U.S. Department of Transportation
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Rational Guidance to Determine the Maximum Factored Compression Load a Driven Pile can Support (Q_{fmax})

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Presentation Outline

- Introduction and overview
- Determination of the maximum factored compression load a driven pile can support (Q_{fmax})
  - Geotechnical strength limit state
  - Drivability analysis
  - Structural strength limit state
- Design Charts

Recent FHWA LRFD Implementation Resources

http://www.fhwa.dot.gov/resourcecenter/teams/geotech/publications.cfm

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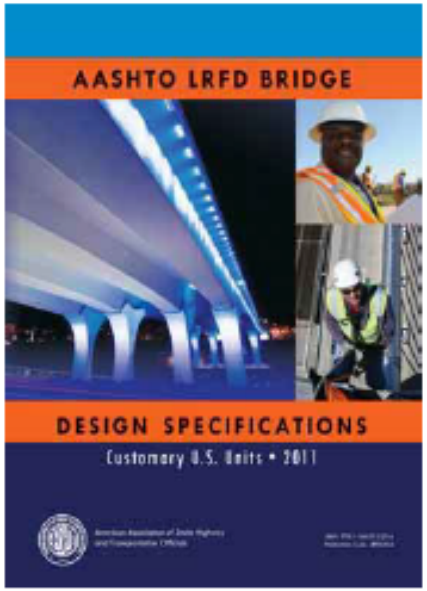
Implementation of AASHTO LRFD Design Specifications for Driven Piles



Report's Goals

- Help highway engineering agencies:
  - Develop more accurate and economical LRFD design procedure for driven piles
  - Implement AASHTO LRFD design specifications for driven piles

Report's 6 Chapters

1. Introduction
2. LRFD Design Limit States and Design Process for Driven Piles
3. Nominal Bearing Resistance of a Single Pile
4. Structural and Drivability Strength Limit States
5. Geotechnical Strength Limit States and Design charts
6. Construction of Driven Piles

Driven Piles Issues Covered in the FHWA Report

- Clarification of AASHTO LRFD limit states for driven piles and the design process to address them
- Improve the agreement between the pile lengths estimated in the design and finalized in the field.
- Determination of the pile contract and order lengths
- Consideration and advantages of:
  - Using static analysis methods to finalize pile length
  - Setup and static load test

AASHTO Limit States for Driven Piles

- Strength Limit States for Axial Compression Resistance of a Single Pile
  - Geotechnical, drivability, and structural
    - *Discussed in this presentation…..*

- Extreme Event Limit States for Axial Compression Resistance of a Single Pile.

- Other Limit States (AASHTO LRFD Article 10.7.6)
  - Minimum penetration pile length, L_m.

2016 Changes: Effect of Downdrag (DD) on the LRFD Design of Driven Piles

Two limiting cases:

- **Piles seated on top of hard rocks**
  - DD impacts the structural strength limit state

- **Piles driven in soils or rocks**
  - **DD impacts only the service limit state not geotechnical strength limit state**
    - *Corrections to previous publications presented next…..*

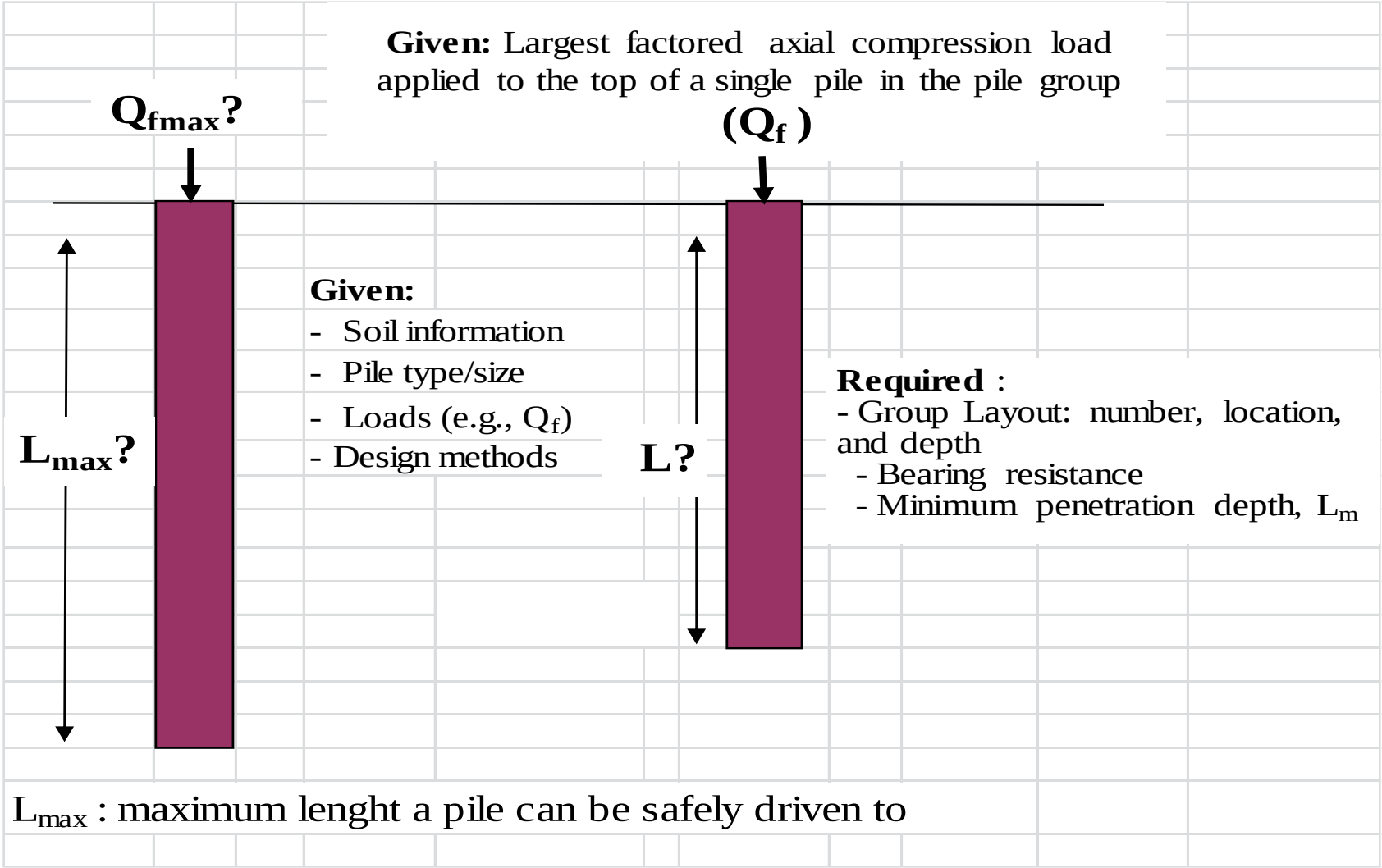
Driven Piles Issues Covered in the FHWA Report

