Mitigation of Lateral Spreading Effects on Bridges

Professor Ross W. Boulanger
Arash Khosravifar, Graduate Student Researcher
Thang Nguyen, Graduate Student Researcher

PEER Transportation Systems Research Program (TSRP)
August 11, 2010

Title:

Mitigation of Lateral Spreading Effects on Bridges

Consider an existing ordinary bridge:

1. **Assess the potential of liquefaction and lateral spreading**
2. **If needs to fix:**
   - I. **Add more piles**
   - II. **Use large diameter extended pile shafts - Arash's work**
   - III. **Use ground improvement techniques, like DSM shear box wall - Thang's work**
   - IV. **Decision making**

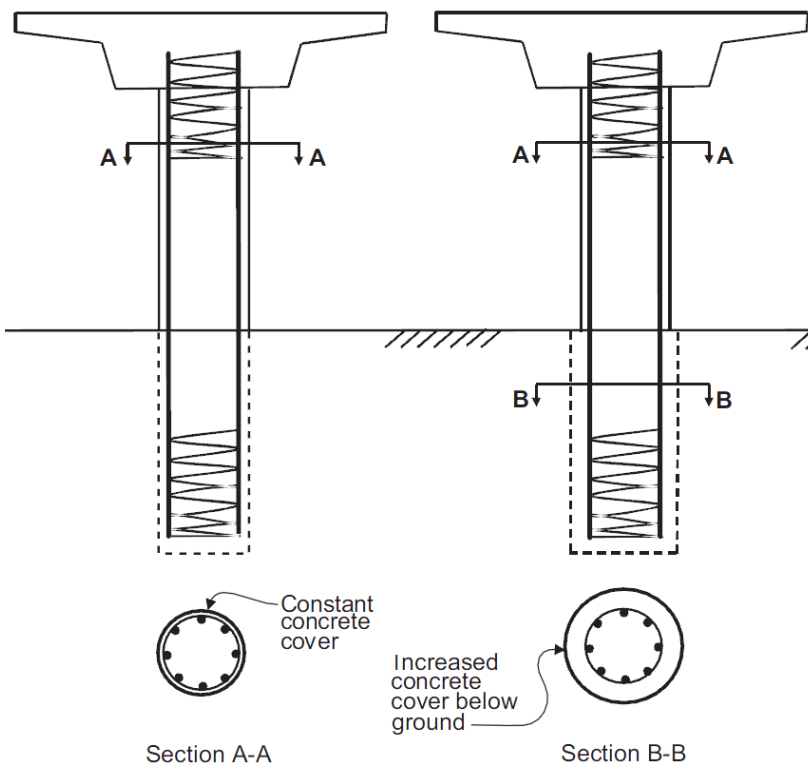
Inelastic Response of

Large Diameter Extended Pile Shafts

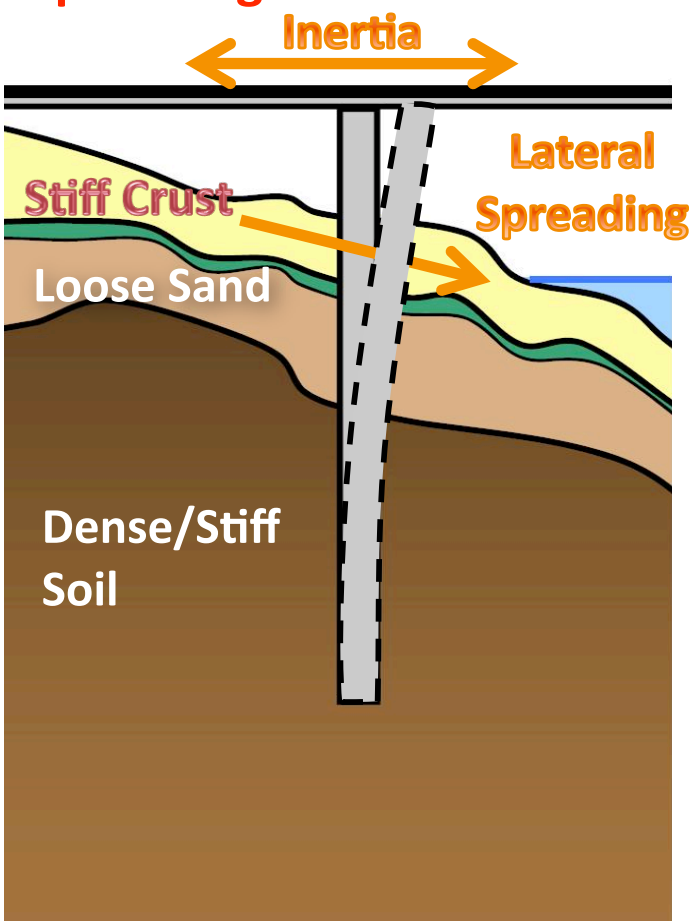
in Laterally Spreading Ground during Earthquakes

Statement of Problem

- **Large diameter extended pile shafts (2 to 3 m) can be an effective choice in areas of potential lateral spreading.**
- **How to design for effects of shaking and lateral spreading?**



TYPE I SHAFTS

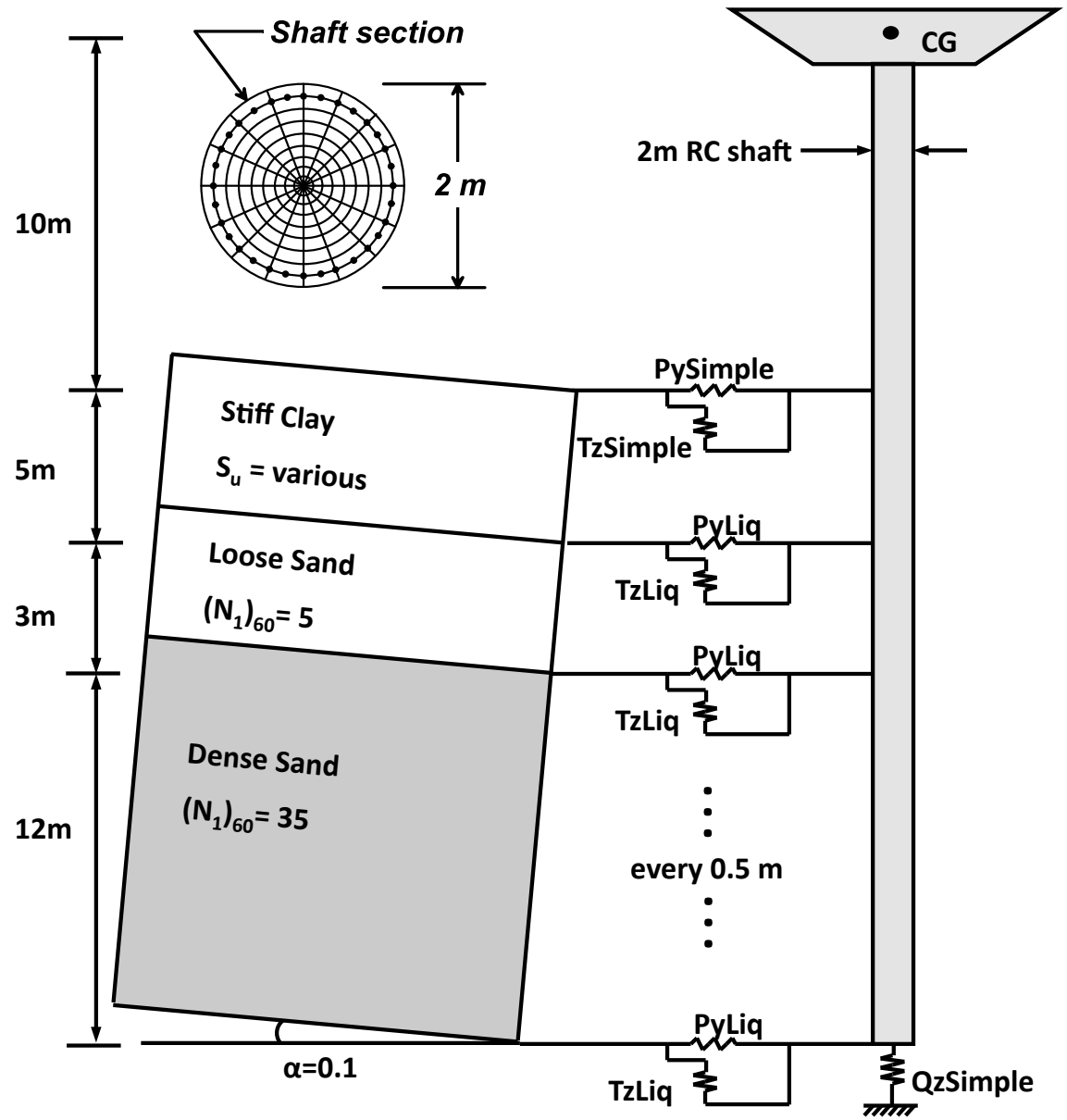


Research Approach

1. Nonlinear Dynamic FE Analyses (NDA)
3. Evaluate Current Caltrans Equivalent Static Analysis (ESA)
4. Develop an Improved Guidance

Nonlinear Dynamic FE

1. OpenSees FE framework
2. Soil elements (far field)
   - Constitutive models (MYPD and MYPI)
   - 2Dim "Up" elements
3. Pile elements
   - Fiber sections
   - Flexibility based nonlinear beam column elements
4. Soil springs
   - PY and PYLiq
   - TZ and TZLiq
   - QZ

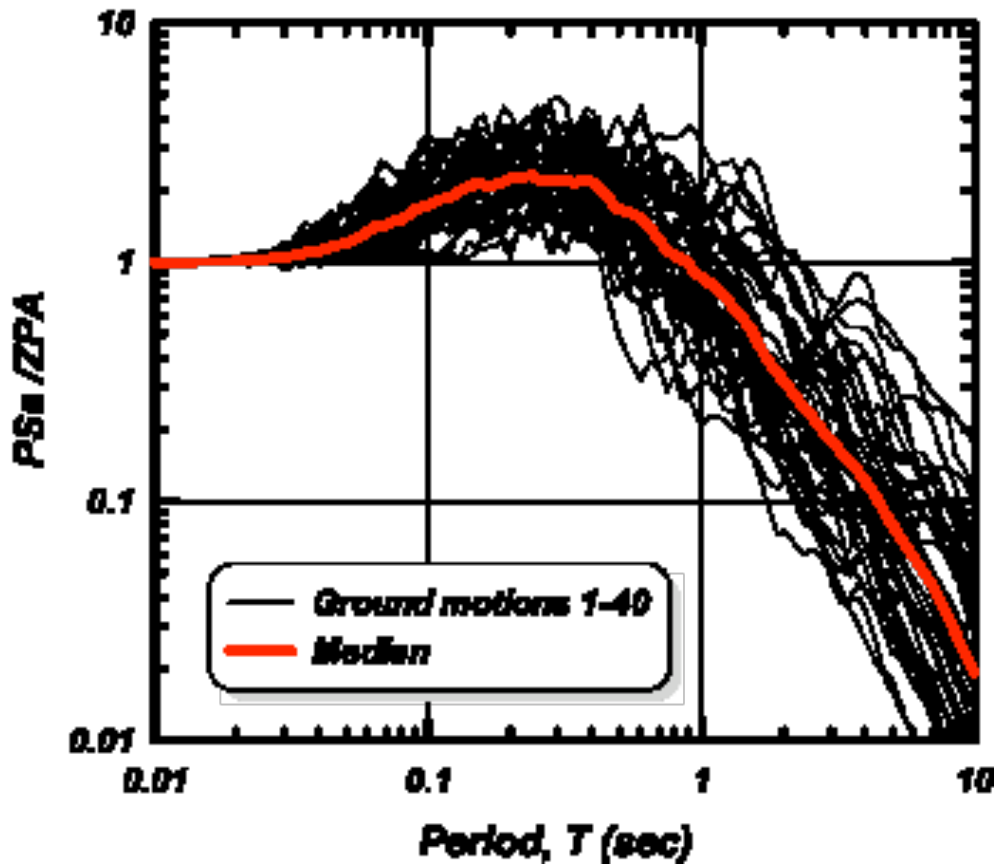


Ground Motions

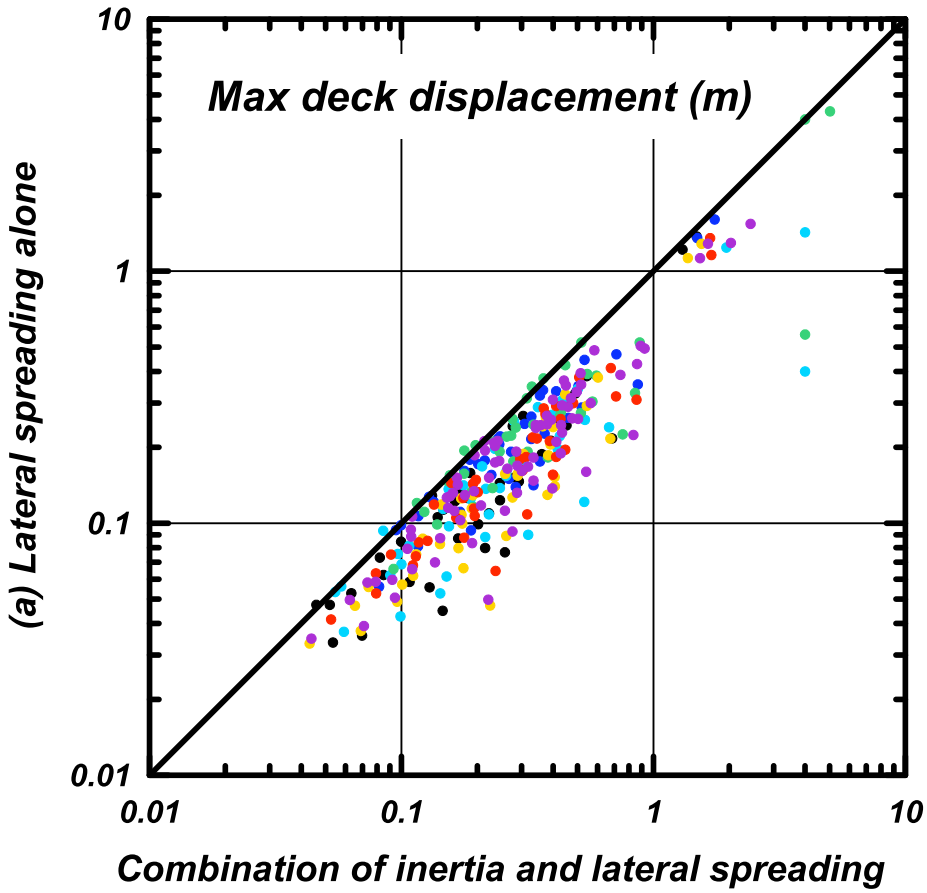
40 ground motions from Professor J. Baker

