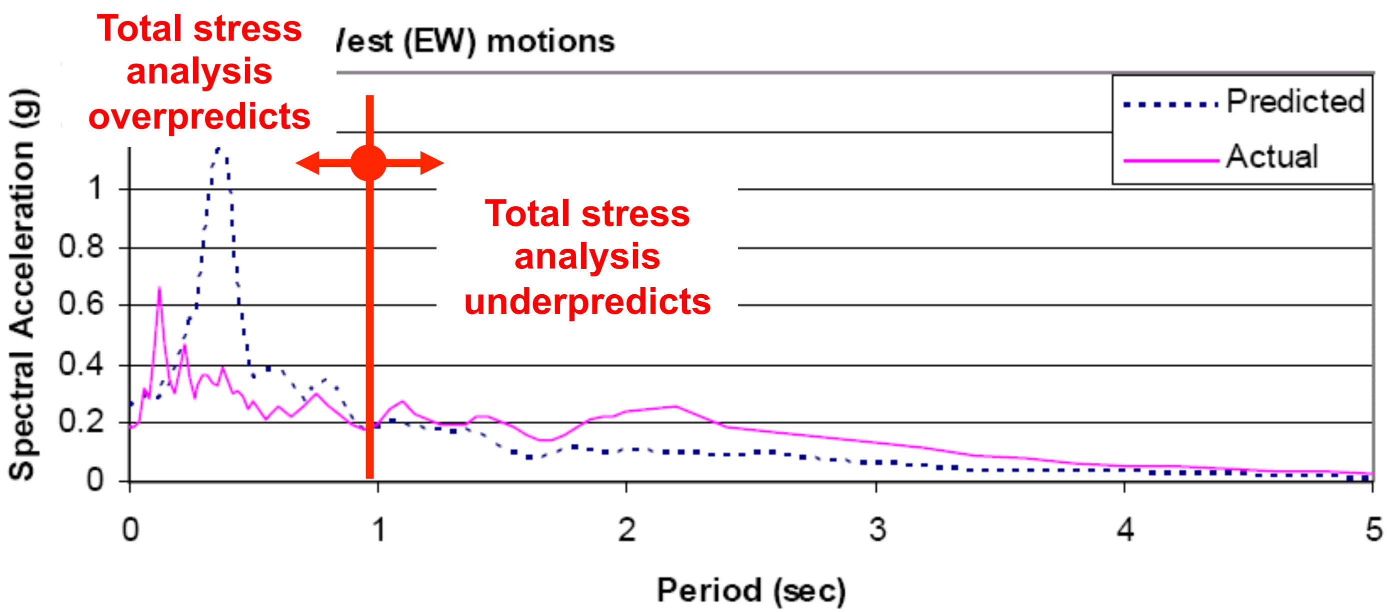


Compared equivalent linear model predictions to actual record – good agreement in first 13 sec, poor after.

Equivalent linear analyses maintained high frequency content after 13 sec due to constant stiffness. Stiffness of actual profile apparently reduced due to liquefaction.

Effects of Liquefaction on Site Response

Youd and Carter (2005)



Analysis of five case histories taken to show:

- **There is generally a reduction in short period spectral response (< 0.7-1.0 sec)**
- **There is generally an amplification of long period spectral response (> 0.7 - 1.0 sec)**

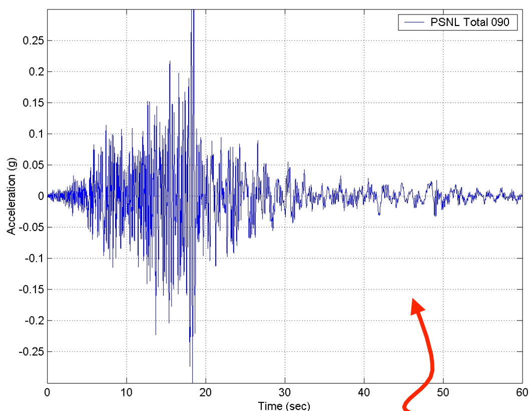
Effects of Liquefaction on Site Response

More detailed investigation

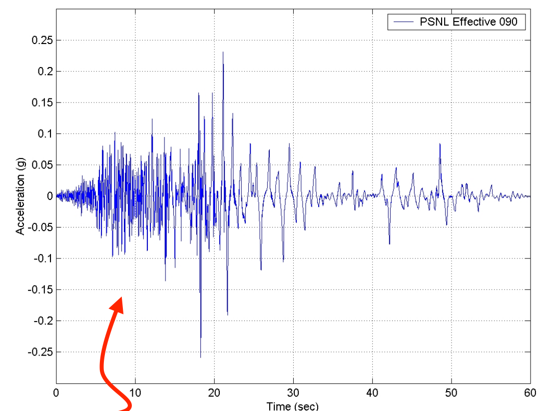
- Develop trial soil profiles
- Propagate ground motions through soil profiles to obtain surface motions
  - Once using total stress analysis, i.e. not allowing liquefaction, (*no* pore pressure generation)
  - Once using effective stress analysis allowing liquefaction, (*with* pore pressure generation)
- Compute ratios of response spectral accelerations at all periods