- **Need for rational procedure to determine the maximum factored compression load a pile can support, Q_{fmax}**

- Development and use of design charts

- Addressing the LRFD design limit states during construction

Given/Required Design Information for Driven Piles



Why Rational Procedure to Determine Q_{fmax}?

- Needed in the design to estimate the preliminary number of piles in a pile group.
- Not discussed in AASHTO/FHWA!
- Common practices are to estimate Q_{fmax} based on the pile structural resistance and check drivability later.
  - Impact of using better geotechnical design method (load test) and setup are not considered

Current DOTs practices to estimate Q_{fmax} are conservative and require lengthy design time.

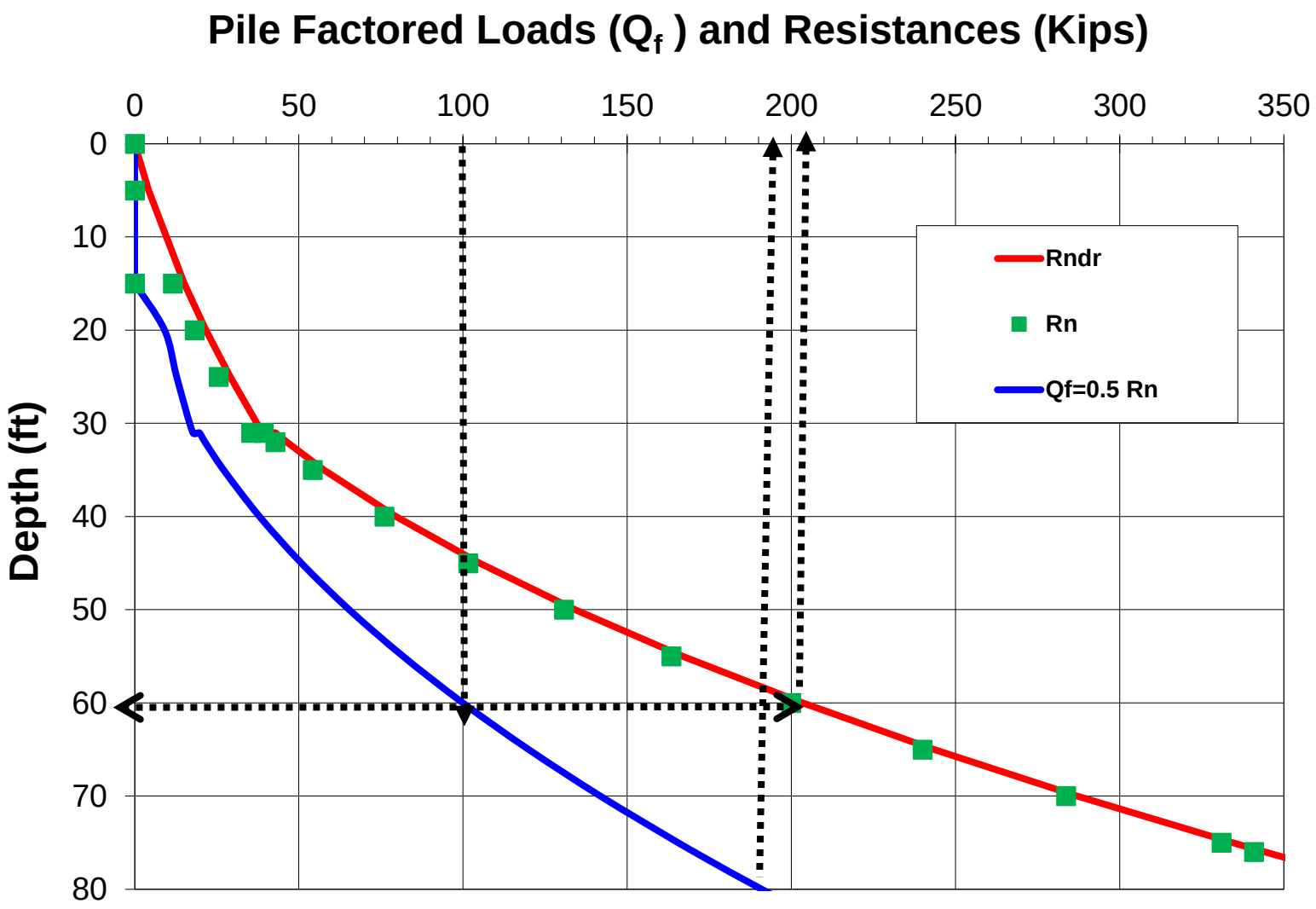
Rational Procedure to Determine Q_{fmax}?