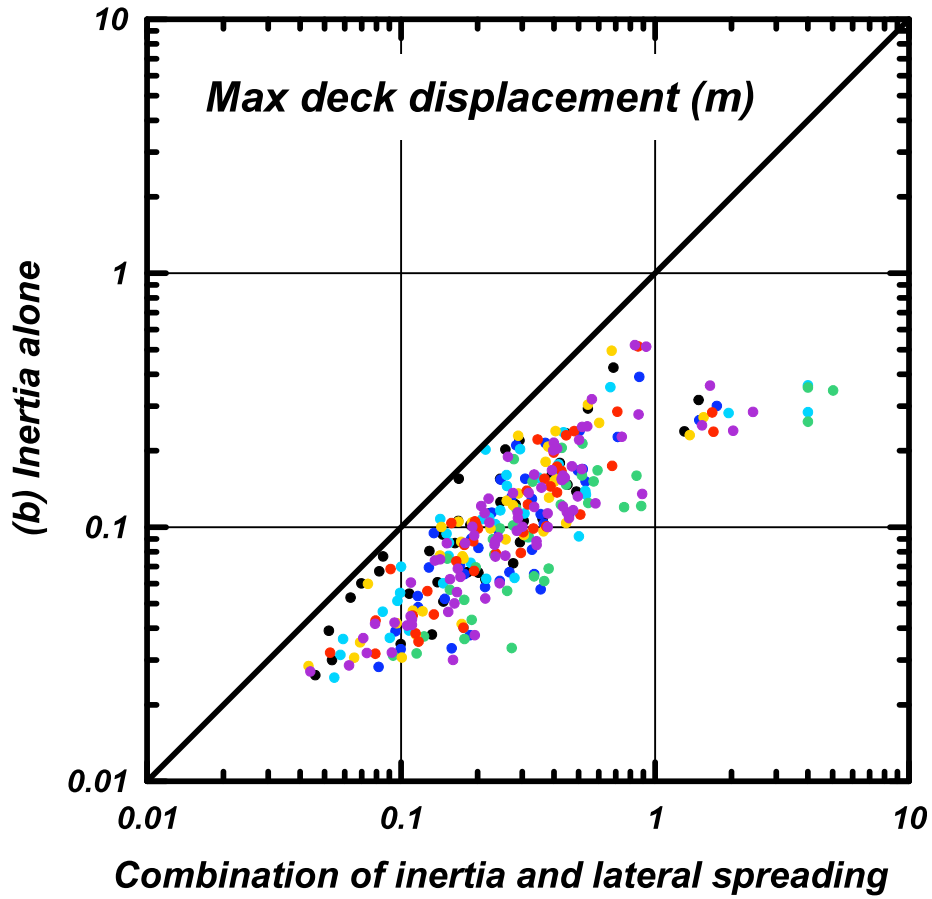
They were selected so that their response spectra match the median and log standard deviations predicted from Boore and Atkinson (2008) model: (from J. Baker, Stanford U.)

- Magnitude = 7 earthquake
- Source-to-site distance = 10 km
- Site Vs30 = 760 m/s
- Earthquake mechanism = strike slip

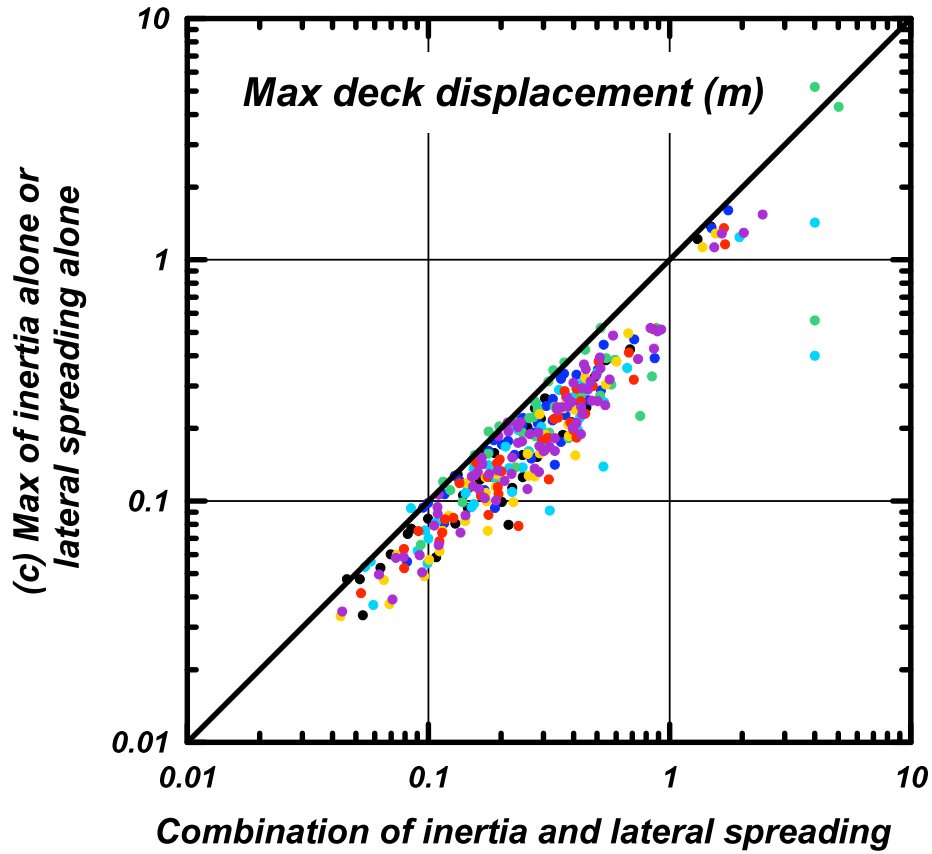


Results


Max deck displacement (m)
(a) Lateral spreading alone
Combination of inertia and lateral spreading
10
1
0.1
0.01
0.01
0.1
1
10


Max deck displacement (m)
(b) Inertia alone
Combination of inertia and lateral spreading
10
1
0.1
0.01
0.01
0.1
1
10

Results


Max deck displacement (m)
(c) Max of inertia alone or lateral spreading alone
Combination of inertia and lateral spreading
10
1
0.1
0.01
0.01
0.1
1
10

Conclusions:

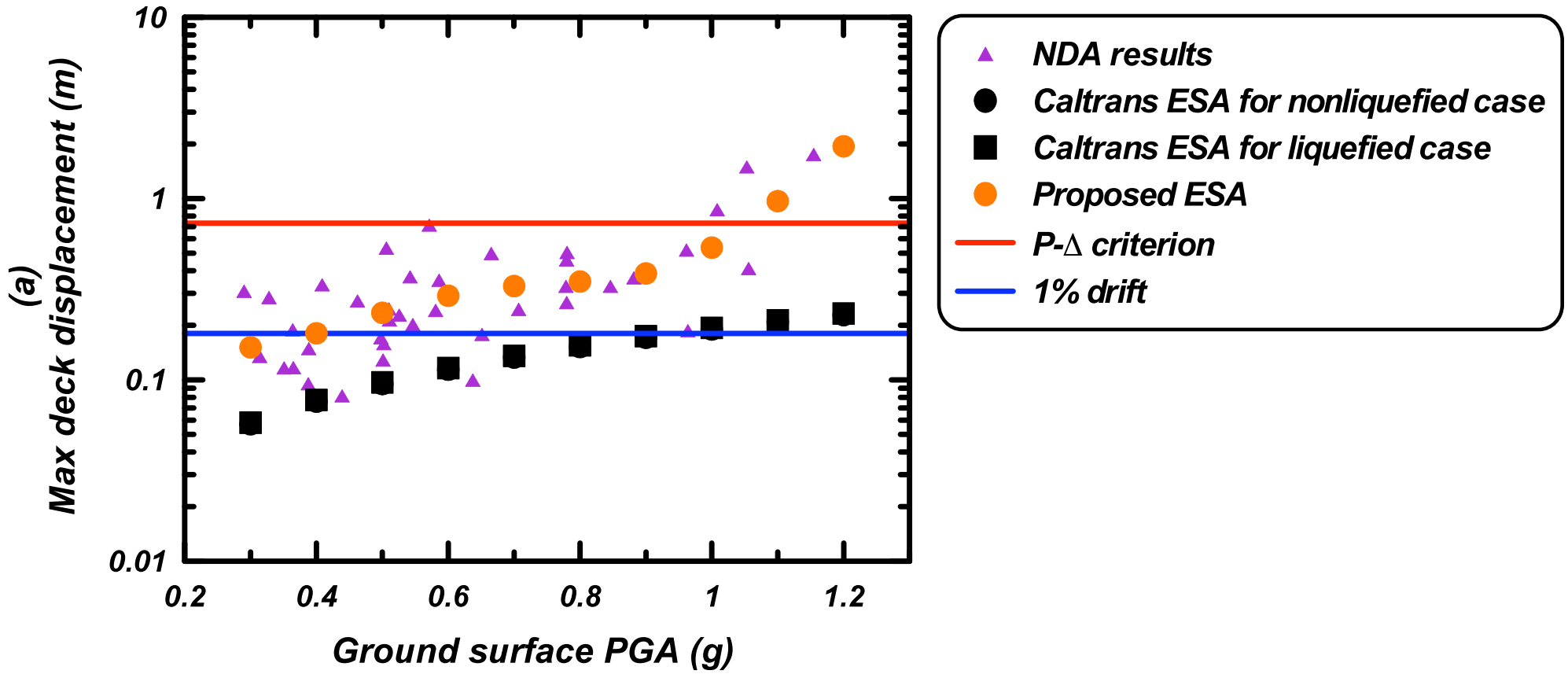
- **Dynamic FE analyses show that:**
  - **coupling of inertial and kinematic demands during lateral spreading can be the governing load case, and**
  - **that is not enveloped by analyzing the inertial and kinematic loading cases separately.**

- **Caltrans DRAFT ESA criteria:**
  - **The ESA underestimate the peak displacement and ductility demands,**
  - **The criterion for M_{LS} being less than 20% M_p did not correlate well with either good or poor performance.**

Conclusions (Cont'd)

- **Draft proposed ESA includes:**
  1. **Analyze the non-liquefaction case.**
  2. **Analyze the liquefaction case by:**
     - i. **Removing p-y springs from liquefied and crust layers,**
     - ii. **Applying full passive earth pressure from the crust,**
     - iii. **Imposing an additional superstructure displacement $\Delta_2 = C_{\Delta L}\ \Delta_{NL}$, where Δ_{NL} is the demand predicted in the absence of liquefaction. Currently, we use $C_{\Delta L}$=1.0 based on the NDA results.**
     - iv. **Adjusting the predicted deck displacement if significant shear strains are estimated to occur in the underlying dense/stiff soils.**
- **The proposed ESA appears to work equally well for structures that do not yield ($\mu_\phi \leq 1$) and do yield ($1 \leq \mu_\phi \leq 3.5$). We are currently performing a broader set of parametric analyses, which may lead to revisions in the ESA procedures.**

Results


(a)
Max deck displacement (m)
10
1
0.1
0.01
0.2
0.4
0.6
0.8
1
1.2
Ground surface PGA (g)
NDA results
Caltrans ESA for nonliquefied case
Caltrans ESA for liquefied case
Proposed ESA
P-Δ criterion
1% drift

Ground Improvement Methods:

Cement-mix shear box

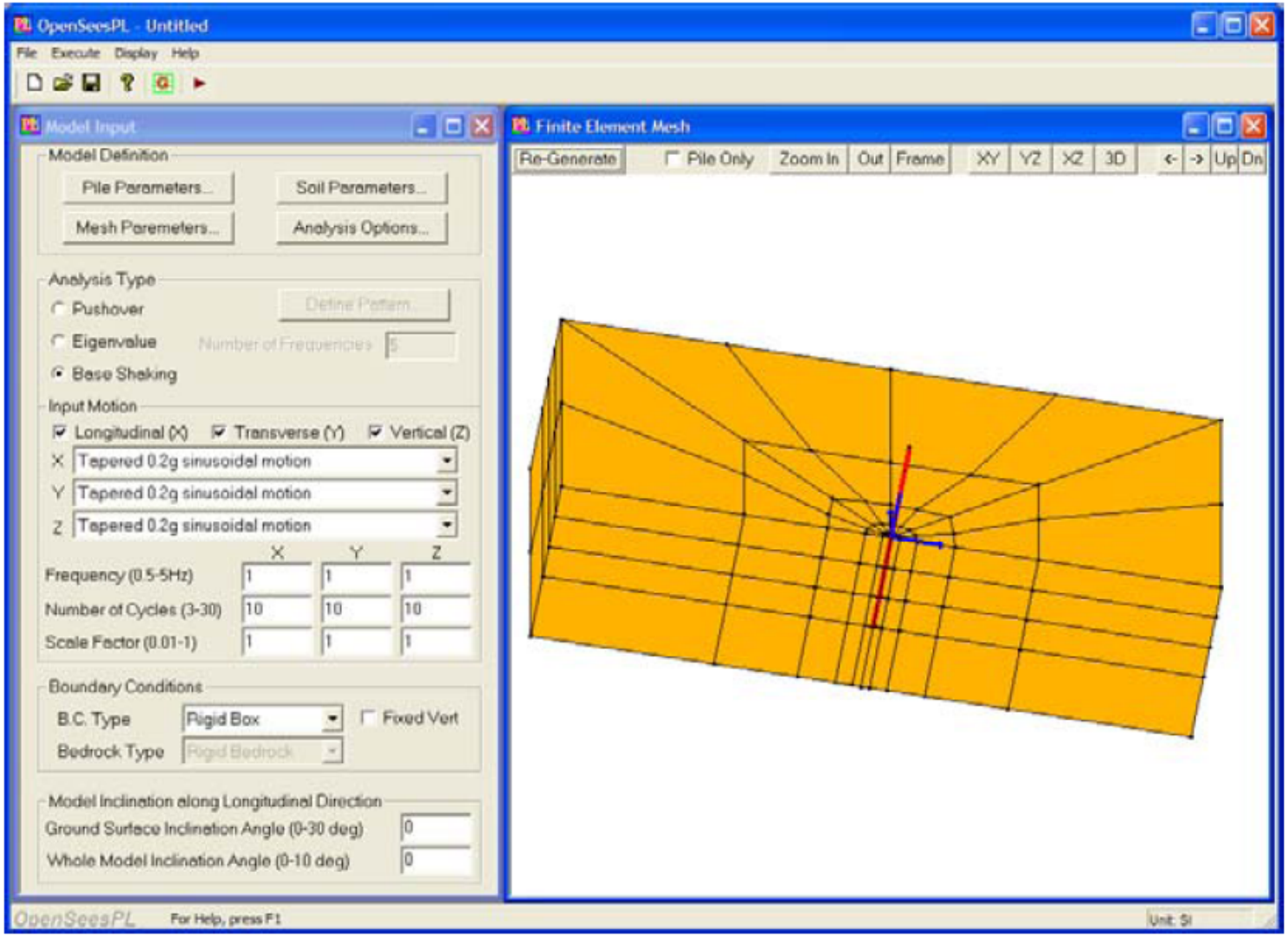


Figure 2.1: OpenSeesPL main window.