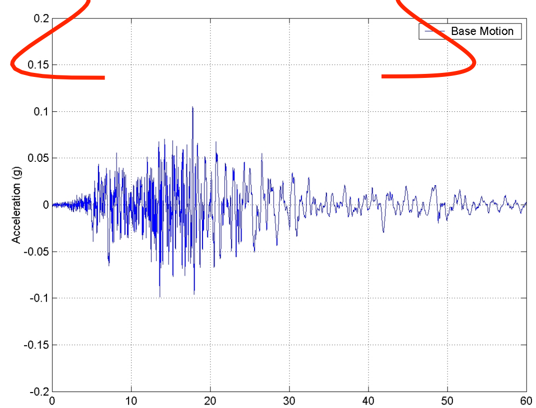
Effects of Liquefaction on Site Response

Total Stress Case



Effective Stress Case

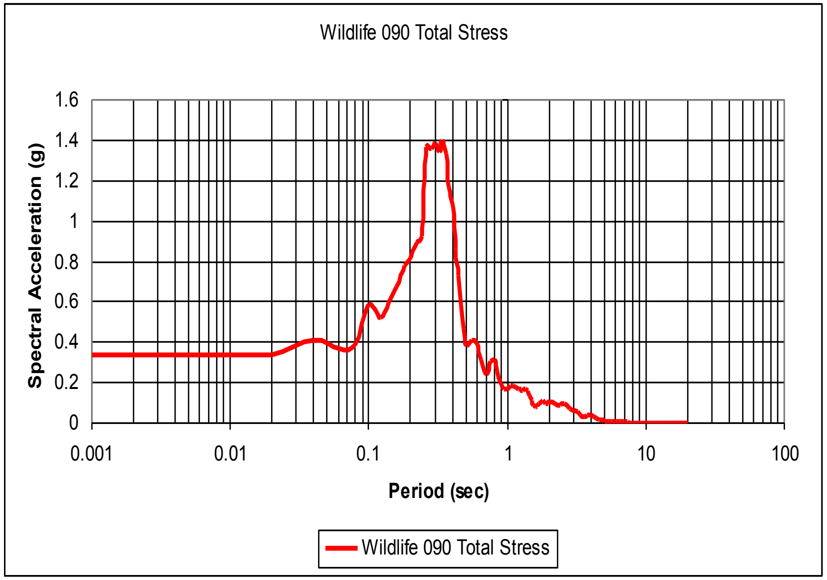




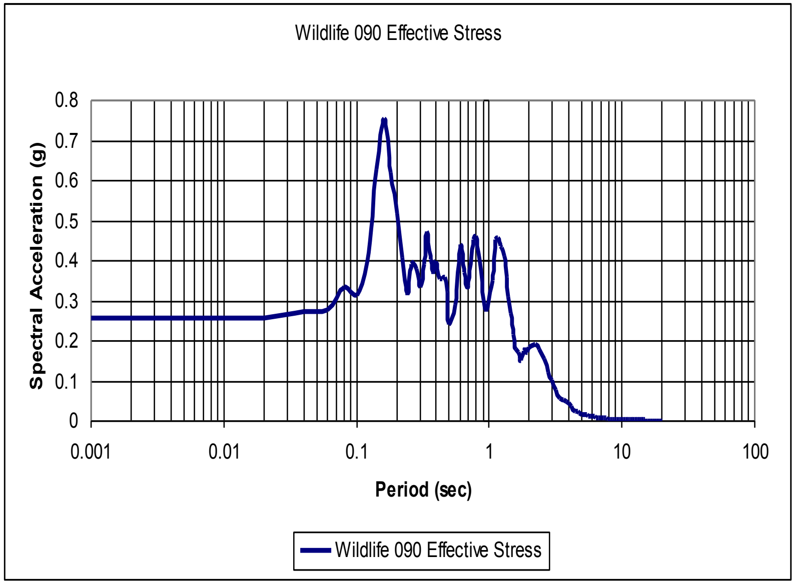
Input Base Motion

Effects of Liquefaction on Site Response

Total Stress Case