By addressing all strength limit states for compression resistance of a single driven pile:

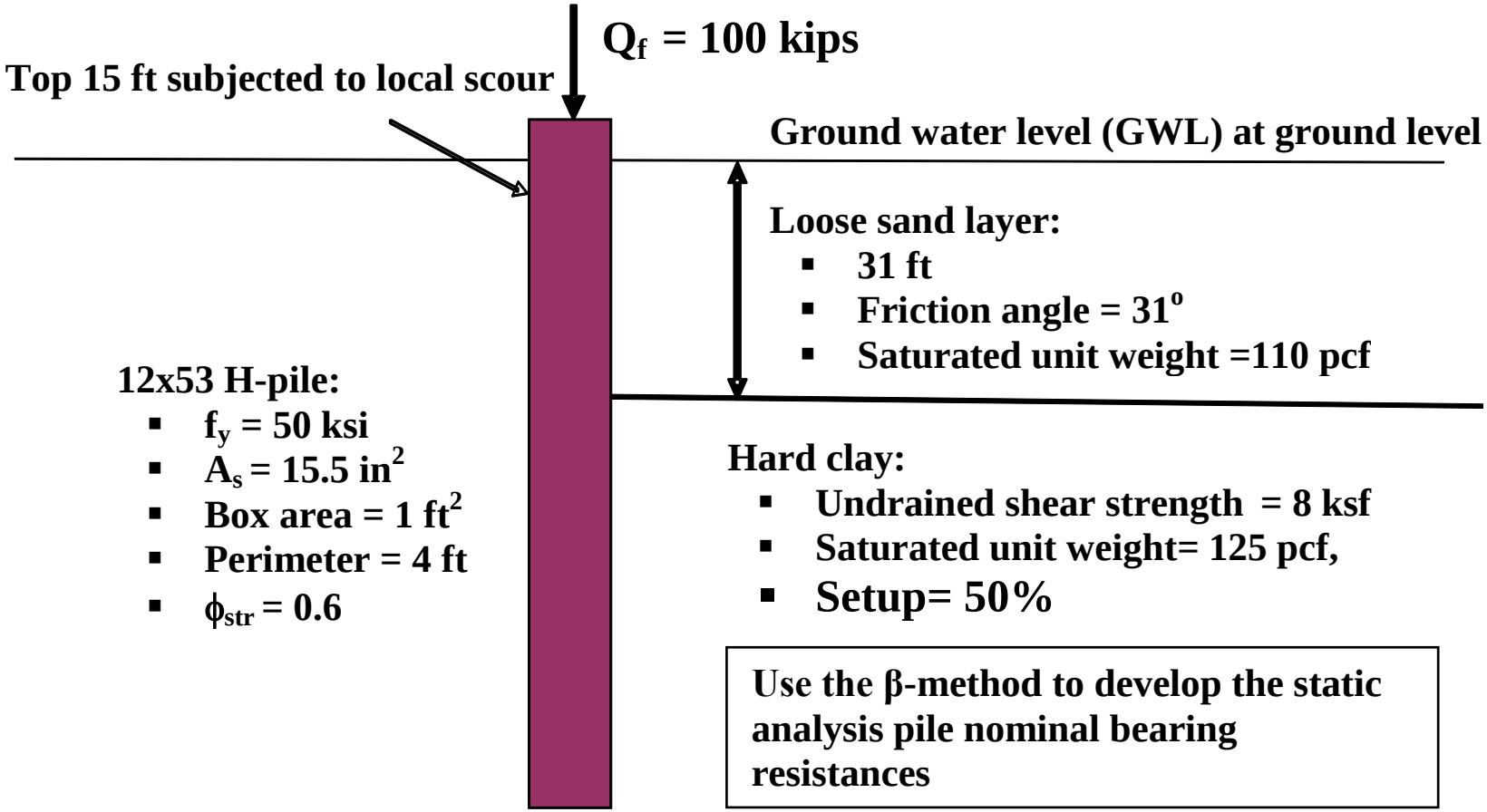
- **Geotechnical: develop Q_f vs. depth curve**
- **Drivability: determine L_{max}**
- **Structural**
- **All above to determine Q_{fmax}**

A Design Chart: include above information for certain pile type and field analysis method

Sample Design Chart: L_{max}= 80 ft, Q_{fmax}= 191 kips



LRFD Design Example-Given



Use the β-method to develop the static analysis pile nominal bearing resistances

LRFD Design Example-Required

- **Develop design charts using:**
  - Wave equation analysis at end of driving (EOD) conditions, ϕ =0.5
  - Wave equation analysis at beginning of redrive (BOR) conditions, ϕ =0.5
  - Axial compression static load test, ϕ = 0.8
- **Use design charts to determine:**
  - Q_{fmax}
  - Required pile length and bearing resistance
  - Check limit states

Geotechnical Strength Limit
Types of Pile Bearing Nominal Resistances

- **Driving Resistance, R_{ndr}**, mobilized during and at EOD conditions

- **Short-term Resistance, R_{nre}**, developed shortly after driving (e.g., include setup) at BOR conditions

- **Long-Term Resistance, R_n (ultimate in ASD)**
  - $R_n = R_{nre} - GL$
  - GL= Geotechnical resistance losses (scour)

Pile Bearing Resistance Determination Methods

1. **Static Analysis Methods** (e.g.,β-method).
   - Soil/rock properties,
   - **Performed during design**

2. **Field Analysis Methods.** Two types:

   - **Dynamic analysis methods:** wave equation, dynamic testing with signal matching, formulas
     - Hammer and soil information, driving records