Next Tasks:

1. 3D vs. 2D simulation using OpenSeesPL
   - How much do the results change?
   - Do the findings change?
   - What are the important factors/parameters?

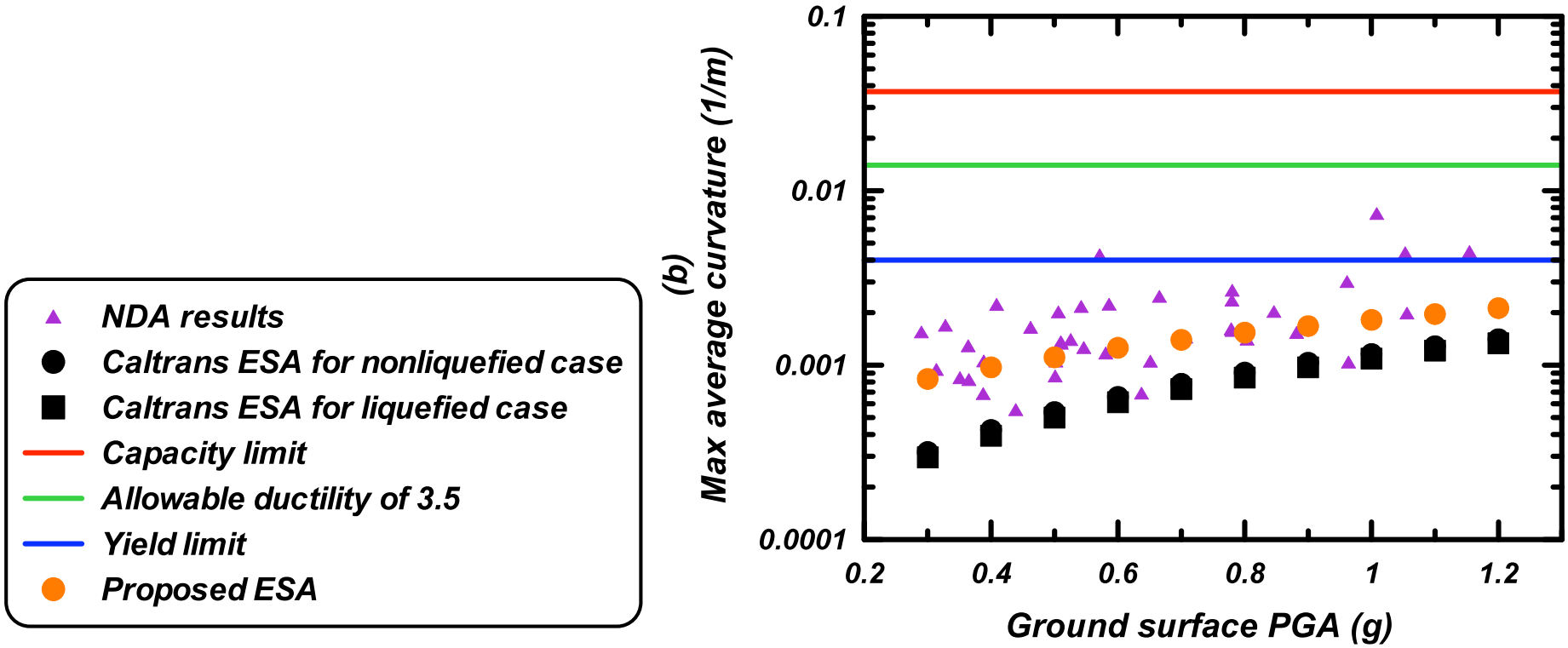
2. Decision Making

   Compare the efficiency and cost of different mitigation techniques
   - Extended pile shaft vs. pile group
   - Extended pile shaft vs. ground improvement

Animation
Nonlinear Dynamic Analysis (NDA)

Thank you

Any question ?


NDA results
Caltrans ESA for nonliquefied case
Caltrans ESA for liquefied case
Capacity limit
Allowable ductility of 3.5
Yield limit
Proposed ESA
(b)
Max average curvature (1/m)
0.1
0.01
0.001
0.0001
0.2
0.4
0.6
0.8
1
1.2
Ground surface PGA (g)

Equivalent Static Analysis (ESA): Caltrans Draft Guidance

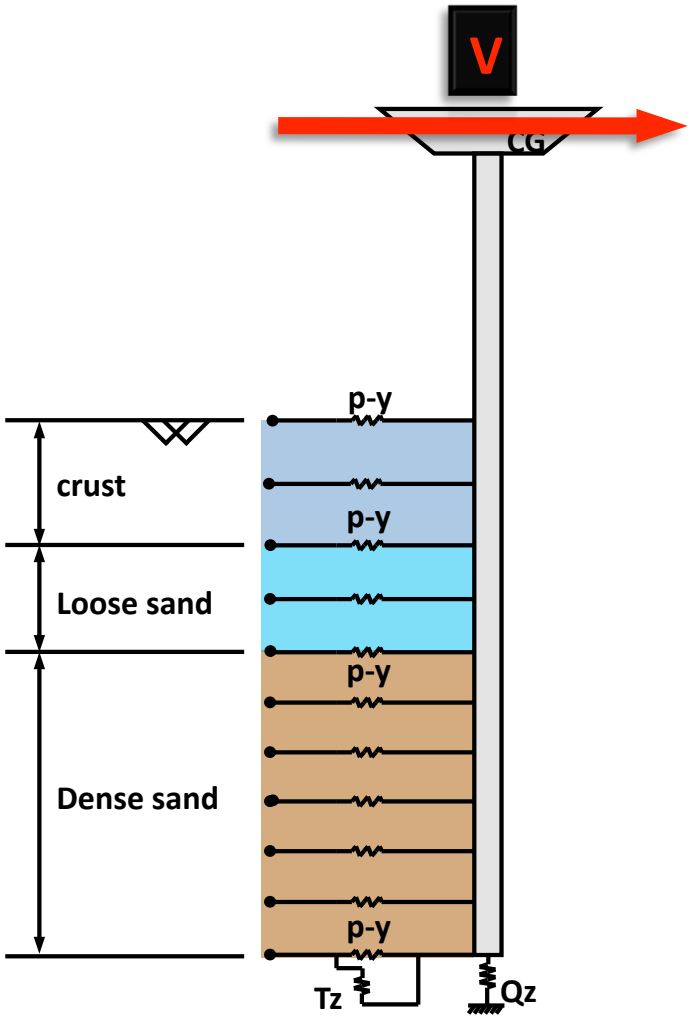
ESA - Caltrans Draft

Steps include:

1. **Pushover analysis without liquefaction**
   - Use non-liquefied p-y and t-z springs

2. **Pushover analysis with liquefaction (no LS)**
   - Use liquefied springs (p-multipliers)

3. **Apply lateral spreading (LS) force alone**
   - Check that $M_{LS} < 0.20\ M_p$



ESA – Deck Displacement Demand w/o Liquefaction (Example)

Elastic period

T_e (non-liq) = 3.2 sec

For 0.6 g at rock outcrop

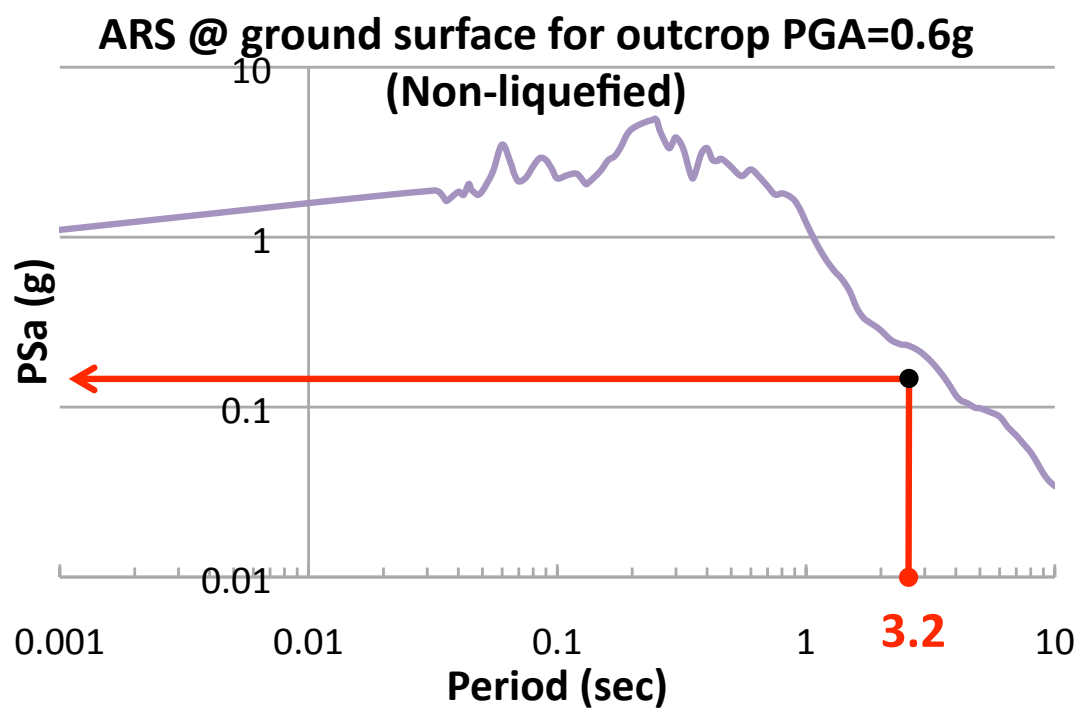
PSa = 0.11 g

$\Delta_e = PSa/\omega^2 = 0.28$ m

Use R-μ-T relationships

High T_e → "equal displacement"

$\Delta_{e\text{-}p} = 0.28$ m



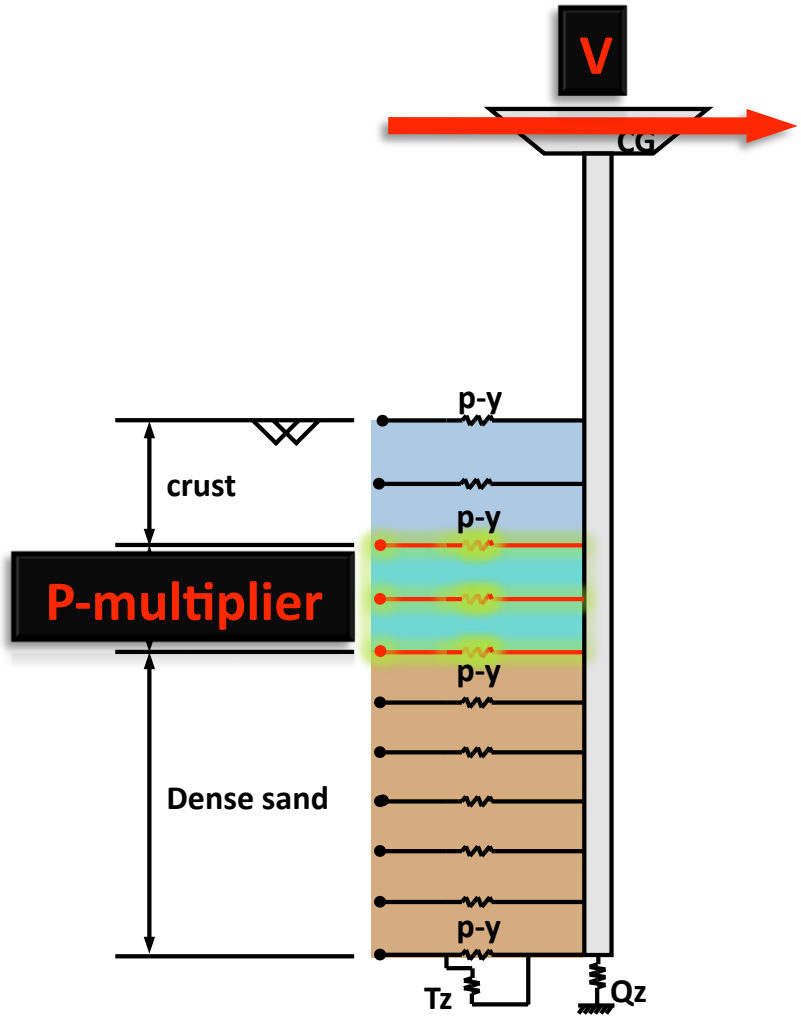
ESA - Caltrans Draft

Steps include:

1. **Pushover analysis without liquefaction**
   - Use non-liquefied p-y and t-z springs

2. **Pushover analysis with liquefaction (no LS)**
   - Use liquefied springs (p-multipliers)

3. **Apply lateral spreading (LS) force alone**
   - Check that $M_{LS} < 0.20$ Mp



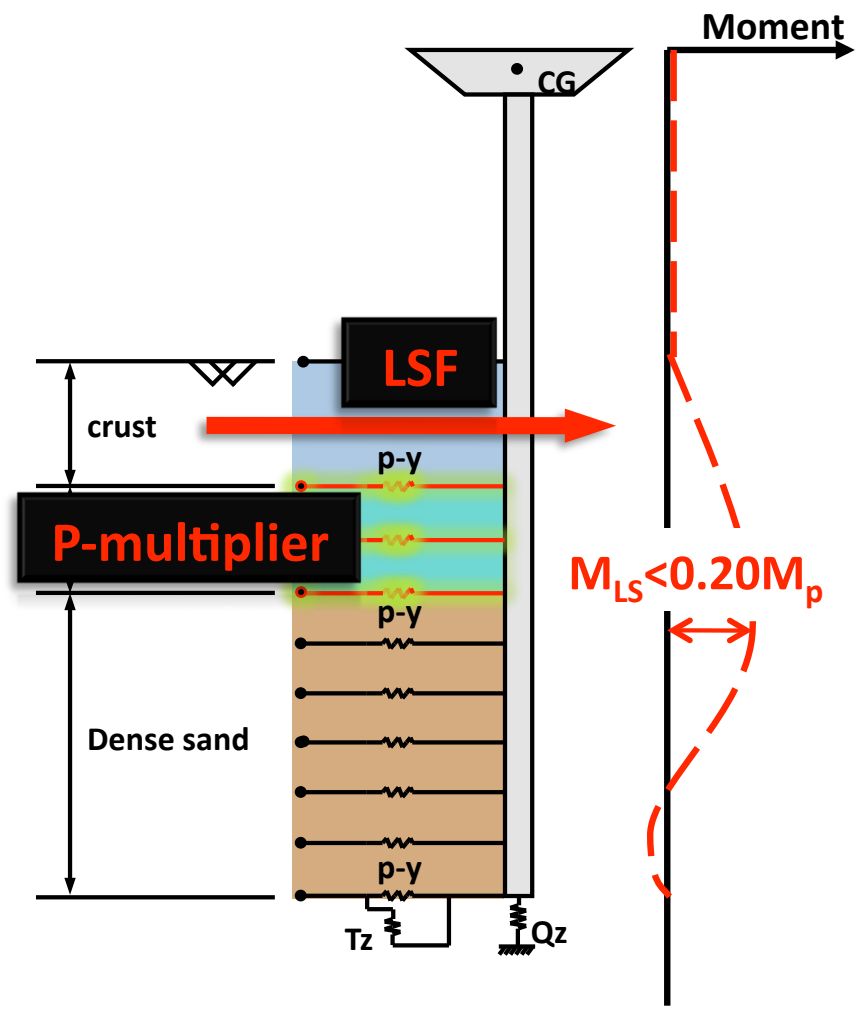
ESA - Caltrans Draft

Steps include:

1. **Pushover analysis without liquefaction**
   - Use non-liquefied p-y and t-z springs

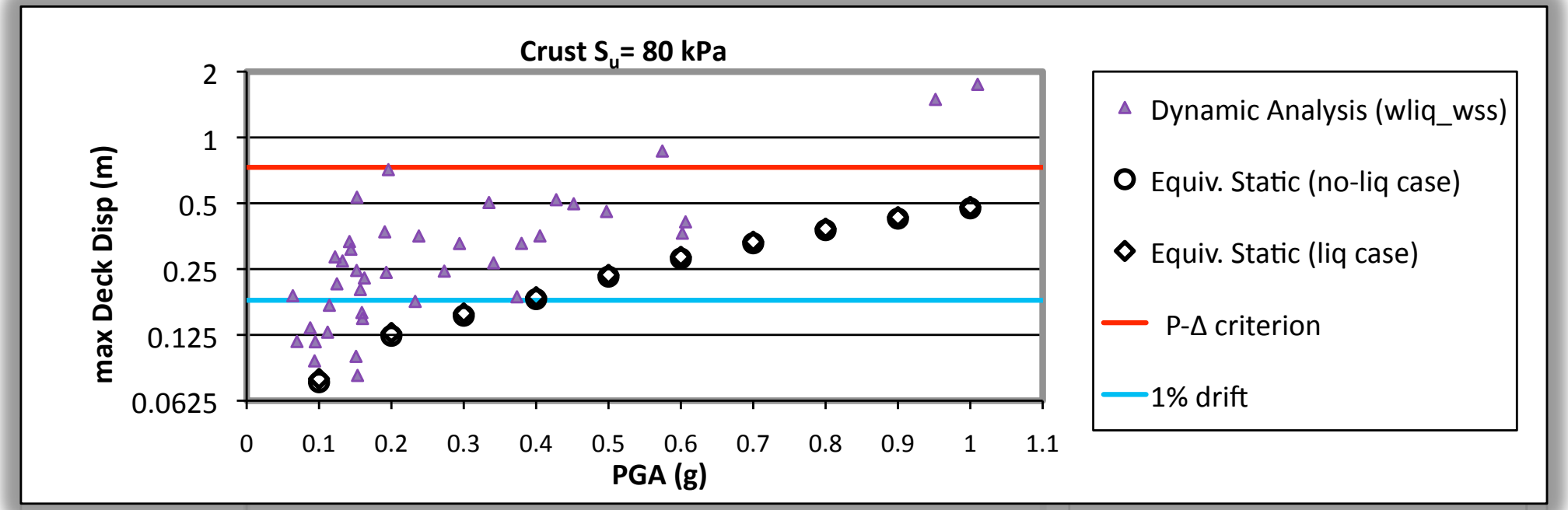
2. **Pushover analysis with liquefaction (no LS)**
   - Use liquefied springs (p-multipliers)

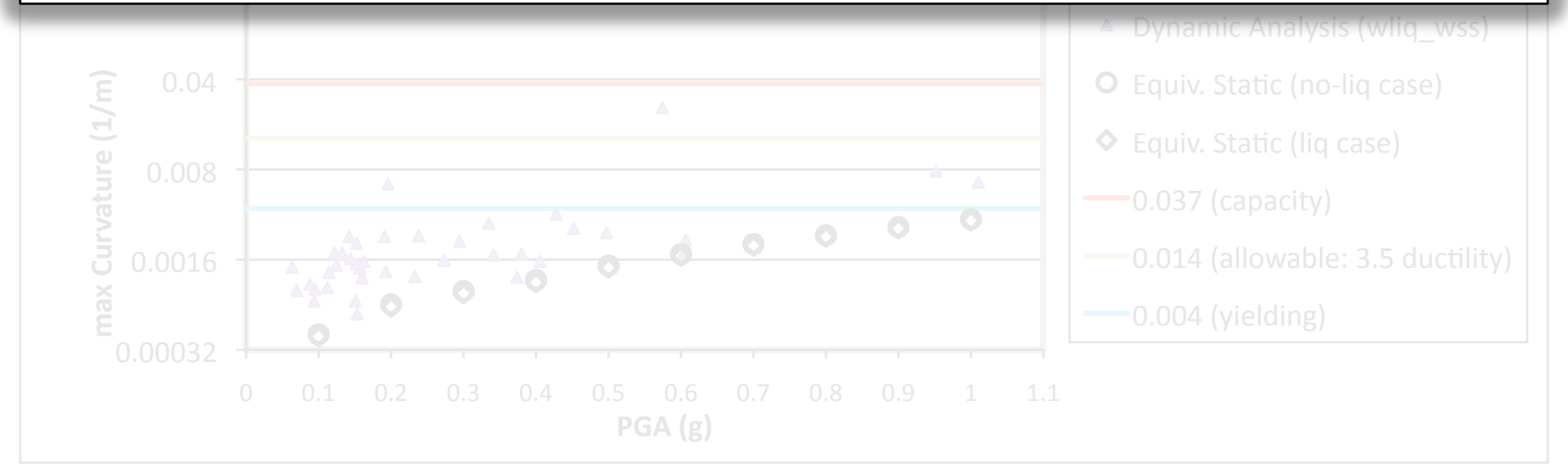
3. **Apply lateral spreading (LS) force alone**
   - Check that $M_{LS} < 0.20$ Mp



ESA-Caltrans vs. FE Nonlinear Dynamic Analysis

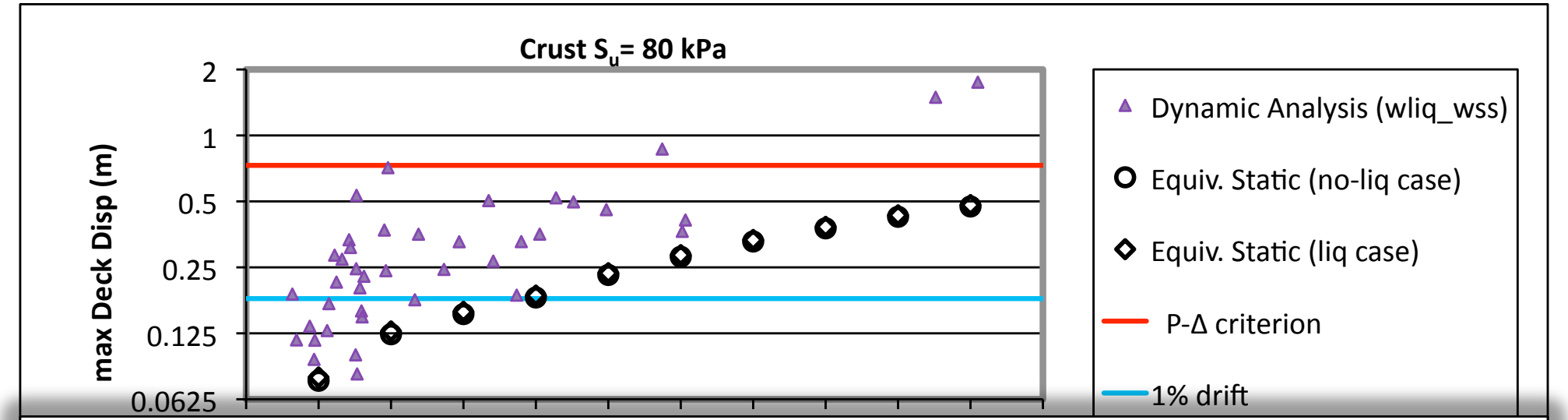
ρ_s = 4%, Axial P = 10% $A_g.f'_c$ ⟶ $\mu_\phi \leq 1$ (low ductility)

