Bridge Foundation Pinning Resistance Implied by Simplified Equivalent Static Analysis Procedure for Lateral Spreading

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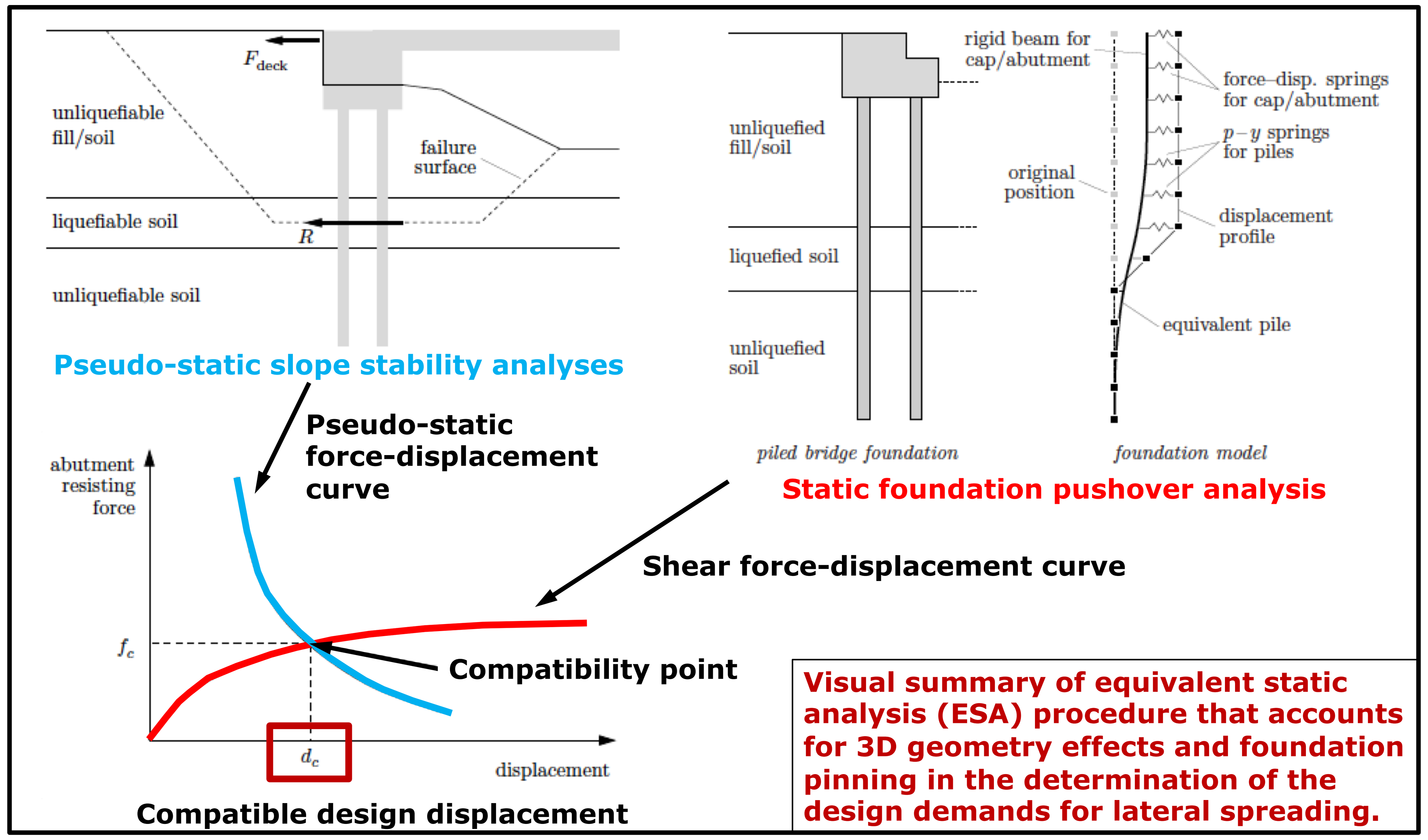
1. Background and Objectives

Liquefaction-induced lateral spreading is a critical design case for many bridges located in high-seismicity regions of the Pacific Northwest. The design procedures currently used in the region tend to rely upon a simplified 2D plane strain analytical approach, and as a result may result in overly conservative and expensive design solutions. In some cases this over-conservatism has limited the feasibility of entire bridge projects. Given the shortcomings of the current design procedure, a modified design framework has been proposed to supplant the existing approach. This modified procedure takes an equivalent static approach (ESA) that makes consideration for 3D effects and foundation pinning through the combination of a foundation pushover analysis with a pseudo-static slope stability analysis to find a compatible foundation displacement as shown below.