   - **Full-scale Load Test.** Most accurate

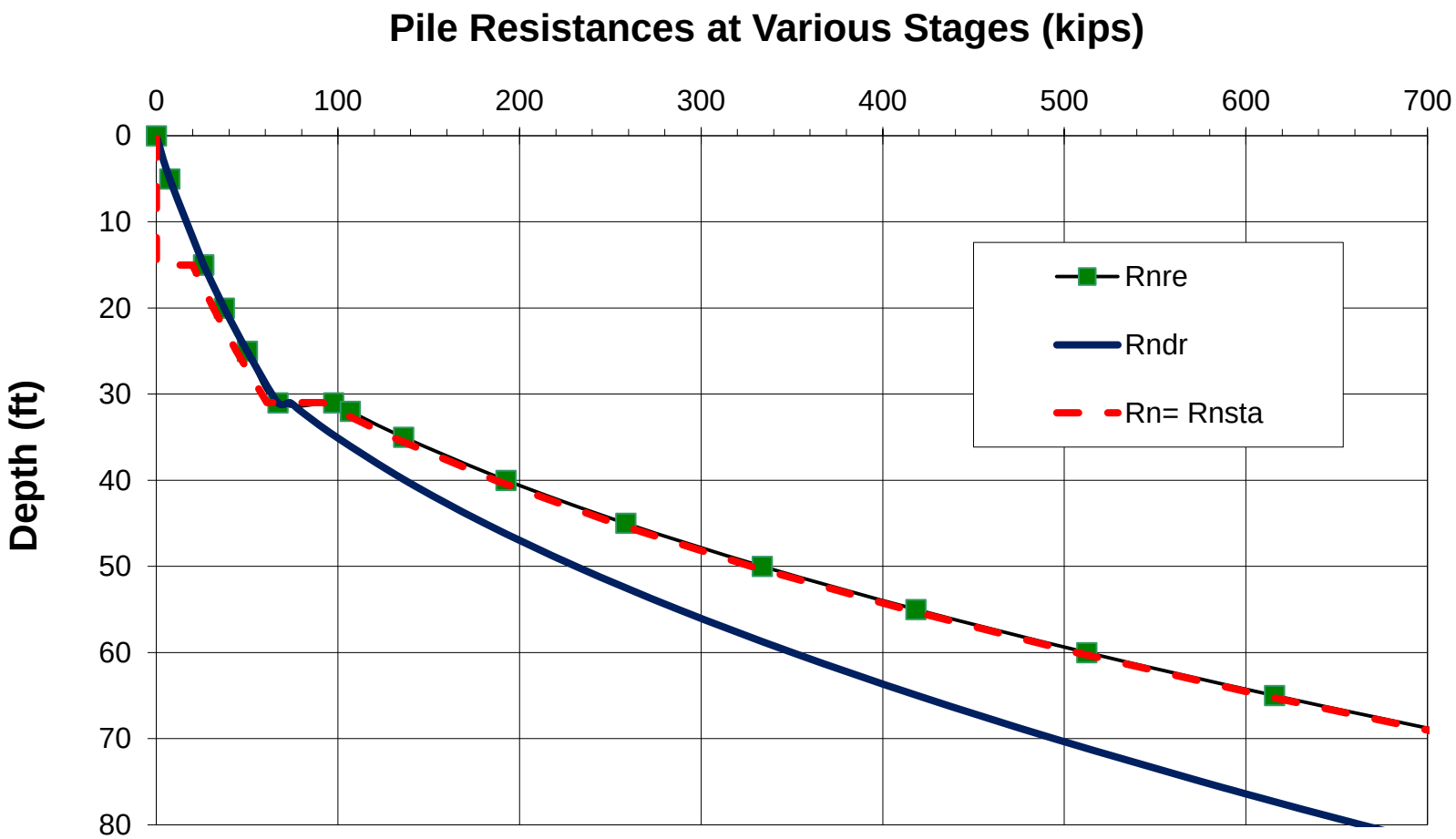
Geotechnical Strength Limit State

- **Governing Equation: $Q_f \leq \phi R_n$**
  - $R_n = R_{nfield}$ & $\phi = \phi_{dyn}$ for field analysis methods

- **Meet the limit state at the pile length, L, where**
  - R_n = Required $R_n = Q_f / \phi$; **or**
  - Q_f = Supported $Q_f = \phi R_n$

- **Outputs:**
  - Required bearing resistance to verify it in the field and finalize pile length
  - Estimate of pile length, L, ***could be different than length finalized in the field***

Static Analysis Methods
Bearing Resistances for the β-Method



Bearing Resistances from Field Analysis Methods Two Options

- **EOD Conditions**: Measure only R_{ndr} at EOD
  - $R_{nfield} = R_{ndr} - GL$ (no direct benefits from setup)
  - Required $R_{ndr} = Q_f/\phi_{dyn} + GL$.

- **BOR Conditions**: Measure both R_{ndr} and R_{nre}
  - $R_{nfield} = R_{nre} - GL$ (benefit from setup)
  - Required $R_{nre} = Q_f/\phi_{dyn} + GL$

R_{nre} measured with restrike or load test

Problem and Solution!!