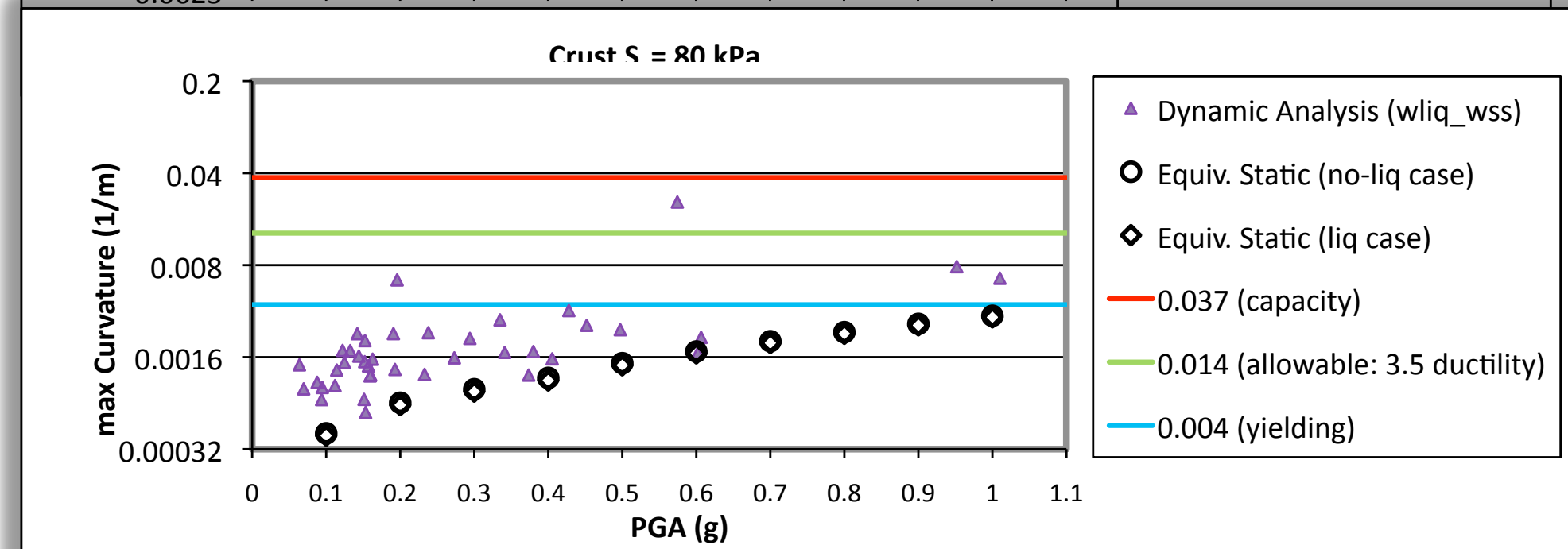




ESA-Caltrans vs. FE Nonlinear Dynamic Analysis

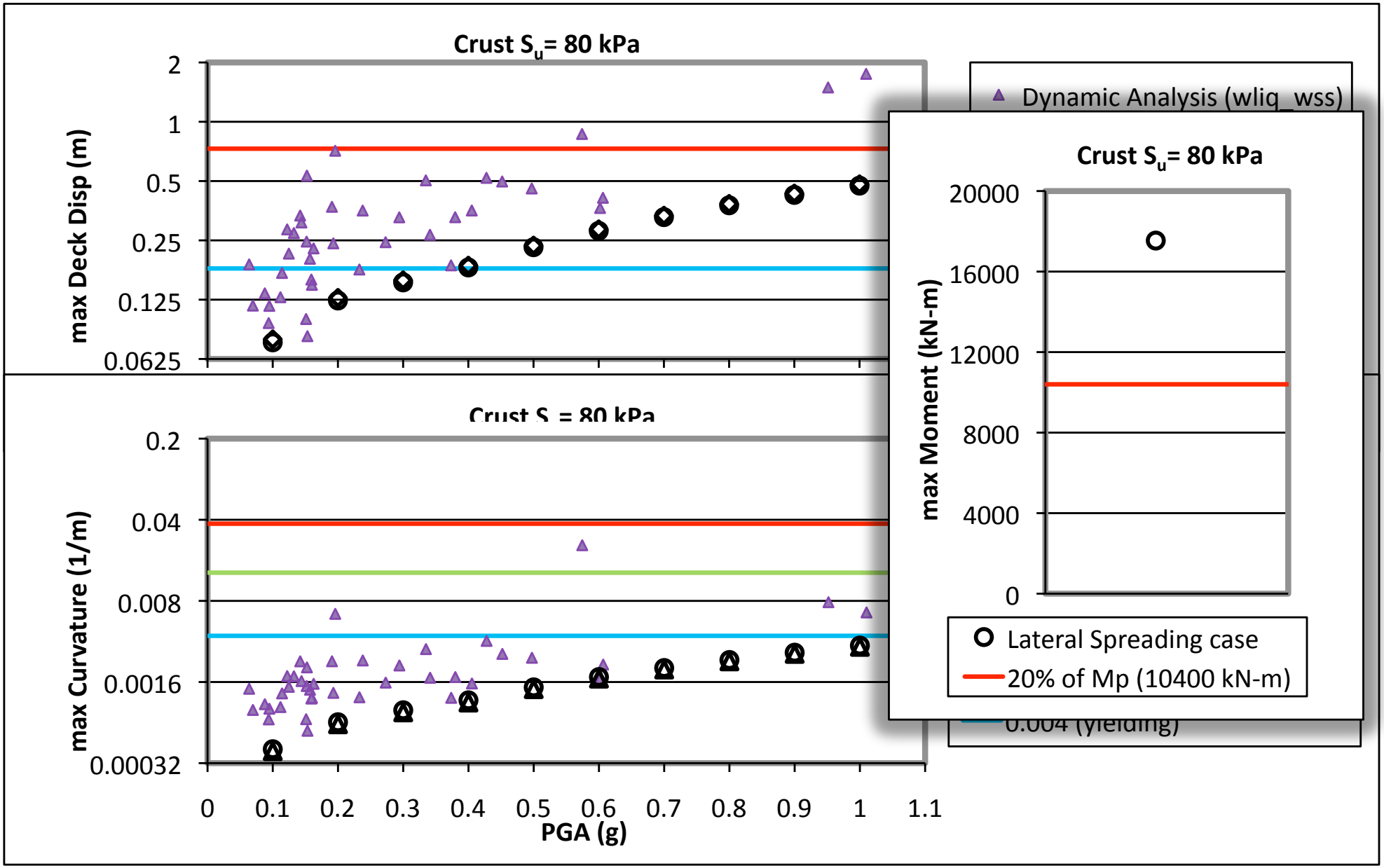
ρ_s = 4%, Axial P = 10% $A_g.f'_c$ ⟶ $\mu_\phi \leq 1$ (low ductility)





ESA-Caltrans vs. FE Nonlinear Dynamic Analysis

ρ_s = 4%, Axial P = 10% $A_g.f'_c$ ⟶ $\mu_\phi \leq 1$ (low ductility)



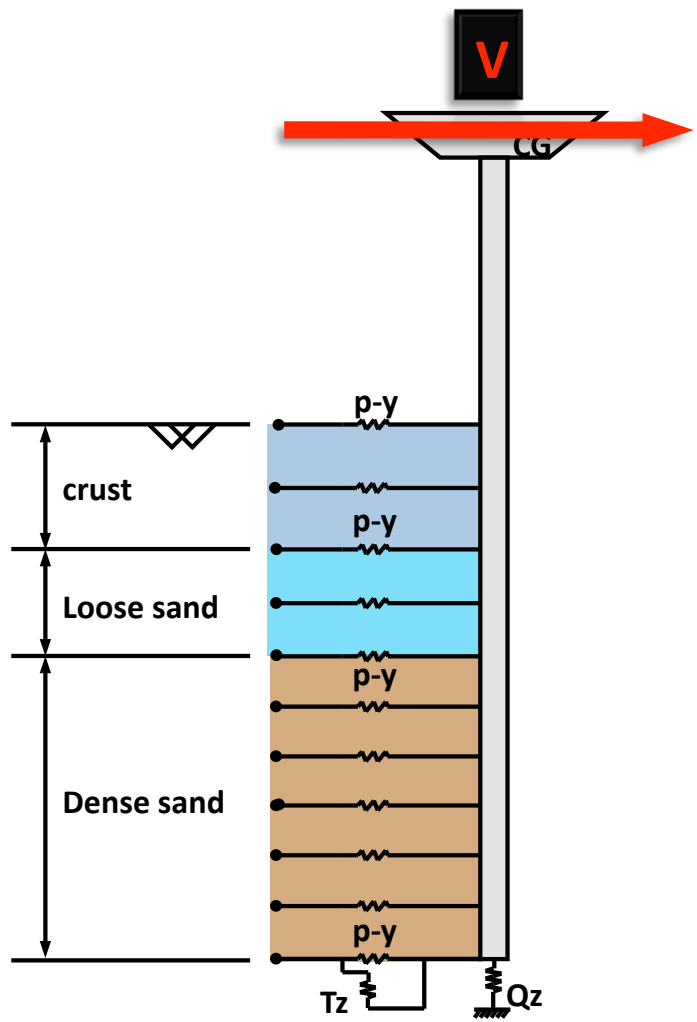
Equivalent Static Analysis (ESA): Draft Proposed Guidance

ESA – Draft Proposed Guidance

Steps include:

1. **Analyze for non-liquefaction case**
   - Use non-liquefied p-y and t-z springs

2. **Analyze the liquefaction case**
   i. removing p-y springs from liquefied and crust layers and applying full passive earth pressure from the crust
   ii. Imposing an additional superstructure displacement $\Delta_2 = C_{\Delta L}\, \Delta_{NL}$, where Δ_{NL} is the demand predicted in the absence of liquefaction. Currently, we use $C_{\Delta L}$=1.0 based on the NDA results.



ESA – Draft Proposed Guidance

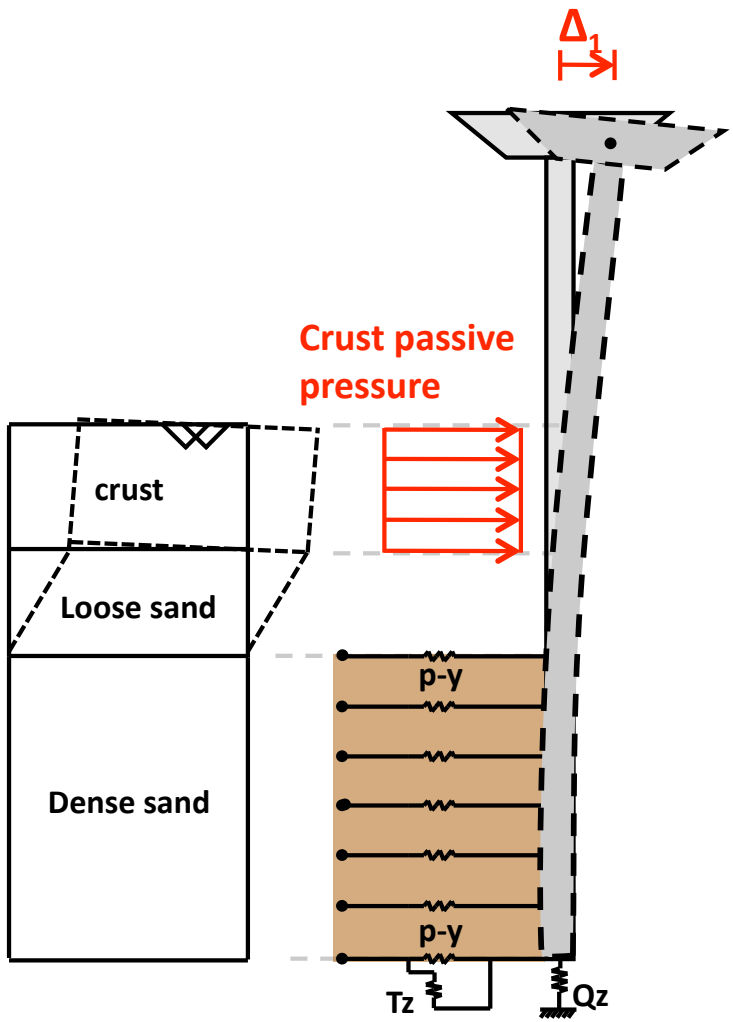
Steps include:

1. **Analyze for non-liquefaction case**
   - Use non-liquefied p-y and t-z springs

2. **Analyze the liquefaction case**

   i. removing p-y springs from liquefied and crust layers and applying full passive earth pressure from the crust

   ii. Imposing an additional superstructure displacement $\Delta_2 = C_{\Delta L}\,\Delta_{NL}$, where Δ_{NL} is the demand predicted in the absence of liquefaction. Currently, we use $C_{\Delta L}$=1.0 based on the NDA results.

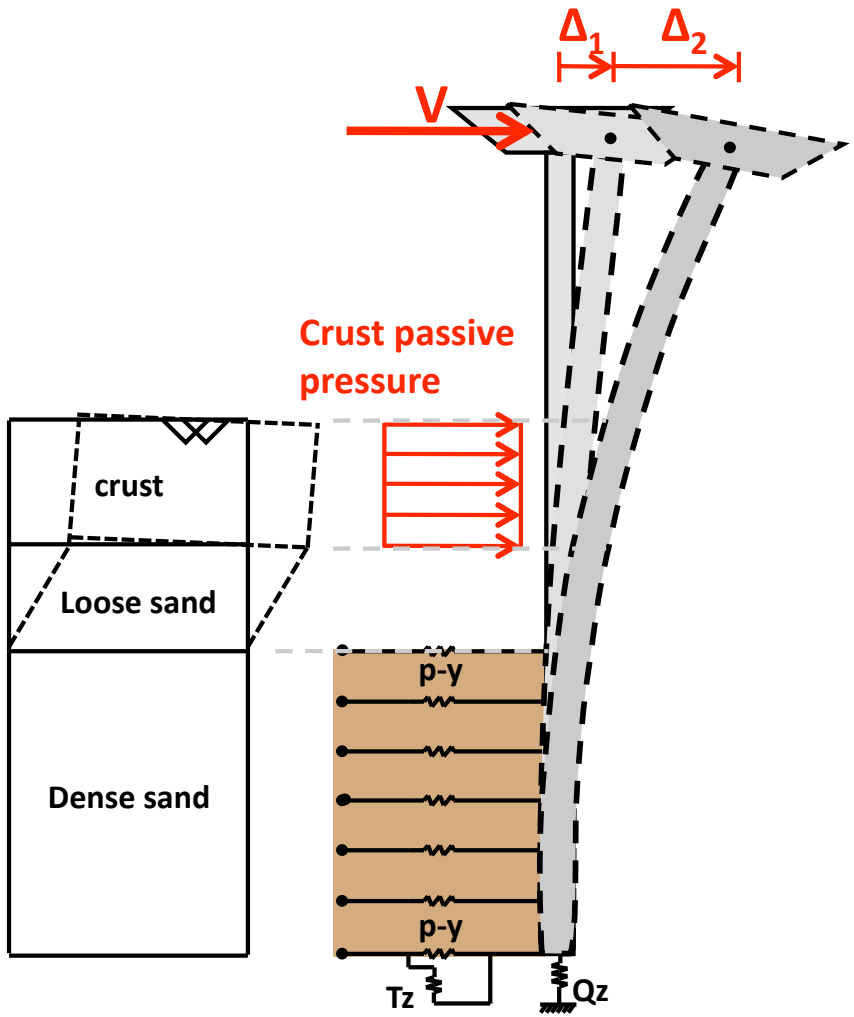


ESA – Draft Proposed Guidance

Steps include:

1. **Analyze for non-liquefaction case**
   - Use non-liquefied p-y and t-z springs

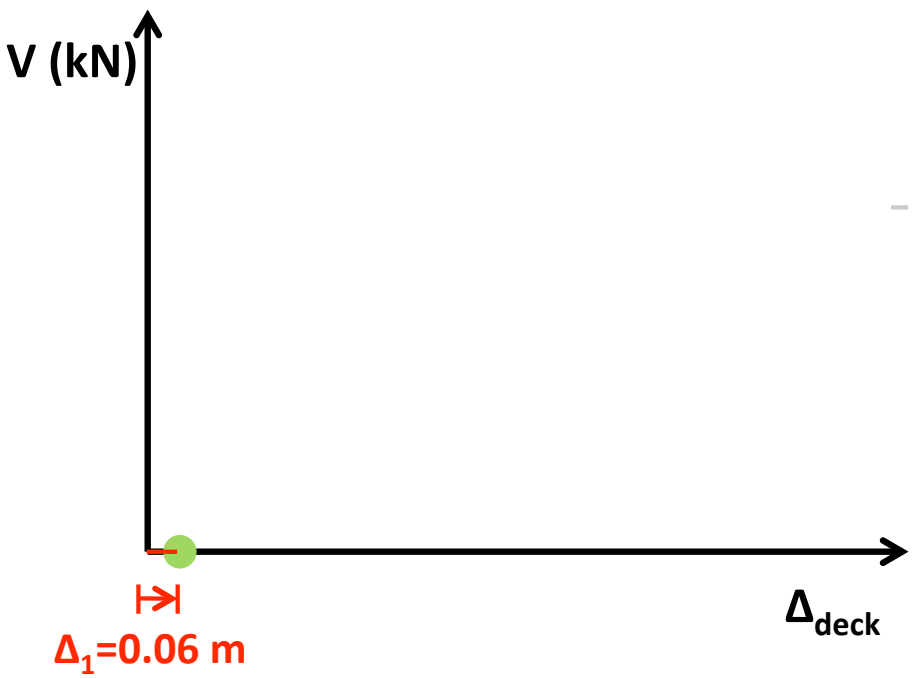
2. **Analyze the liquefaction case**
   i. removing p-y springs from liquefied and crust layers and applying full passive earth pressure from the crust
   ii. Imposing an additional superstructure displacement $\Delta_2 = C_{\Delta L}\,\Delta_{NL}$, where Δ_{NL} is the demand predicted in the absence of liquefaction. Currently, we use $C_{\Delta L}$=1.0 based on the NDA results.