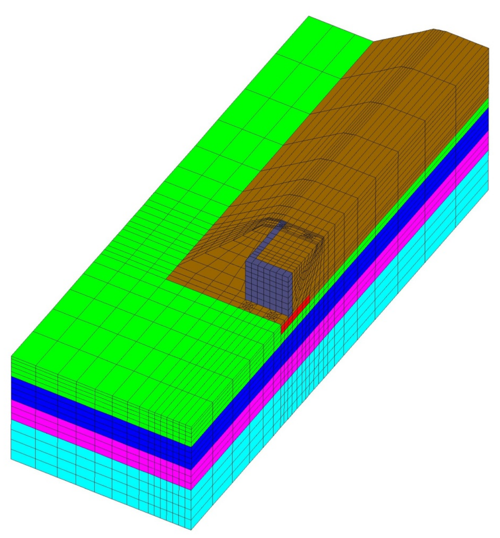
Visual summary of equivalent static analysis (ESA) procedure that accounts for 3D geometry effects and foundation pinning in the determination of the design demands for lateral spreading.

The potential cost savings related with a better assessment of the demands of lateral spreading on embedded bridge foundations are quite attractive, however, relatively little focus has been given to the validation and verification of this modified procedure. Bridges are critical lifelines for numerous regions and prior to the adoption of the modified lateral spreading design procedure by local agencies, it is important to verify the adequacy and safety of the resulting bridge and foundation designs for conditions typical to the region.

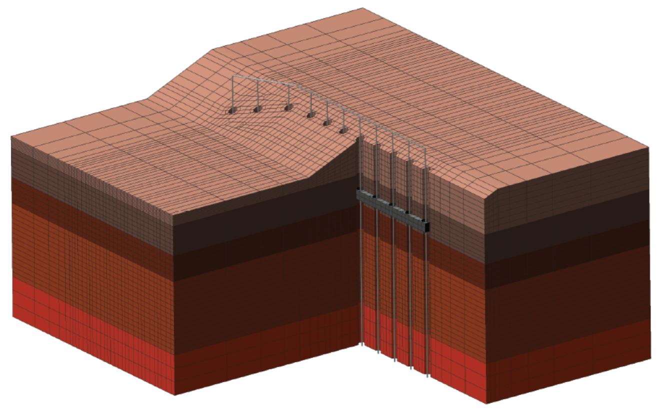
2. Model Verification Approach – 3D Nonlinear FEA

3D nonlinear finite element analysis using OpenSees was used to verify the equivalent static lateral spreading analysis procedure. This technique has been used to successfully capture the salient system response features of two Chilean highway bridges subjected to lateral spreading in the 2010 Maule earthquake (Mataquito and Llacolen bridge models shown below).

- **General modeling approach:**
  - Static analysis with free-field lateral spreading demands applied at boundaries of the model
  - Deep foundations are modeled using beam elements, soil is modeled using solid elements, and beam-solid contact element for modeling the soil-foundation interface.
  - Captures important kinematic features of the foundation demands due to lateral spreading



Mataquito bridge model
McGann and Arduino (2014)