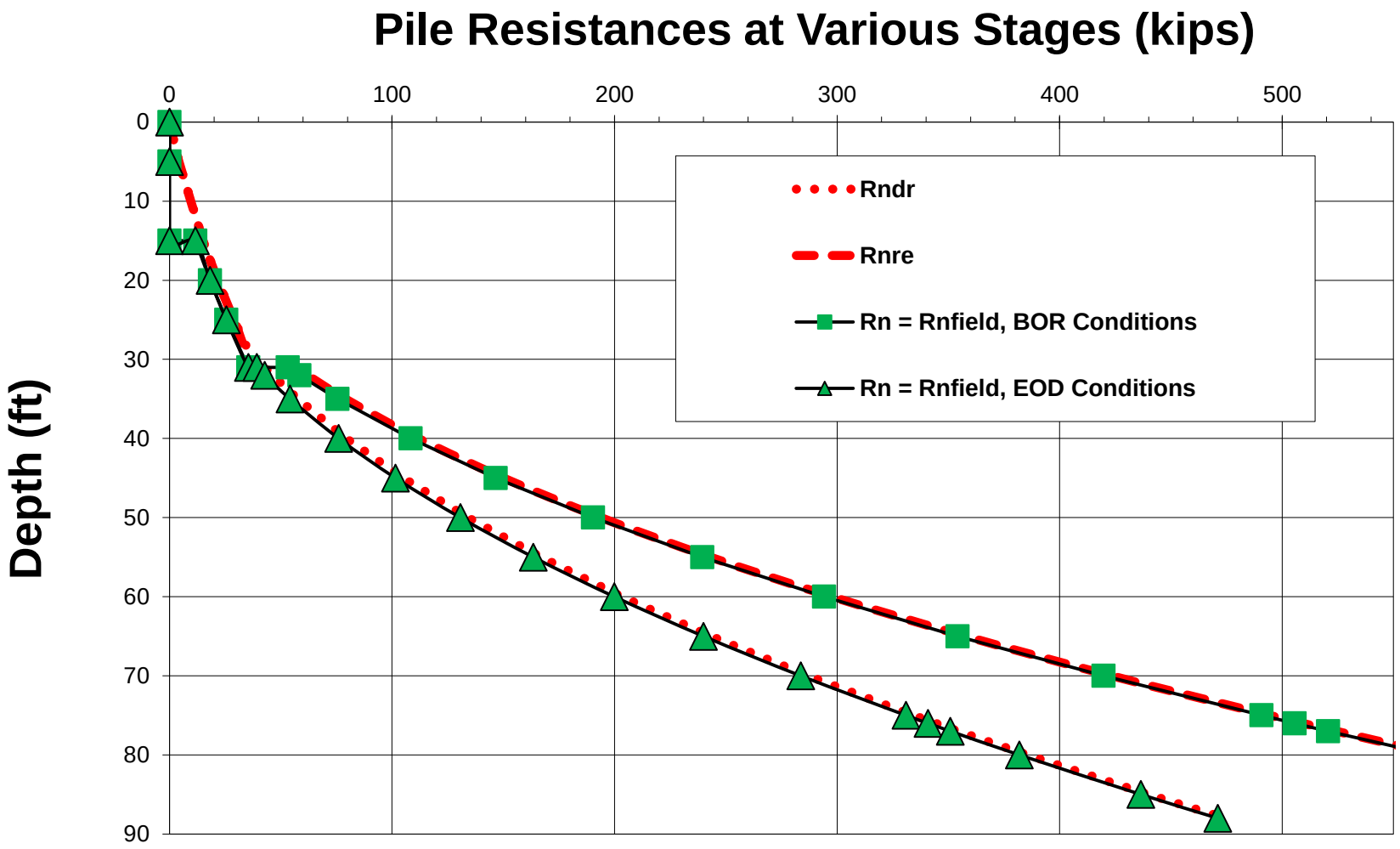
- **Problem:** Pile bearing resistances from field analysis methods (R_{nfield}) are not available in the design
  - **Differences between design and field pile lengths**

- **Solution:** use the following equation to predict more accurately R_{nfield} resistances in the design:

$$\mathbf{R_{nfield} = \alpha\, R_{nstat}}$$

Where α is the resistance median bias between the field and static analysis methods selected in the design.

Bearing Resistances for Wave Equation Analysis



Drivability Analysis in the Design Phase Using Wave Equation Analysis Program (WEAP)

- **Purpose?** To ensure piles can be safely driven to the required field resistance and depth.

- **How?** Estimate driving stresses (σ_{da}) and blow count, (N_b), then ensure that:
  - $\sigma_{da} \leq \phi_{da}\ \sigma_{da\text{-}maximum}$; and
  - $2.5 \leq N_b$ (bpi) ≤ 10

- **Evaluation?** For two driving conditions:
  - During driving conditions, including EOD.
  - Restrike (BOR) conditions

WEAP Analysis Using the "Drivability Option"

Input Data:

- WEAP R_{ndr} vs. depth to evaluate driving conditions.
- WEAP R_{nre} vs. depth to evaluate restrike conditions
- Pile/soil information, and
- **Consider Common driving systems**

Output

- Blow count vs. depth, and
- Driving stress vs. depth

New Procedure to Evaluate Drivability Using WEAP "Driving Option" Results

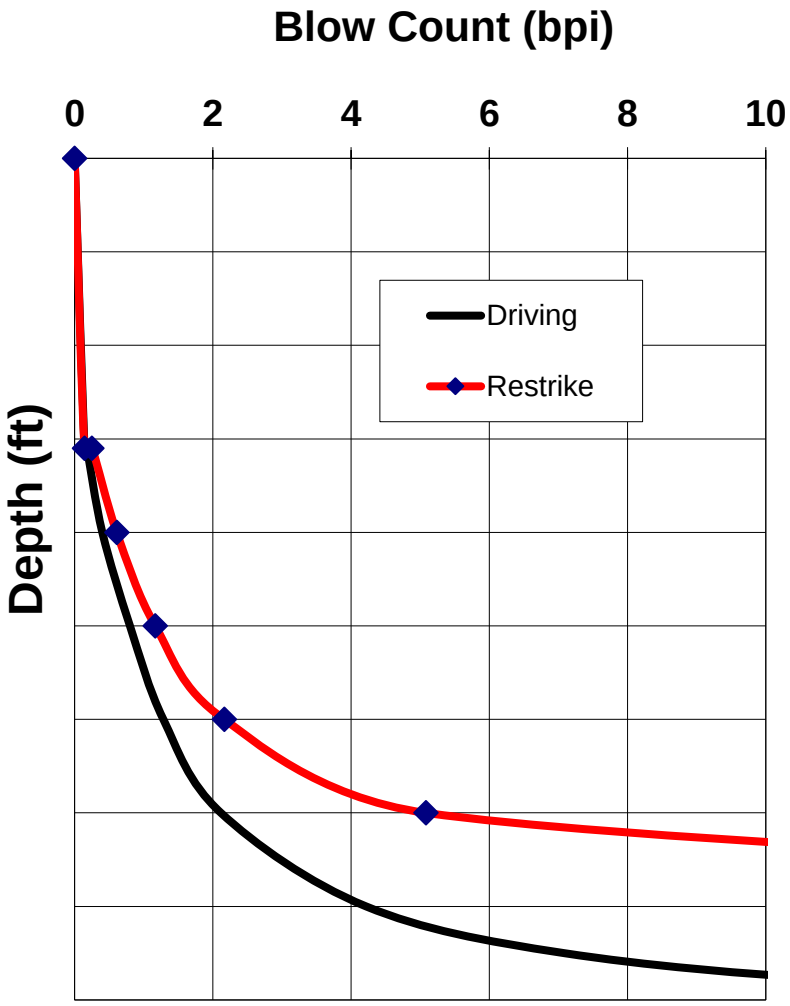
- L_{max} is the maximum length a pile can be safely driven to, determined at the depth where:
  - Max allowable driving stress is reached; OR
  - Max allowable blow count is reached