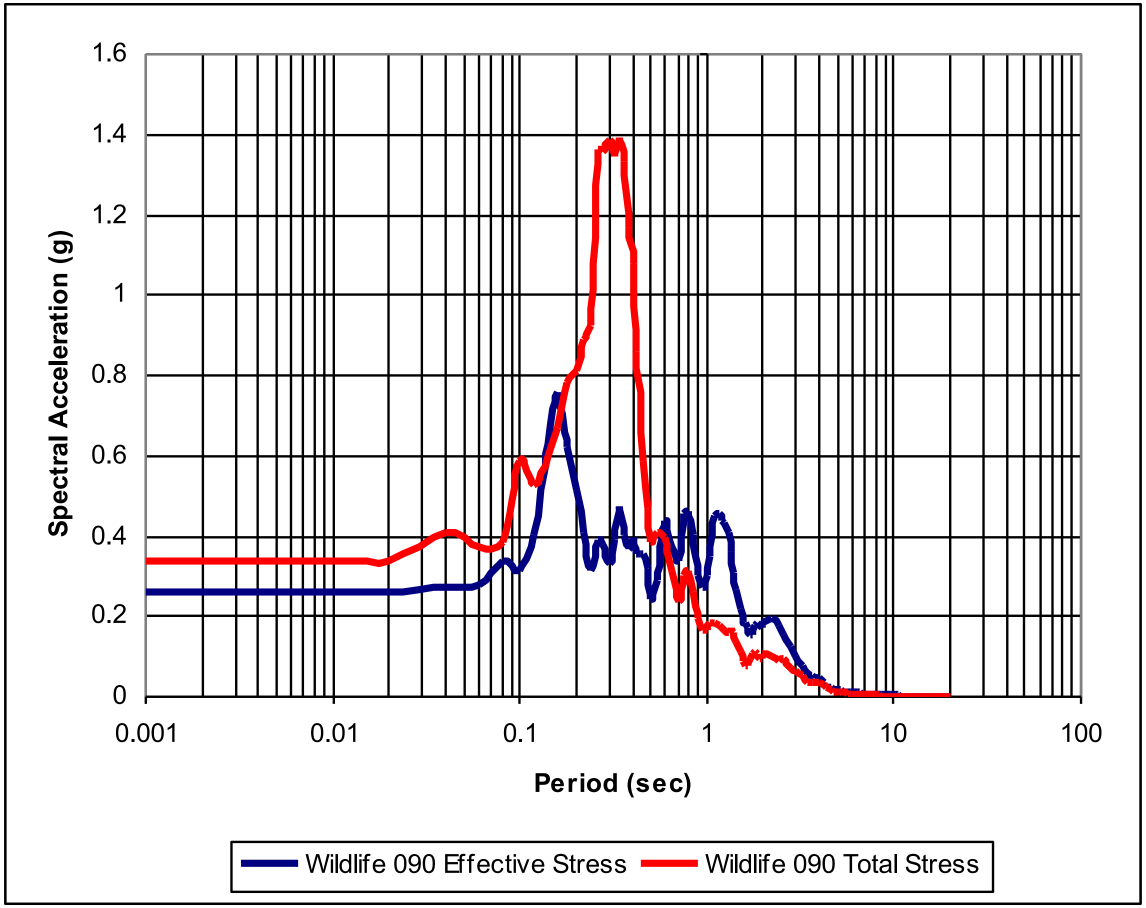
Effective Stress Case



Effects of Liquefaction on Site Response

Spectral ratio defined as

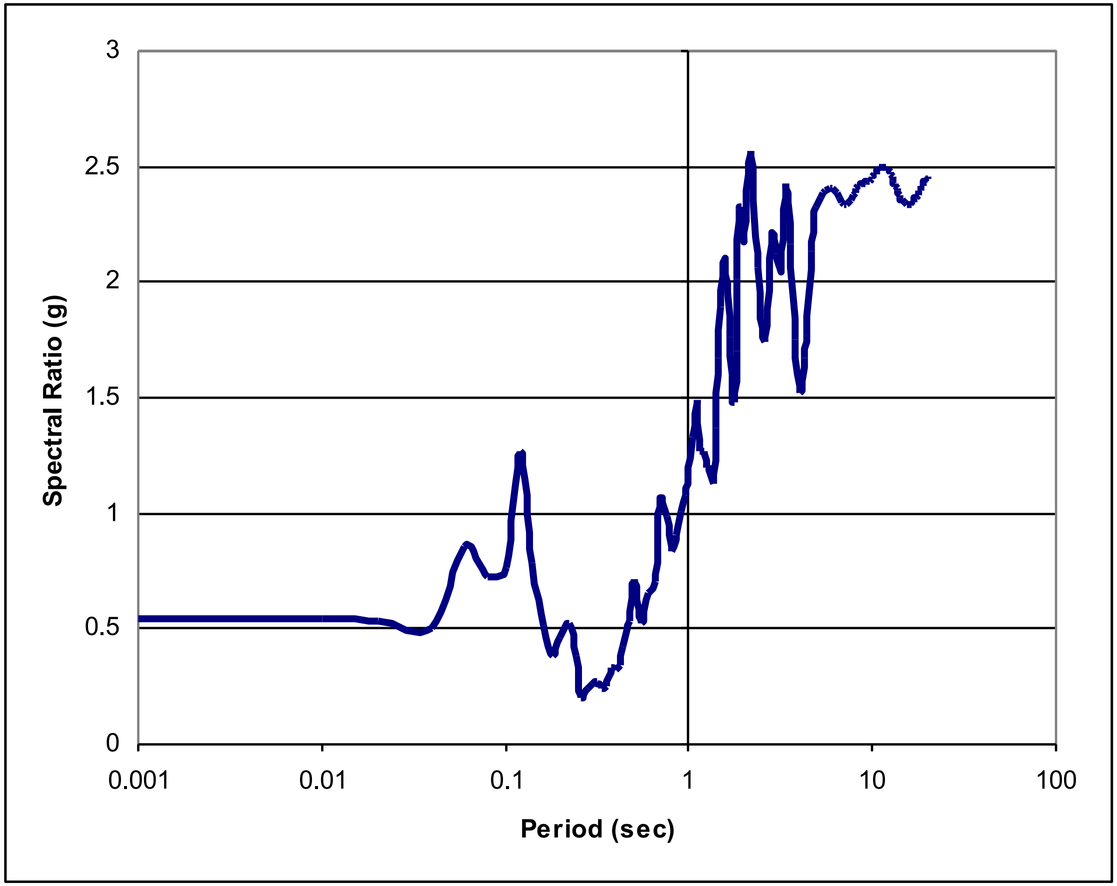
$$R(T) = \frac{S_a^{eff}}{S_a^{tot}}$$



Effects of Liquefaction on Site Response

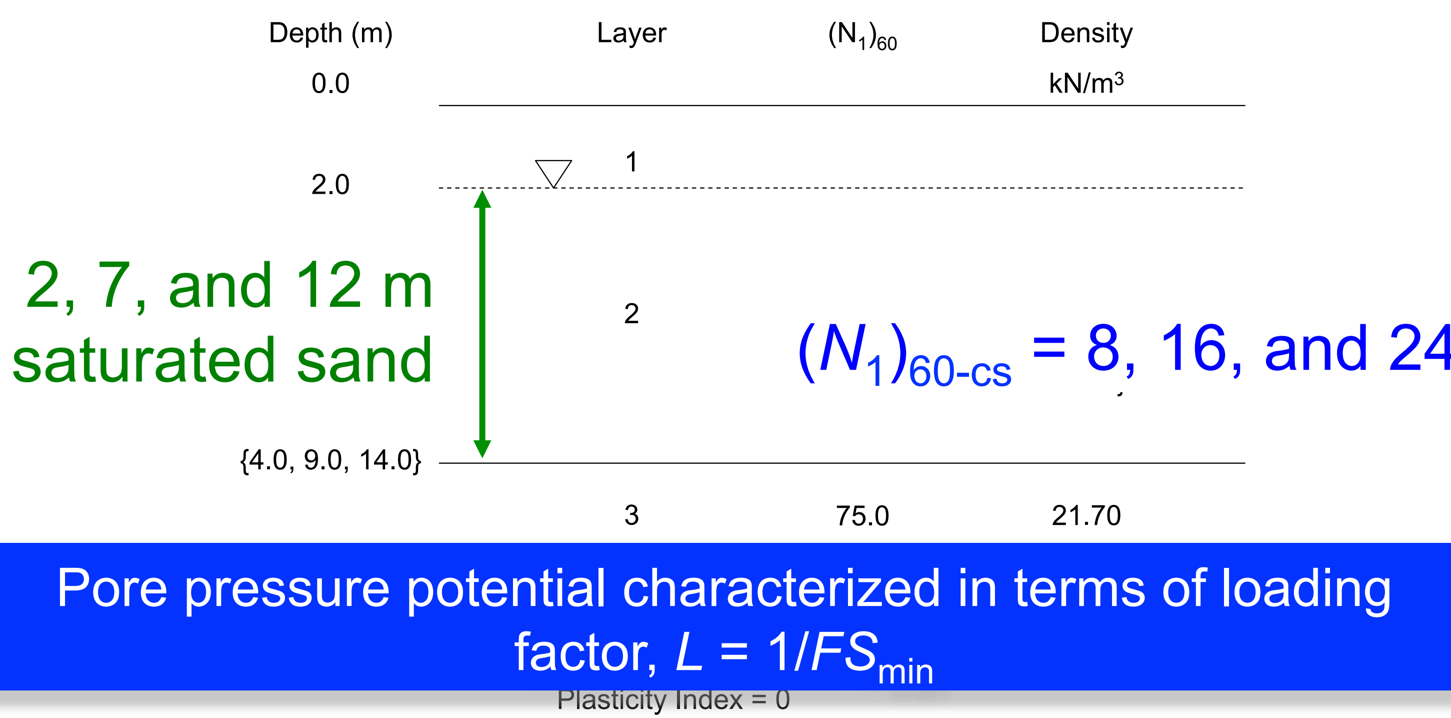
Spectral ratio defined as

$$R(T) = \frac{S_a^{eff}}{S_a^{tot}}$$



Effects of Liquefaction on Site Response

- Binned database of 140 motions
  - **Magnitudes range from 4.9 to 7.6**
  - **Distances range from 10 to 100 km**
- Suite of nine idealized soil profiles