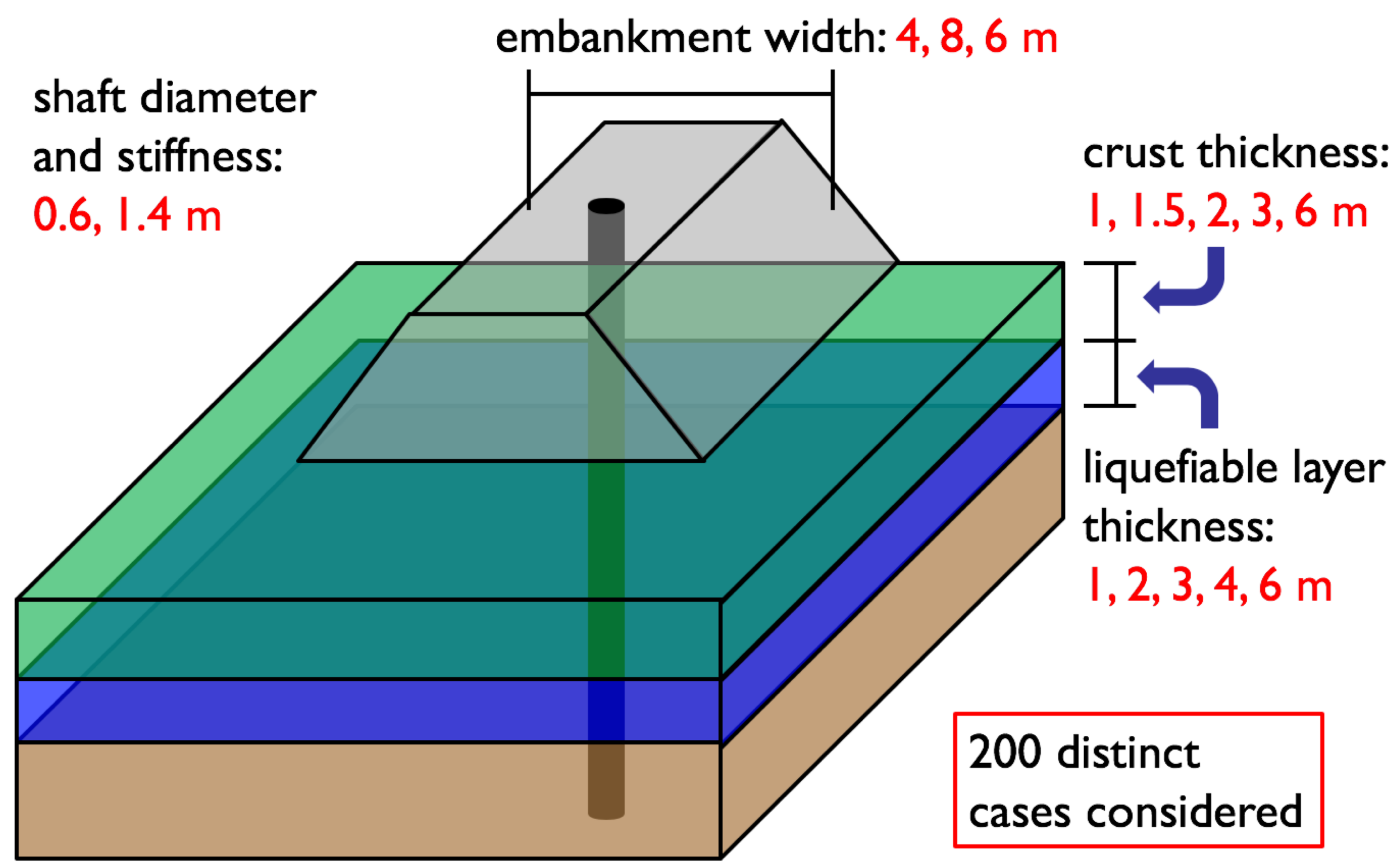


Llacolen bridge model
Ghofrani (2016)

3. Parameter Studies using 3D FEA and Equivalent Static Analysis

An additional focus of this research project is to better identify the 3D geometric site conditions that strongly influence lateral spreading demands on foundations. To accomplish this, a parameter study was conducted using 3D FEA in OpenSees to consider the effects of various site geometries on the system response. These models consider a single deep foundation embedded in a liquefiable soil profile.

A corresponding parameter study was conducted using the equivalent static analysis procedure. The results of the two parameter studies were compared to evaluate if changes in geometry have the same effect on the results in both analysis contexts.