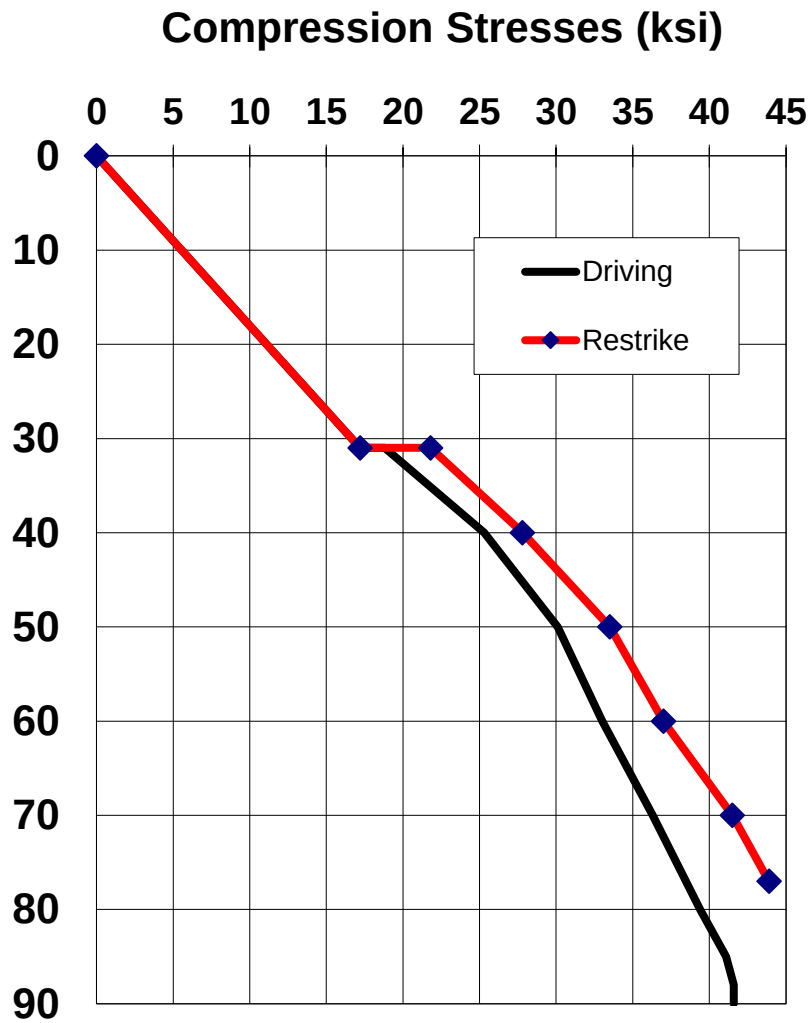
- Determine L_{max} for driving and restrike conditions

- Check drivability for all limit states:
  - $L \leq L_{max}$,
  - $L_m \leq L_{max}$

Drivability Results: Using D30-23 Diesel Hammer

L_{max} = 80 ft and 70 ft for Driving and Restrike Conditions





Structural Limit State and Finalization of Q_{fmax}

- **Meet structural limit state:**
  - $Q_f \leq \phi_{str} P_n$ or $Q_f \leq \phi_{str} P_n$
  - $\mathbf{Q_{fmax\text{-}structural}} = \phi_{str} P_n$;
    - = 0.6x50x15.5= **465 kips for the LRFD Example**

- **Meet geotechnical and drivability limit states:**
  - Determine $Q_{fmax\text{-}geotechnical}$ from Q_f vs. L at L_{max}