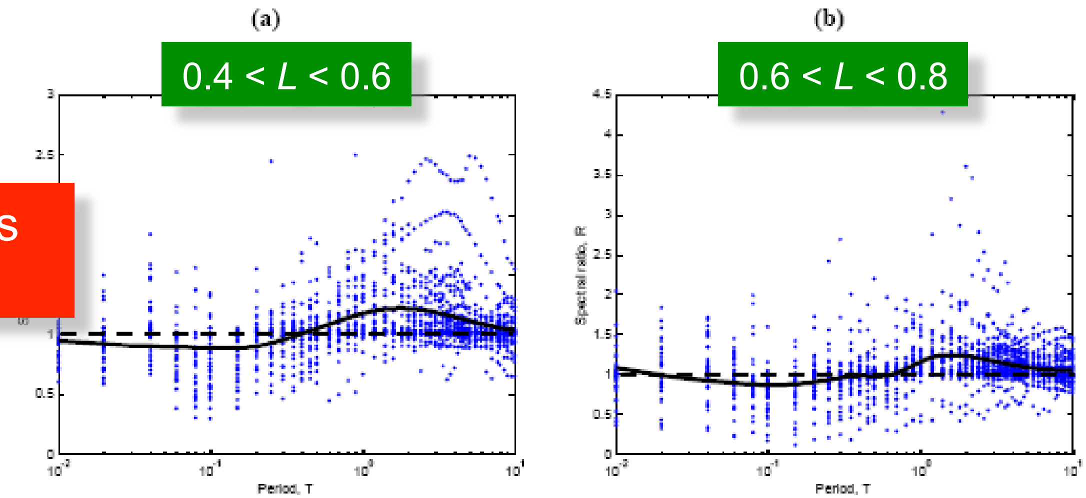


Pore pressure potential characterized in terms of loading factor, $L = 1/FS_{min}$