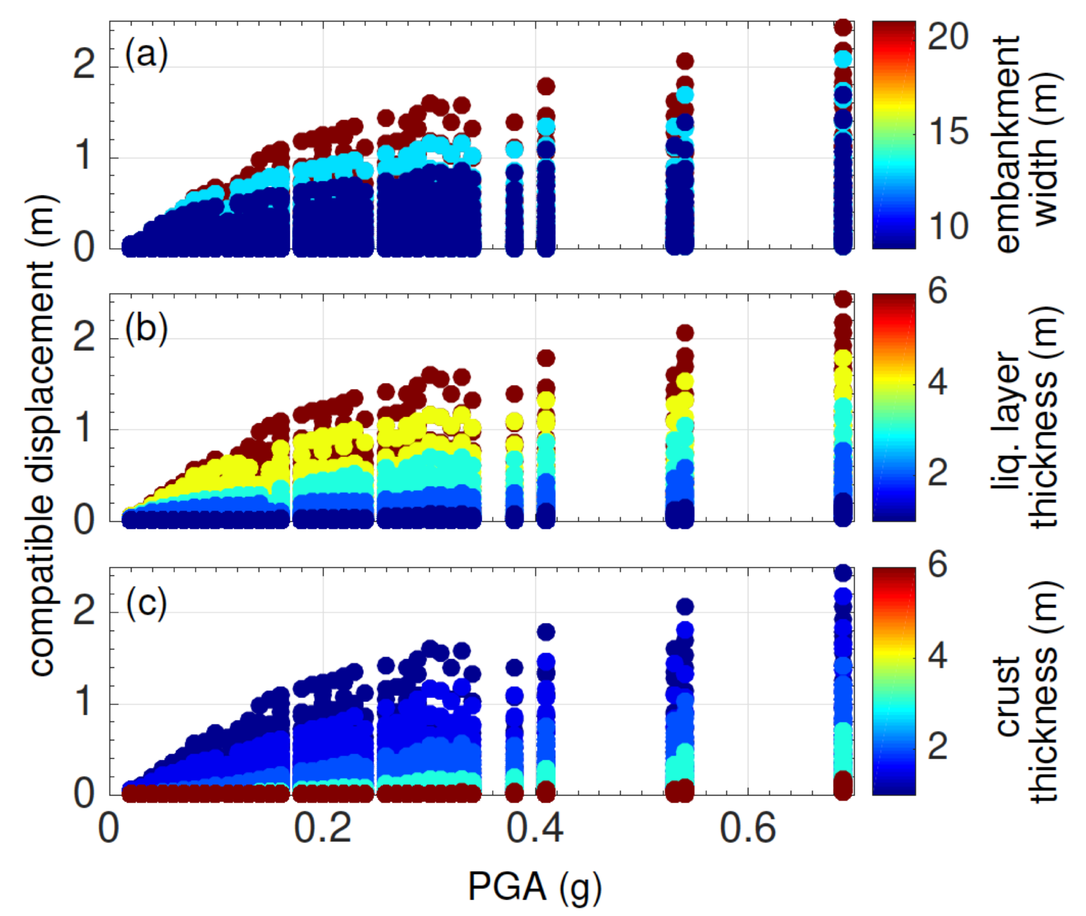


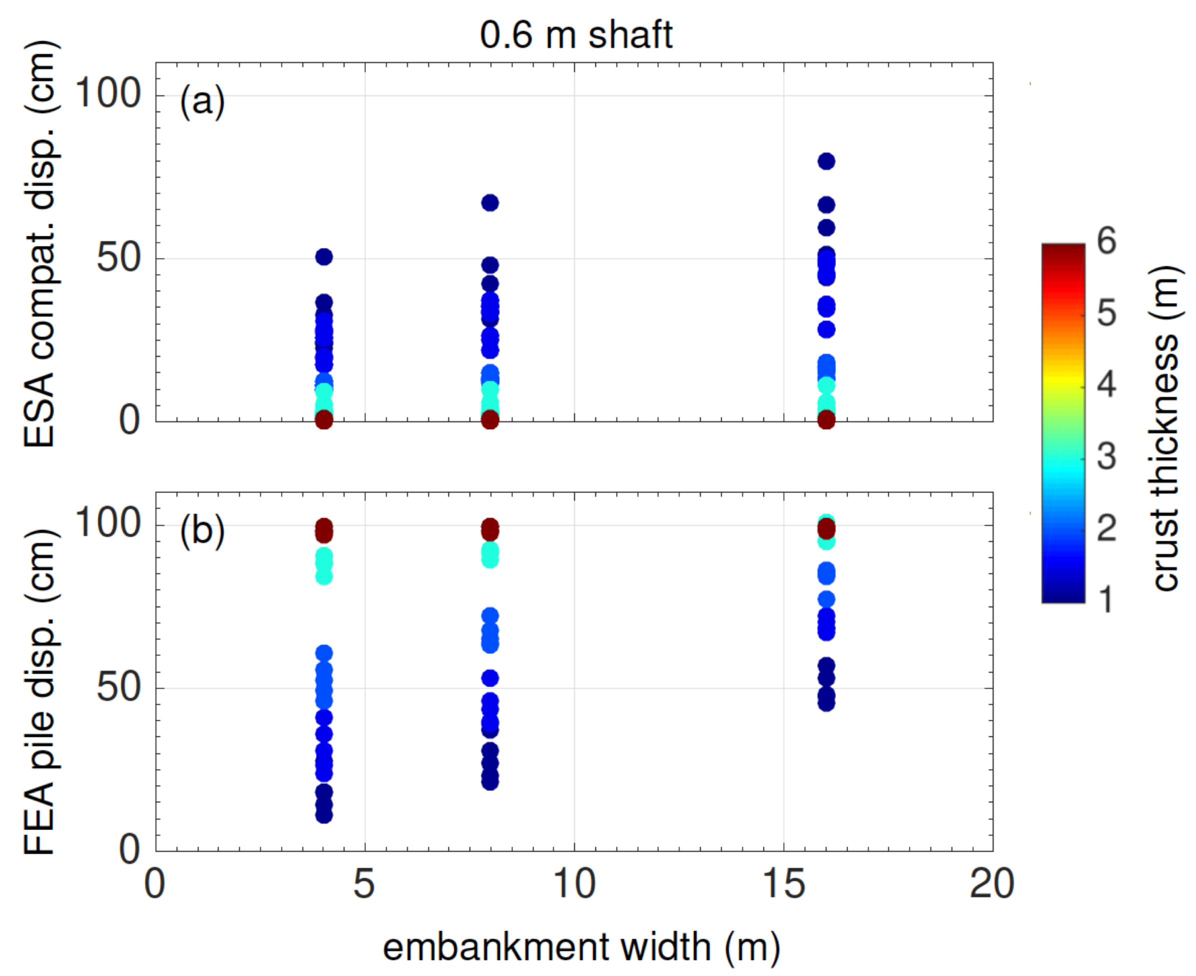
4. Observations and Implications from Parameter Studies

General Observations:

Many of the general trends in the equivalent static analysis results shown at right correspond with both the 3D FEA and the expected system behaviour:

- **PGA of input motion:** Increasing PGA increases the magnitude of the compatible displacement.
- **Embankment Width:** Increasing the embankment width leads to larger compatible displacements, implying less foundation pinning resistance. This is also observed in the 3D FEA at at case histories.
- **Liquefiable Layer Thickness:** Increases in the thickness of the liquefiable layer lead to larger compatible displacements and less implied pinning.
- **Crust Thickness:** The trend for increasing crust thickness is problematic as it the opposite of what would be expected and what is observed in 3D.





Issues with Crust Thickness in the ESA:

Increasing the crust thickness in the ESA leads to significant increases in implied pinning resistance. This goes against observations from 3D FEA and the general physics of the problem. The results at right compare the effects of increasing thickness of crust in the ESA and 3D FEA parameter studies.

- **3D FEA:** Increasing the crust thickness for a constant free-field lateral spreading demand reduces the foundation pinning as more soil is imposing a lateral force on the foundation.
- **ESA:** Increasing crust thickness greatly reduces the compatible displacement, which implies a great increase in foundation pinning. This behaviour is driven by the slope deformation analysis phase of the ESA procedure, as the thicker crust results in increased resistance to slope failure for constant foundation resistance.