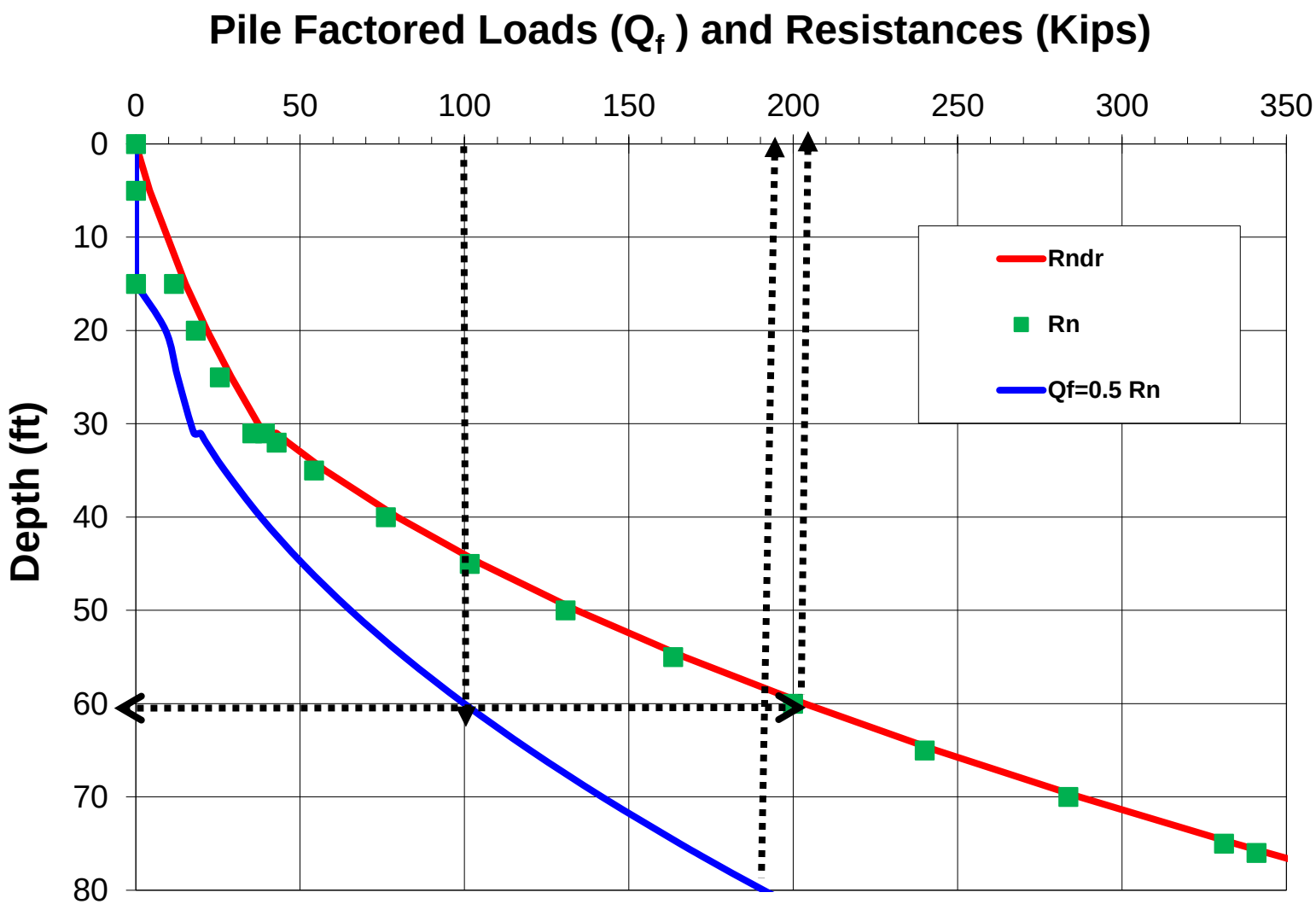
- **Q_{fmax}: the smaller of**
  - **$Q_{fmax\text{-}structural}$, and**
  - **$Q_{fmax\text{-}geotechnical}$**

A Design Chart

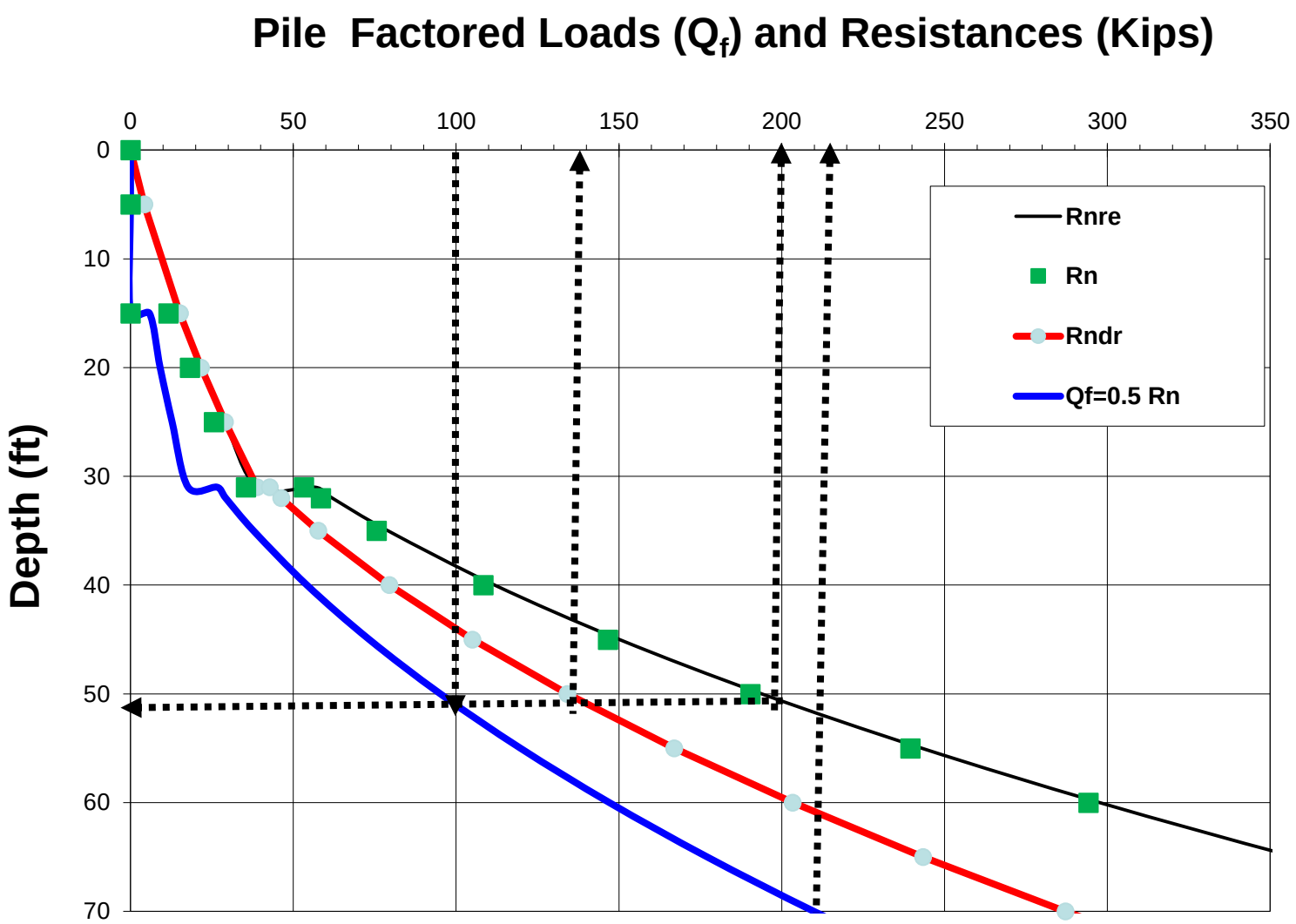
- **Definition:** curves of supported Q_f and bearing resistances at various depths up to Q_{fmax} and L_{max}
  - Supported $Q_f = \phi R_n$
  - For certain pile type and field analysis method