Effects of Liquefaction on Site Response

Overview of Results

Small Changes for low *L*



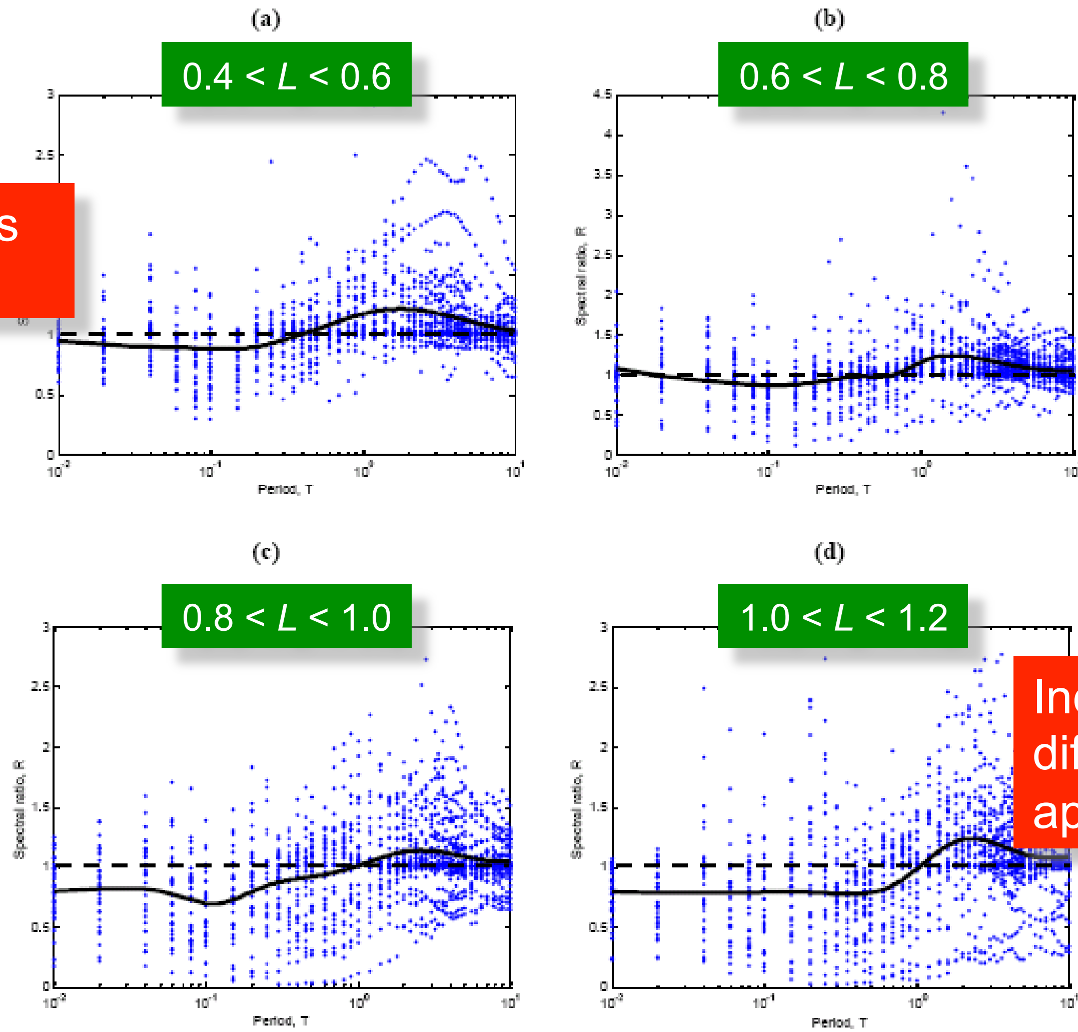
Significant scatter

Low correlation between periods

Effects of Liquefaction on Site Response

Overview of Results

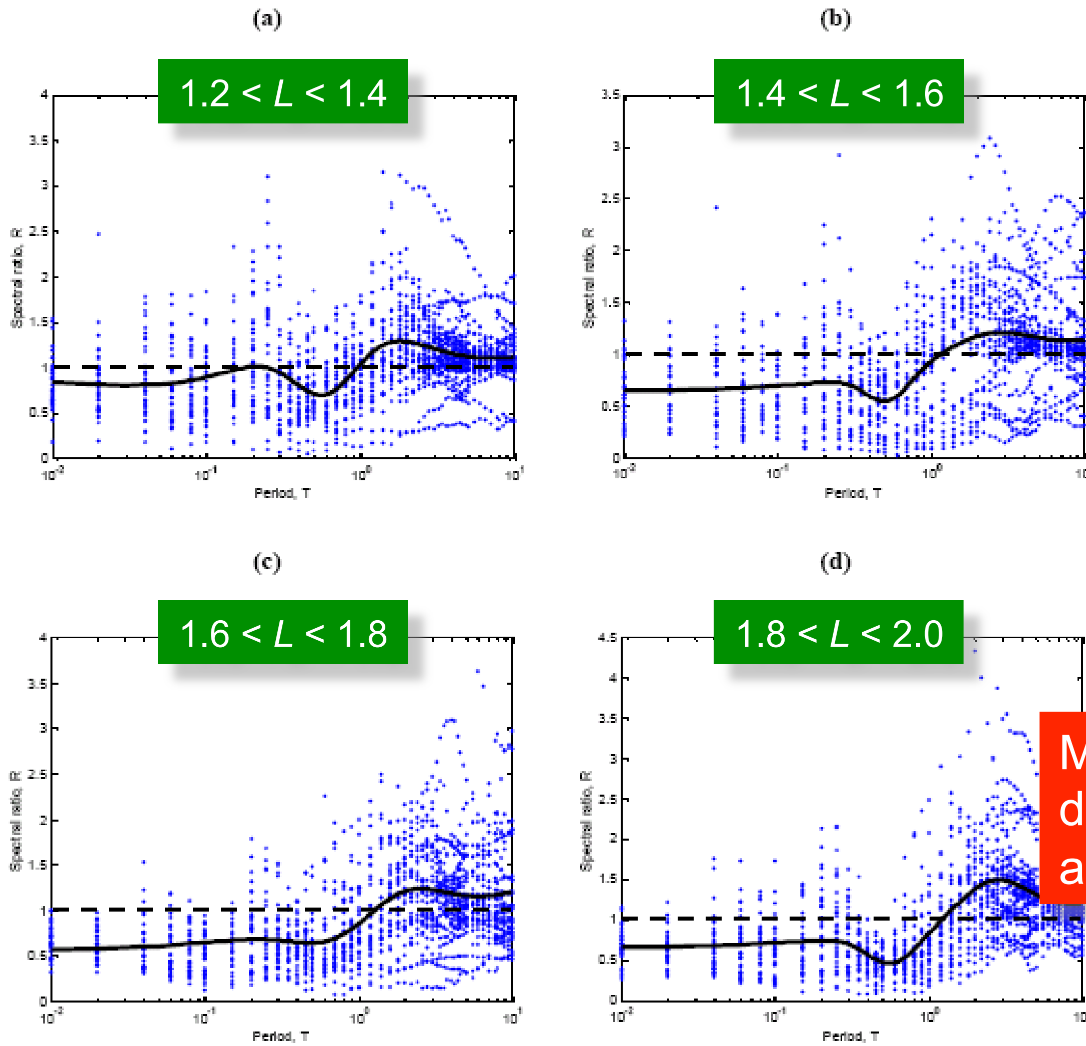
Small Changes for low *L*



Increased differences as *L* approaches 1.0

Effects of Liquefaction on Site Response

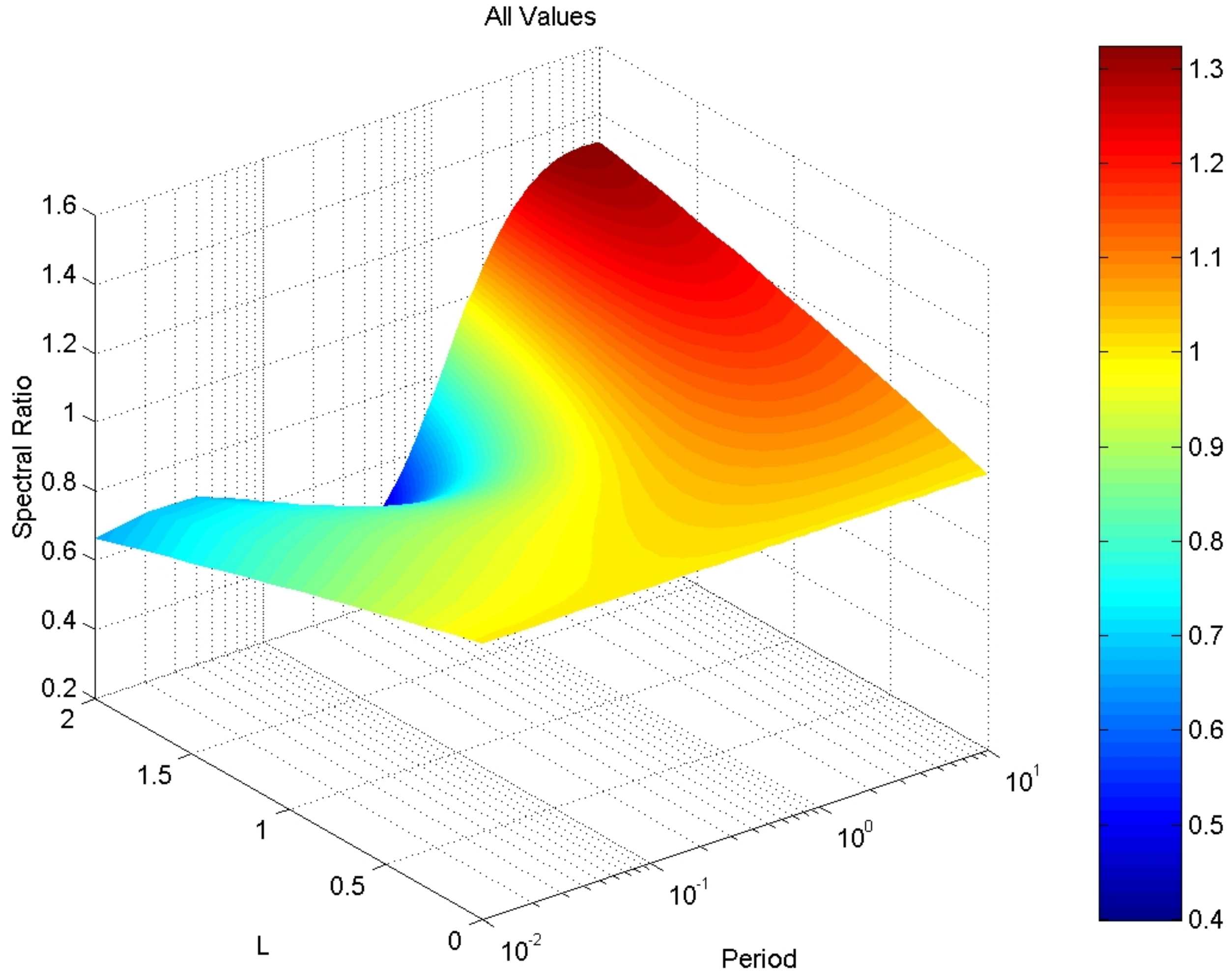
Overview of Results