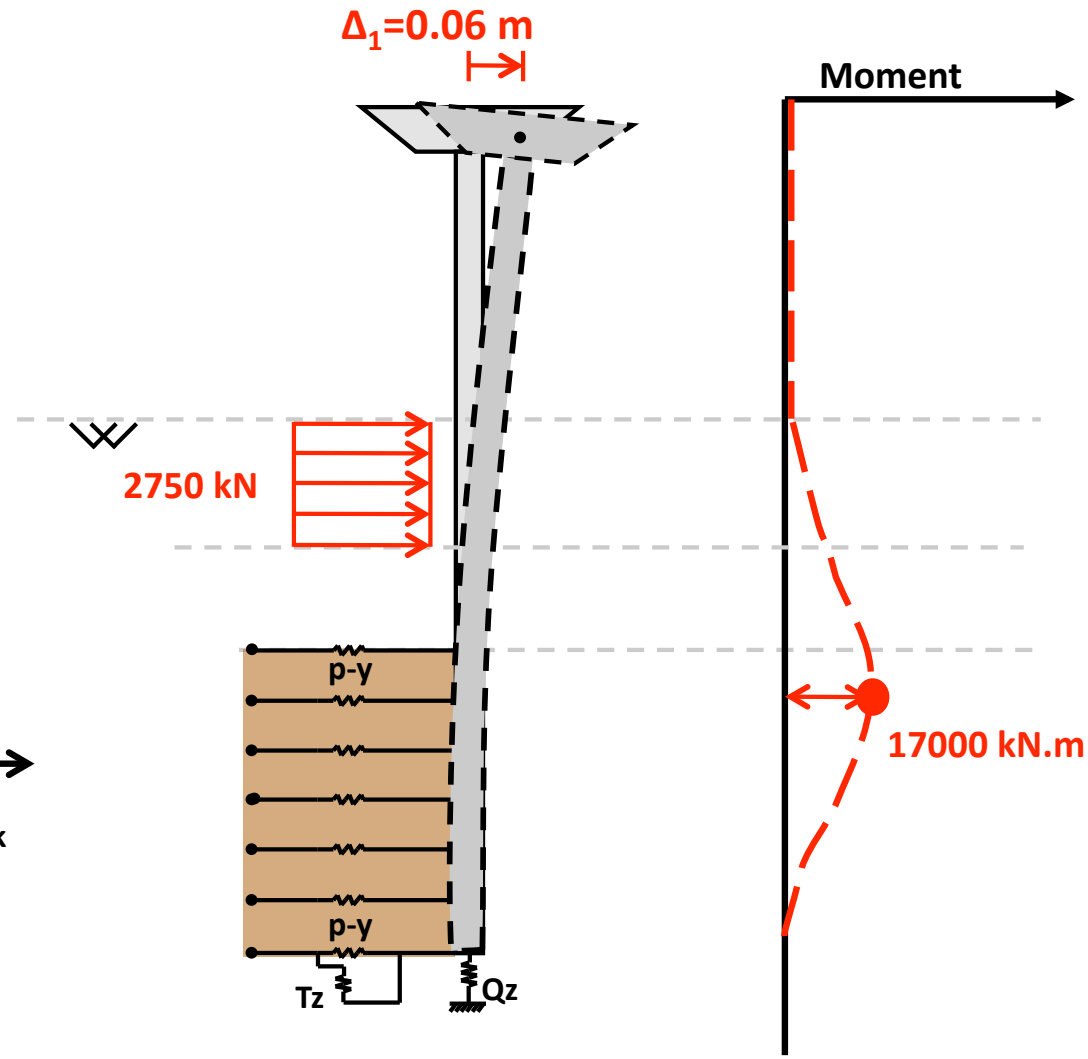


ESA – Draft Proposed (Example)

i. Applying full passive earth pressure from the crust

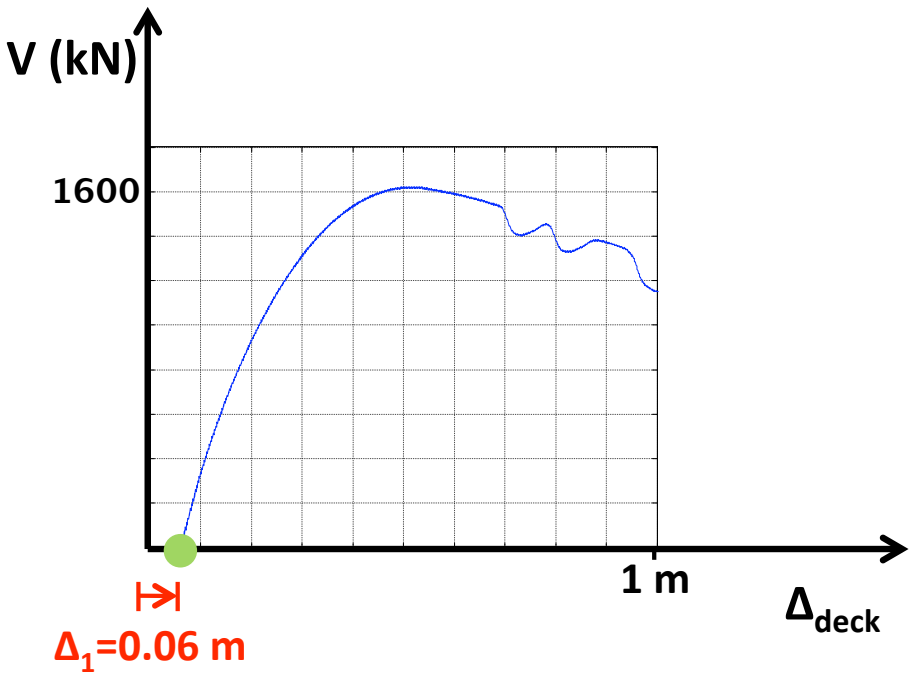
(Crust S_u = 80 kPa)

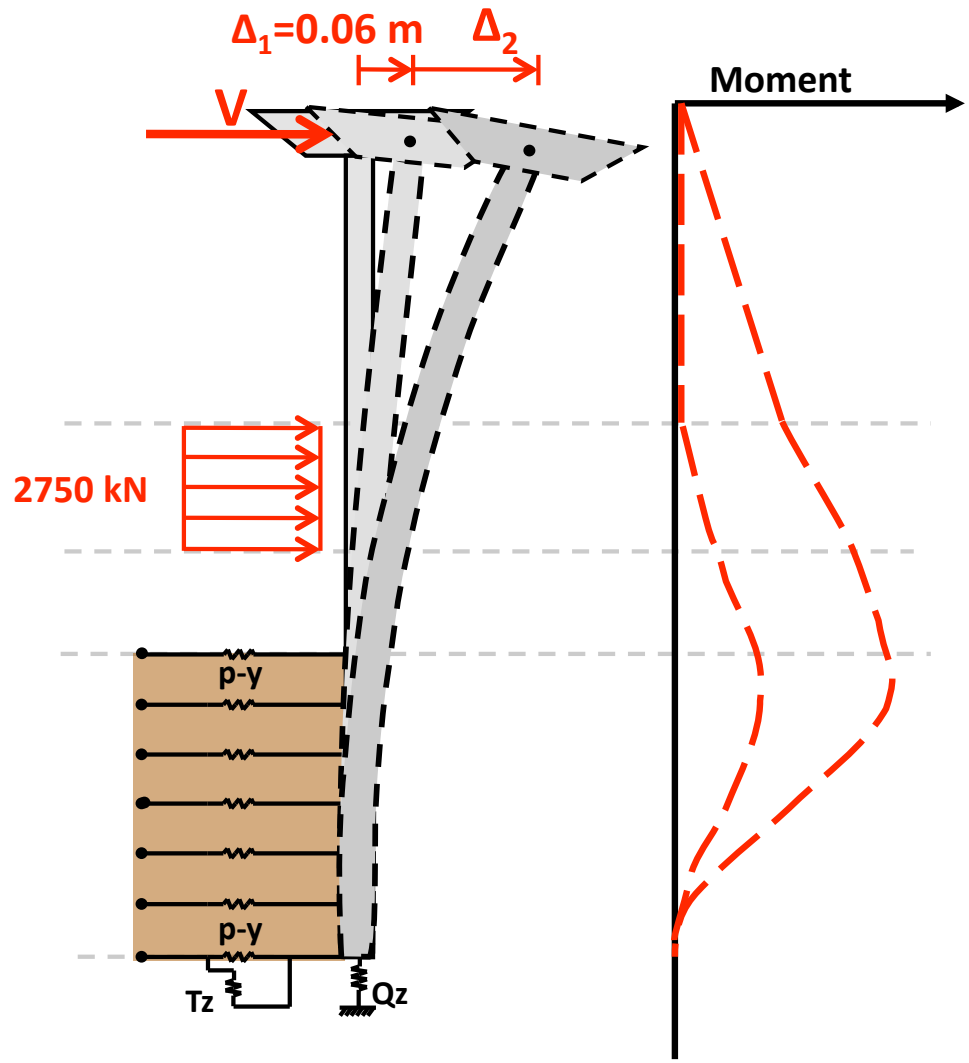




ESA – Draft Proposed (Example)

ii. Imposing an additional superstructure displacement





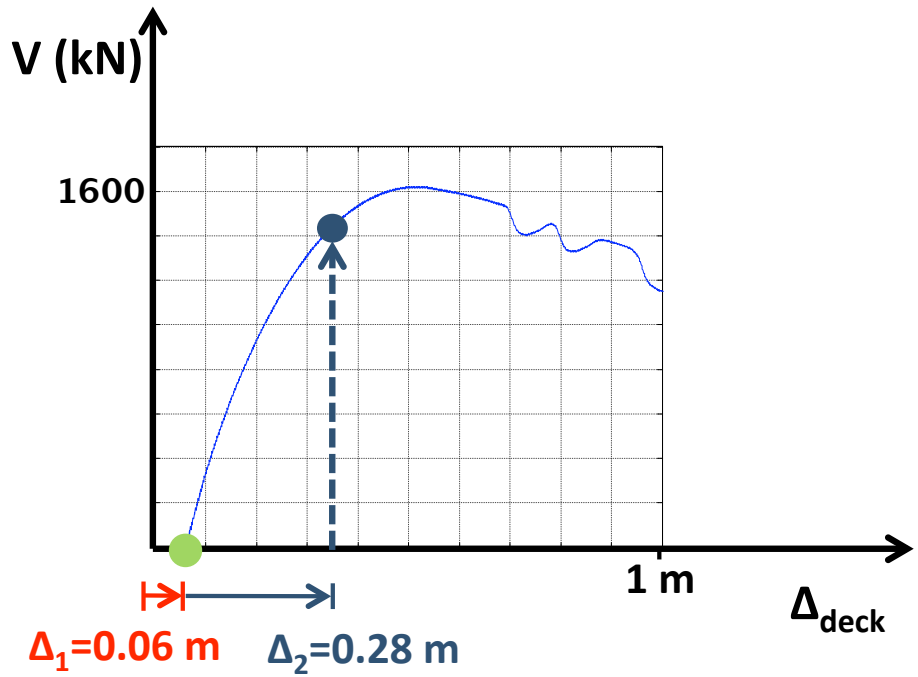
ESA – Draft Proposed (Example)

Additional Disp:

$\Delta_2 = C_{\Delta L}\, \Delta_{NL} = 1.0(0.28\text{ m}) = 0.28\text{ m}$

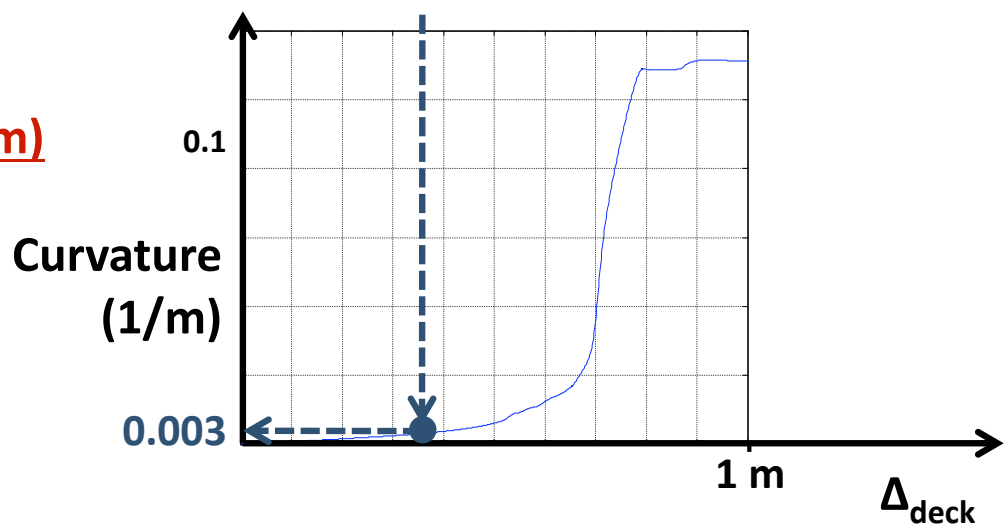
Global Disp demand:

$\Delta_1 + \Delta_2 = \underline{0.34\text{ m}}$



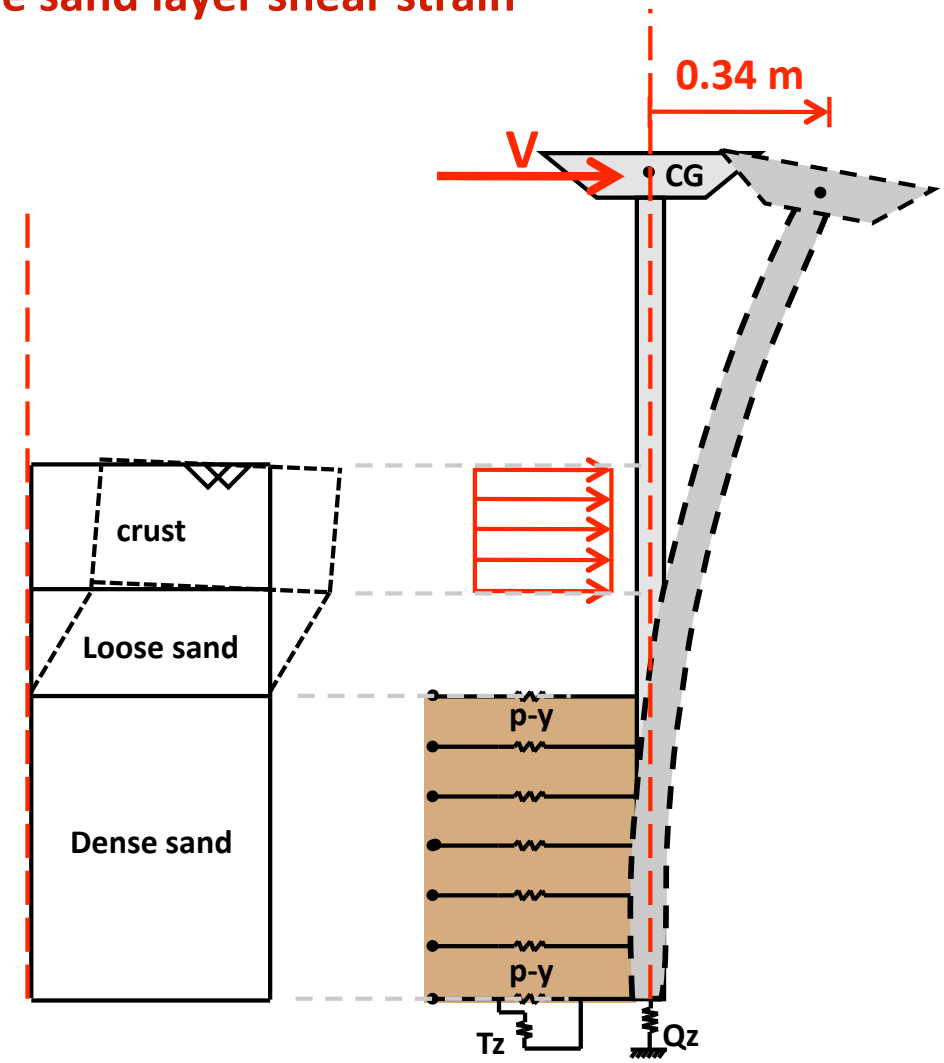
From pushover analysis:

Local curvature demand = <u>0.003 (1/m)</u>



ESA – Draft Proposed

Adjust displacement for dense sand layer shear strain



ESA – Draft Proposed

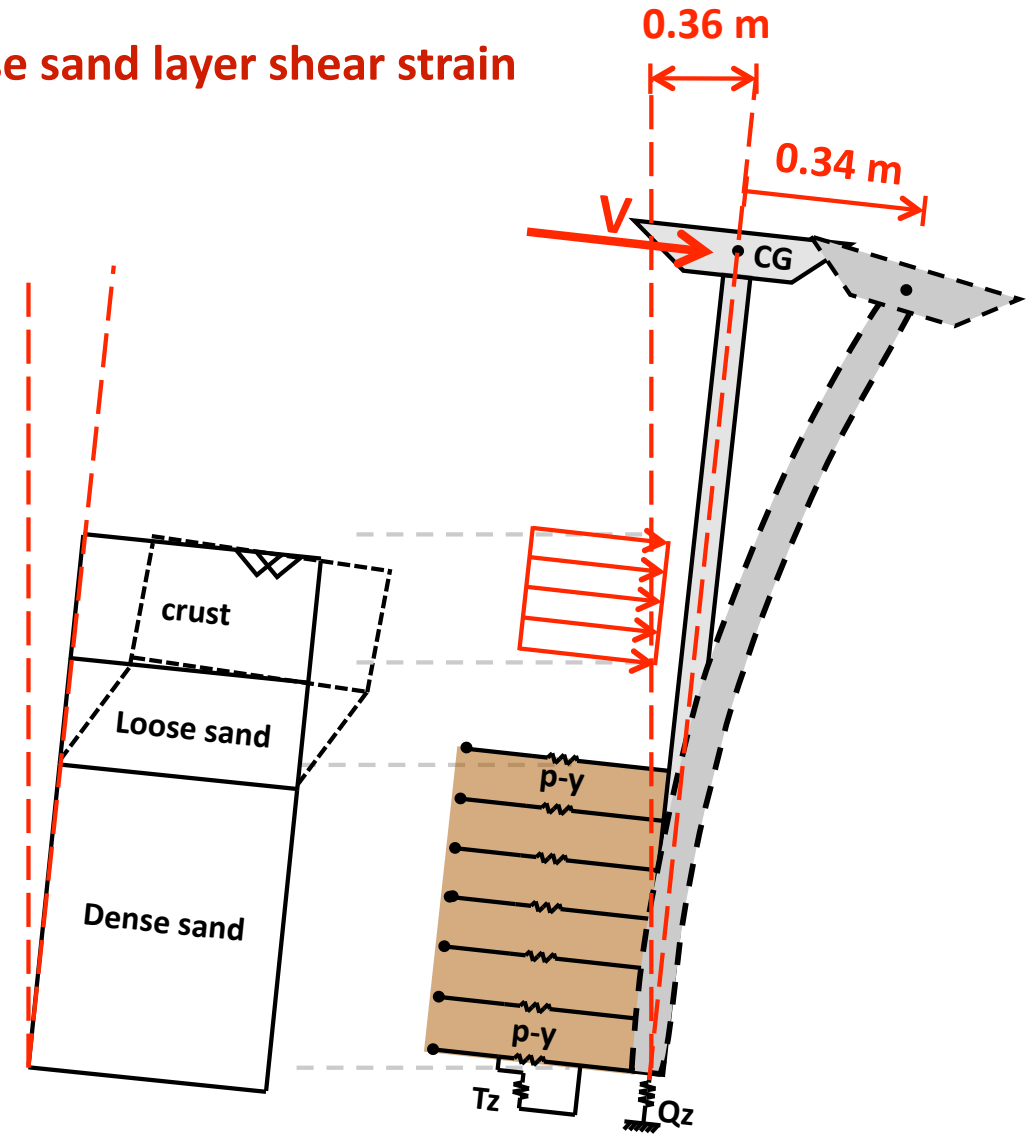
Adjust displacement for dense sand layer shear strain

For 0.6 g shake:

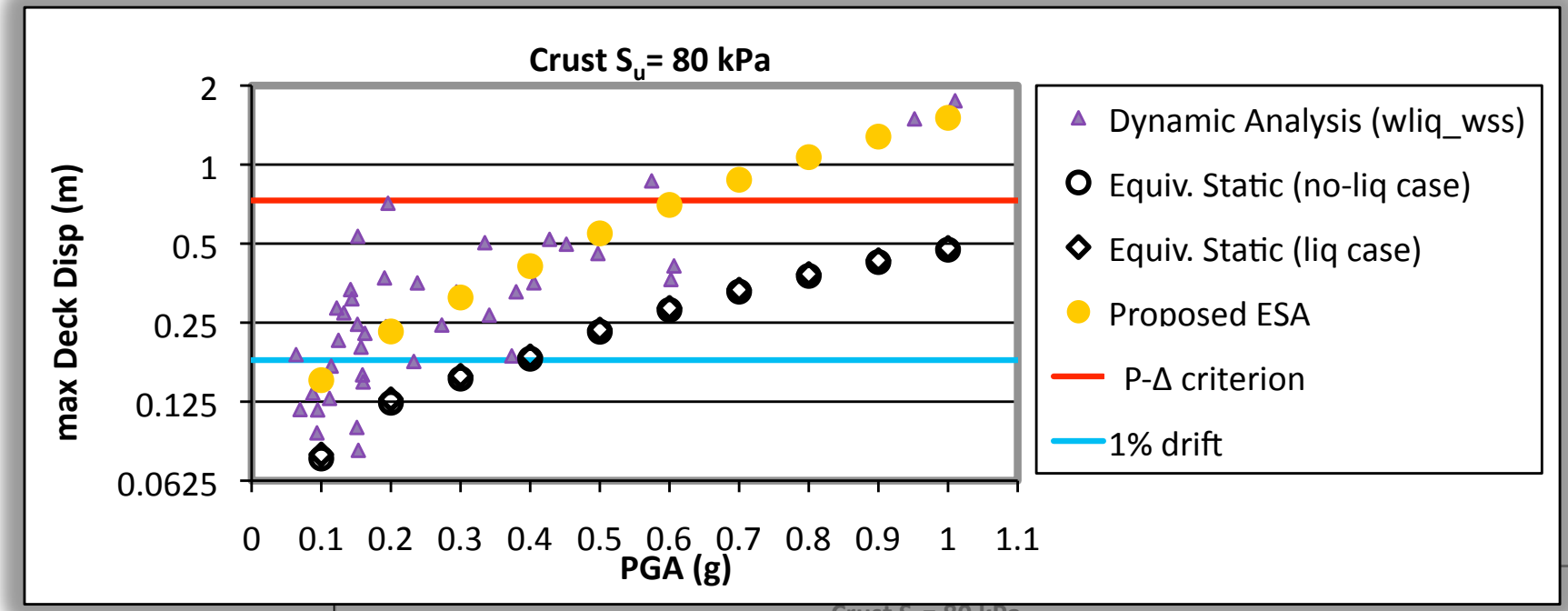
Avg. γ = 1.2%

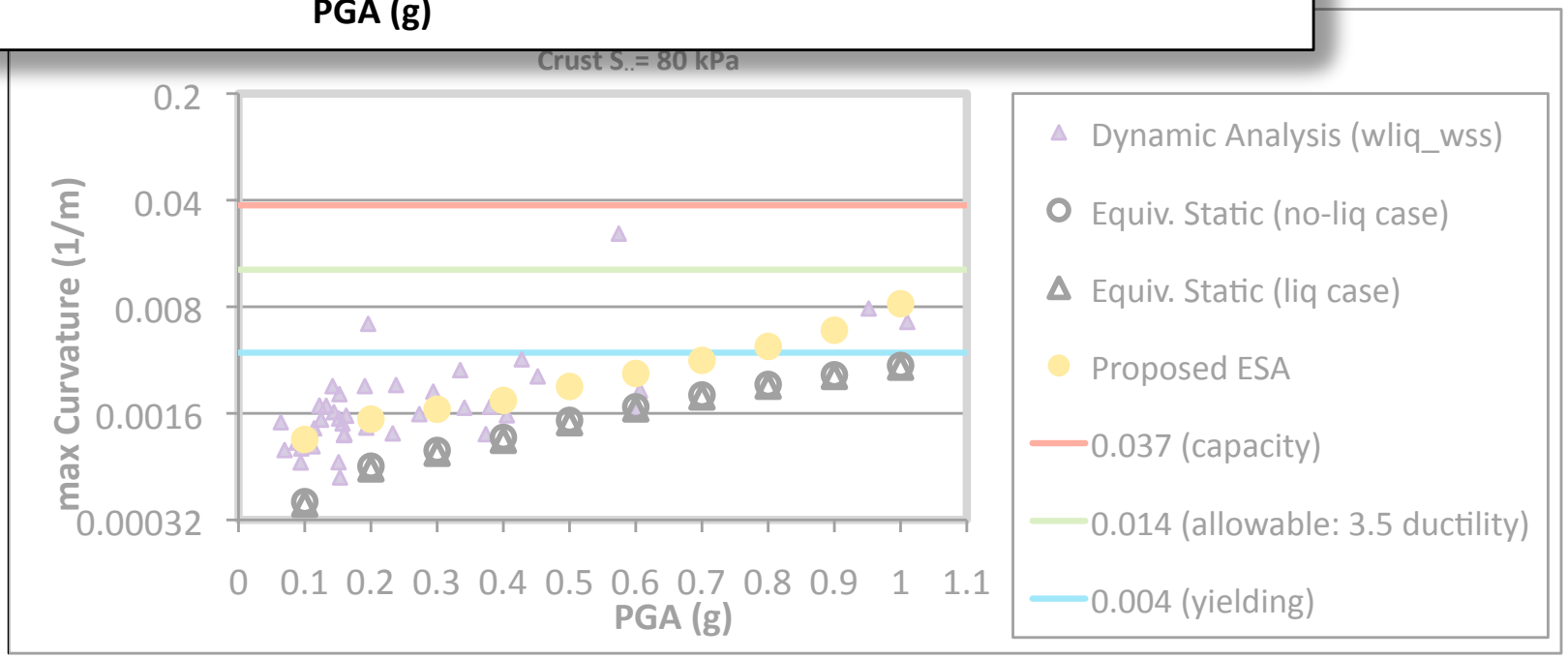
L = 30 m

γ×L = 0.36 m



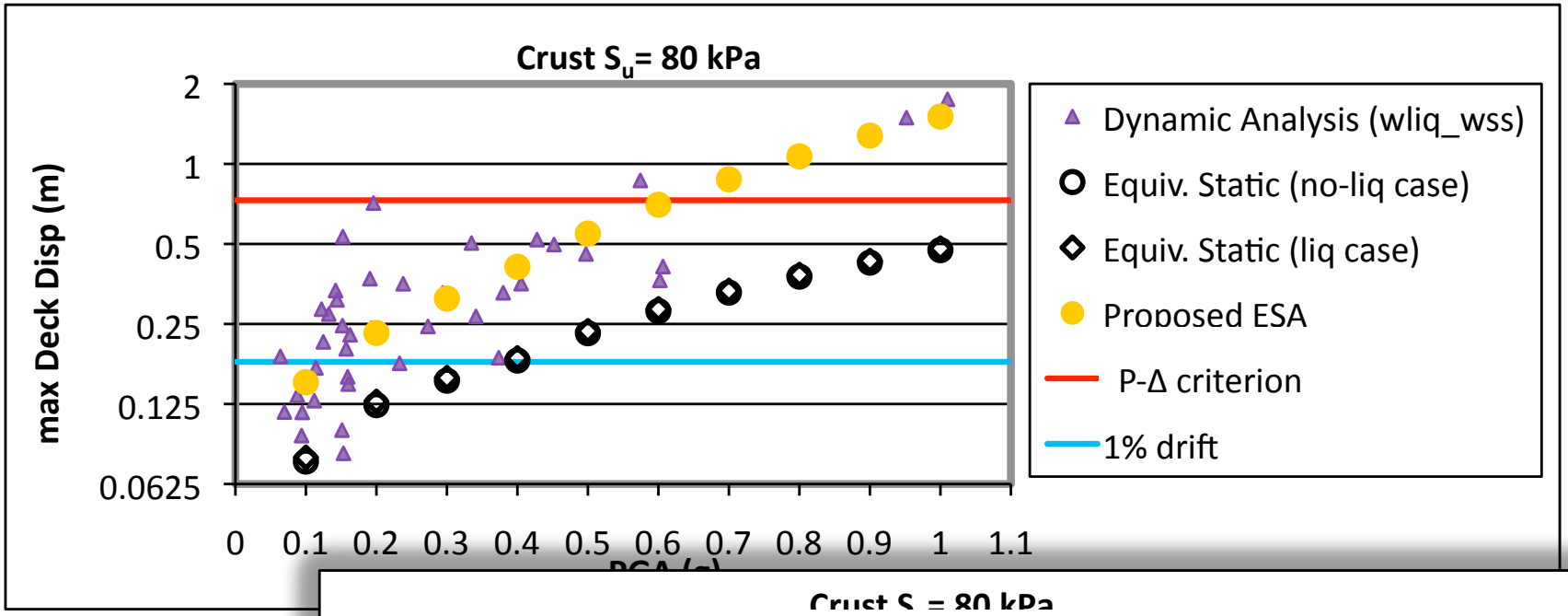
ESA – Draft Proposed results

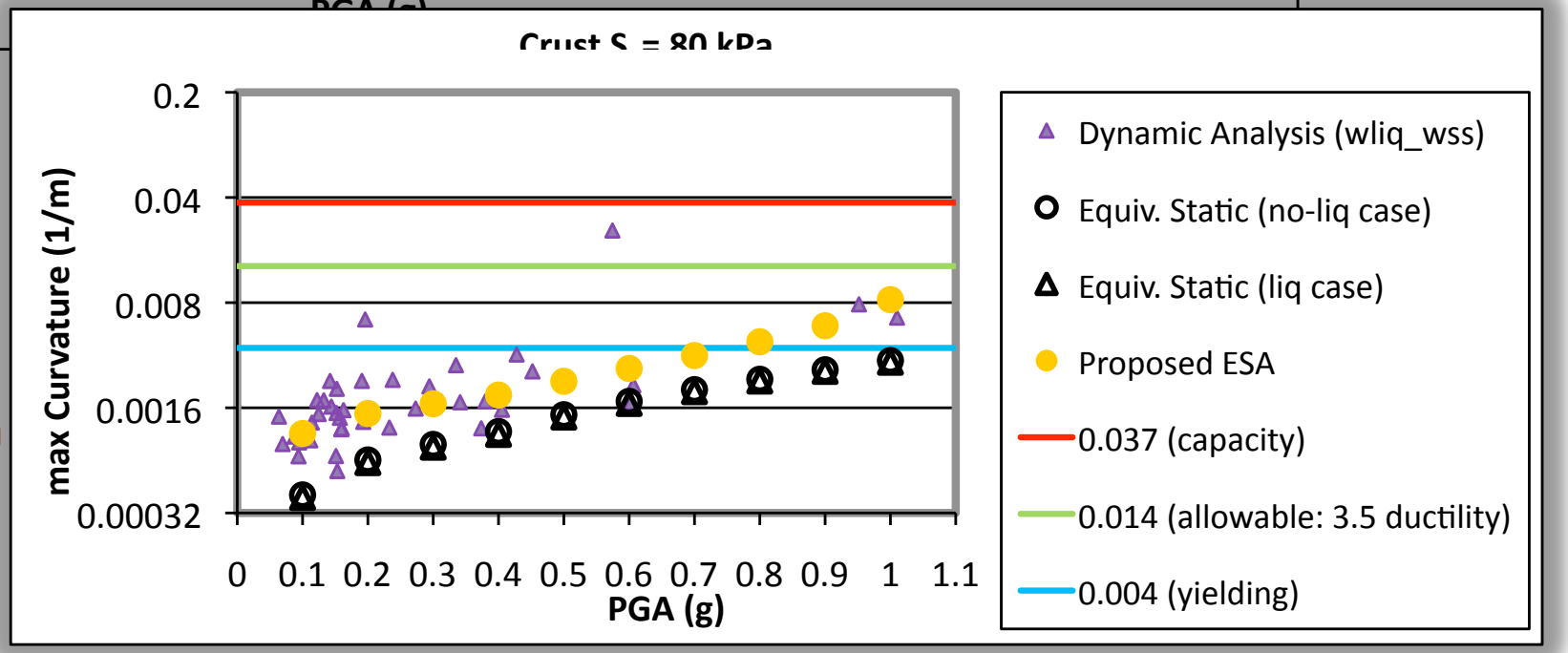




ρ_s = 4%,
Axial P = 10%
Crust S_u = 80 kPa

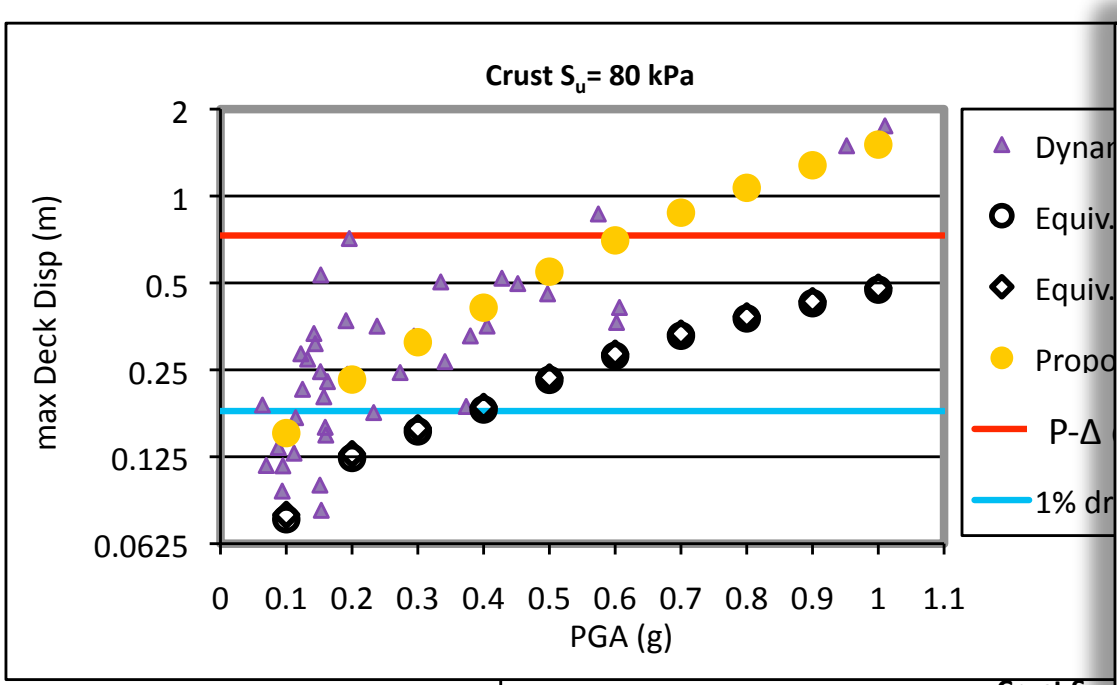
ESA – Draft Proposed results

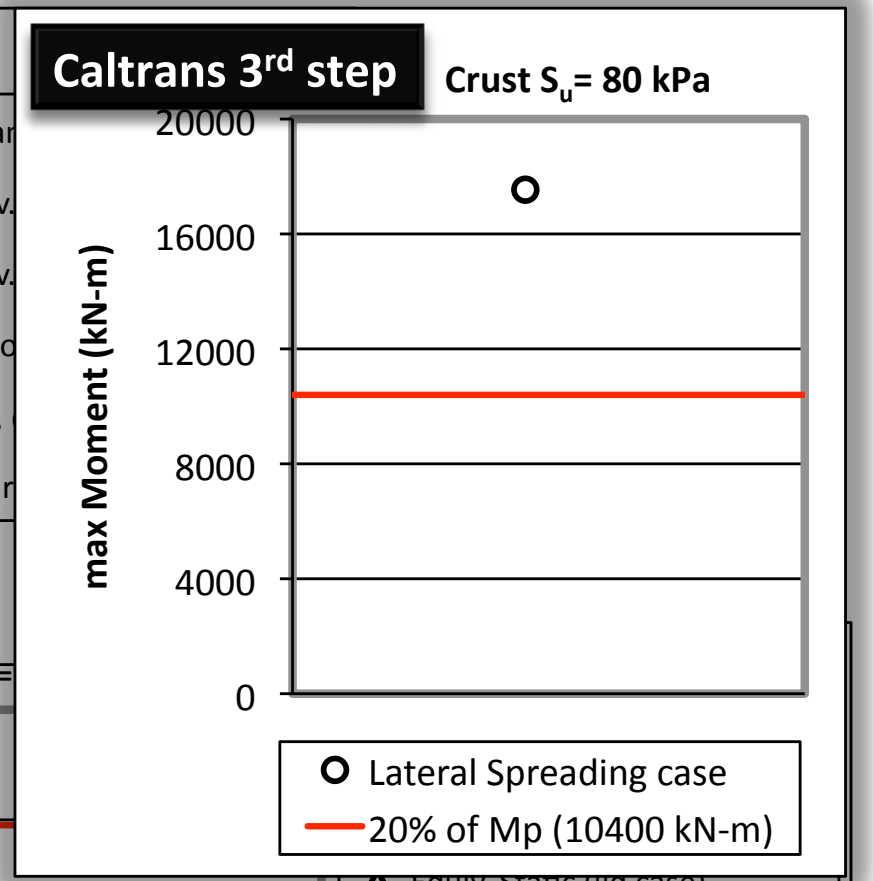


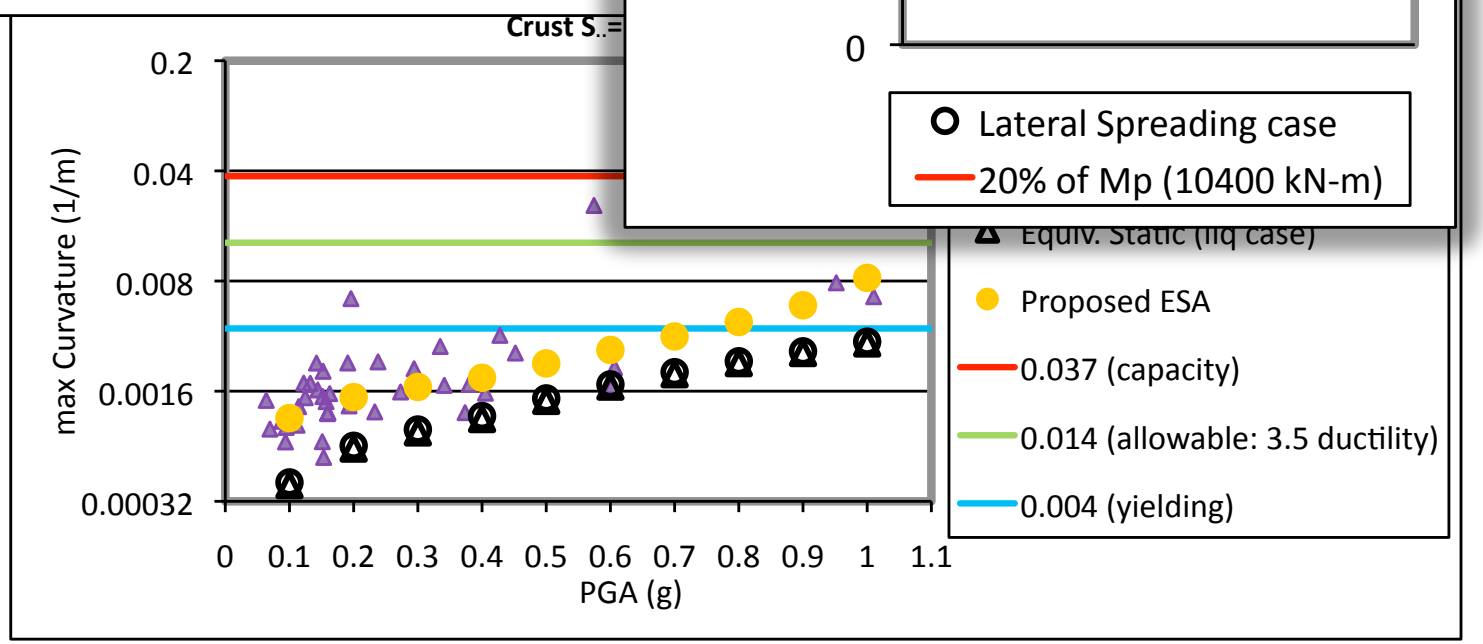


ρ_s = 4%,
Axial P = 10%
Crust S_u = 80 kPa

ESA – Draft Proposed results







ρ_s = 4%, Axial P = 10%
Crust S_u = 80 kPa