- **Applications**
  - Determine Q_{fmax}
  - Check several limit states
  - For any Q_f, determine required
    - Pile length, L
    - Nominal bearing resistance

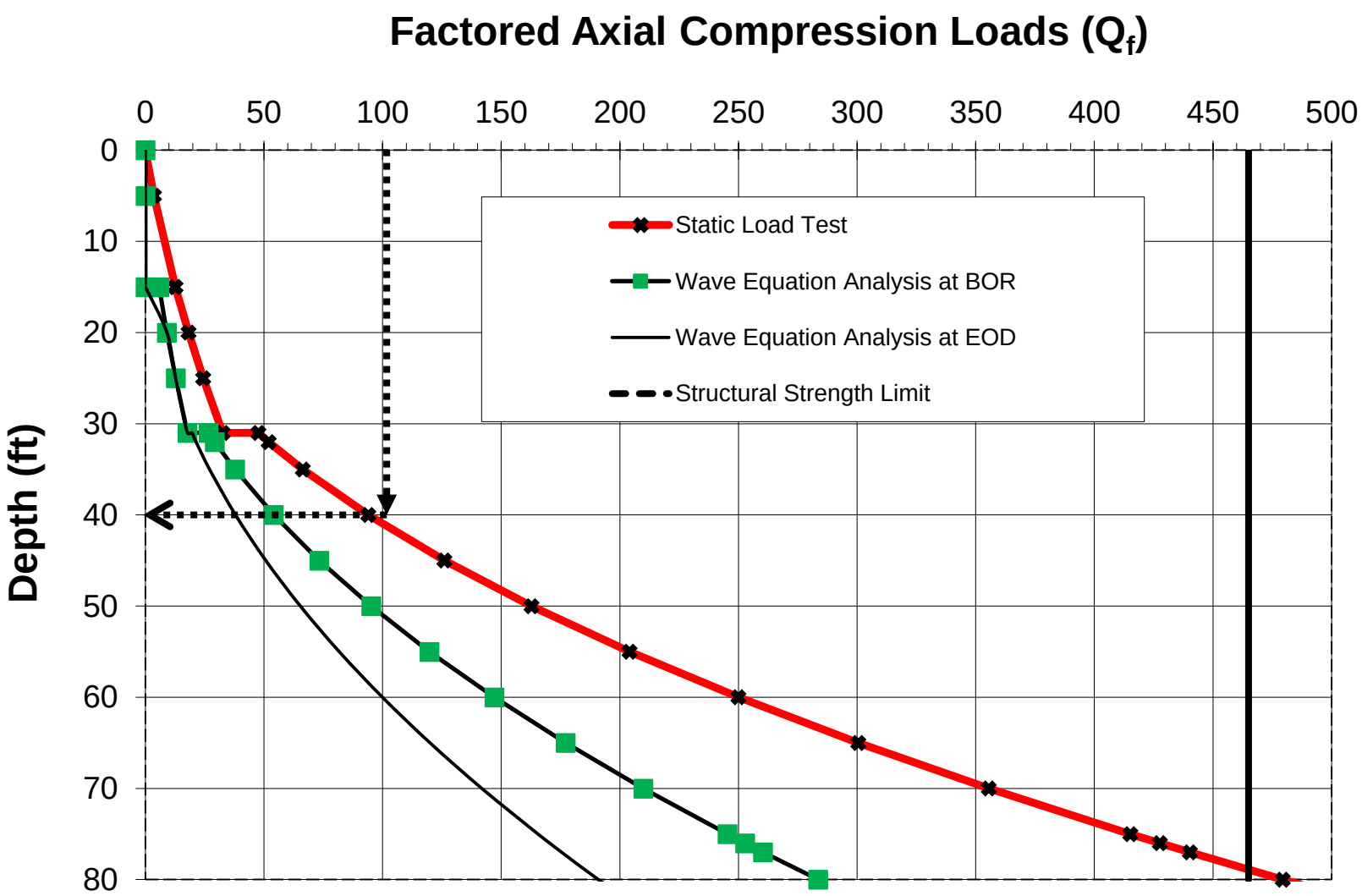
Design Chart for Wave Equation Analysis at EOD



Design Chart for Wave Equation Analysis at BOR



Design Curves for Various Design Methods



Advantages of Setup and Load Tests Using LRFD Design Example Results

Method	Results for Q_f = 100 kips			L_{max} (ft)	Q_{fmax} (kips)
	Pile length (ft)	Required Nominal Bearing Resistance (kips)			
		R_{ndr}	R_{nre}		
Wave Equation (EOD)	60	203.5	N/A	80	191
Wave Equation (BOR)	51	139	203.5	70	209
Static Load Test	41	85*	128**	80	465

Advantages of Design Charts/Curves

Simple and flexible approach to obtain, finalize, and optimize the design

- Easily obtain data needed in construction plans
- Handle easily continuous changes in design loads
- Address pile drivability for any limit state, and other compression strength limit states of a single pile
- Compare various pile types and select the best
- Compare field analysis methods and select the best
- Evaluate various layout for pile group and identify the most cost-effective layout

Questions?

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