More defined differences as *L* approaches 2.0

Effects of Liquefaction on Site Response

Predictive model



Effects of Liquefaction on Site Response

Model Validation

Accomplished by computation of “actual” spectral response

For *L*<1.0: Need ground motion where no pore pressure generation occurred (Elmore Ranch)

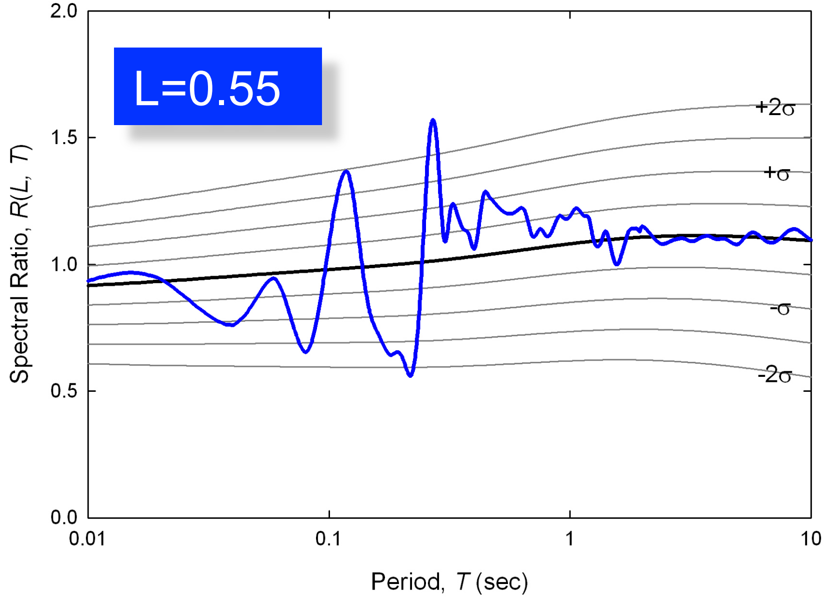
For *L*>1.0: Need ground motion where pore pressure generation has occurred (Superstition Hills)

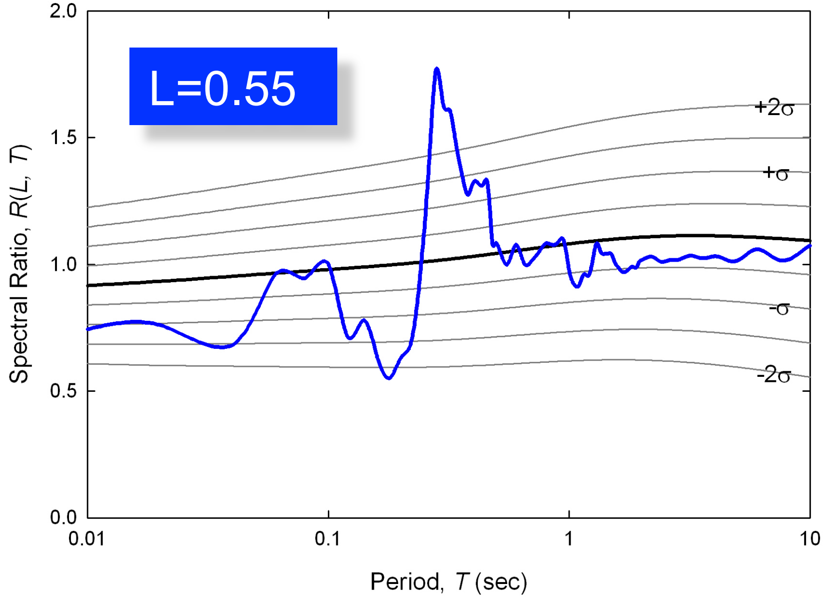
Effects of Liquefaction on Site Response

Elmore Ranch Earthquake

"Actual" Computed as

Recorded / Total Stress Analysis



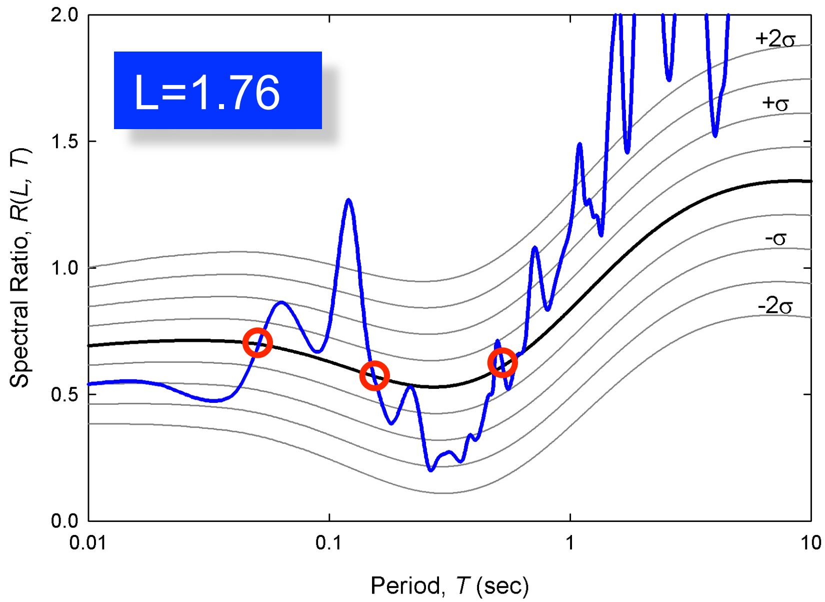


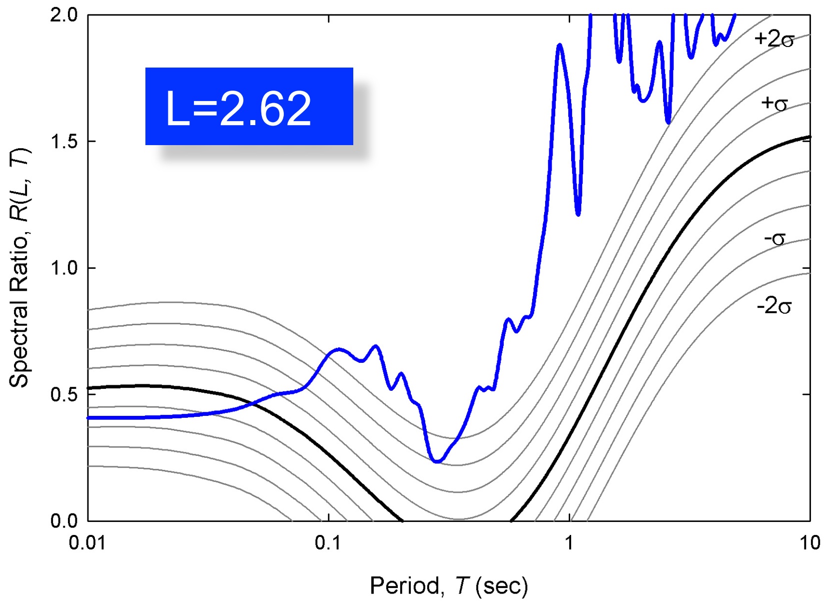
Effects of Liquefaction on Site Response

Superstition Hills Earthquake

"Actual" Computed as

Recorded / Total Stress Analysis





Summary

Liquefaction is a complex phenomenon, and understanding its mechanics is important in modeling response at sites underlain by liquefiable soils

Significant advances have been made in modeling the behavior of liquefiable soils up to and beyond the point of initial liquefaction

Many factors that affect recorded ground motions are not accounted for in commonly used site response prediction models

Summary

Despite challenges, recent models allow representation of many important characteristics of liquefiable soil profile behavior

- Reduction in amplitude of high frequency components
- Increase in amplitude of low frequency components
- Evolving change in frequency content
- Occurrence of dilation following triggering of liquefaction

Vertical arrays will play important role in further development and validation of site response models, particularly for profiles containing liquefiable soils

Thank you