Civil & Coastal Engineering

Resistance factors for 100% dynamic testing, w/ & w/o static load tests

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Project Managers:

Rodrigo Herrera, PE

Peter Lai, PE

Researchers:

Haki Klammler, PhD

Mike McVay, PhD

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Overview

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- Current FDOT practice
- Prediction bias and uncertainty
- Probability of failure at pile, pier and bridge level – what do we want?
- Adding spatial uncertainty to FB-Deep method (SPT/CPT) for single piles
- Geostatistical approach for pile groups
- Regression approach for pile groups
- Practical example

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Current FDOT Practice

- Predefined **Φ** for whole site depending on monitoring method and minimum degree of monitoring (based on "past experience", i.e., predicted vs. measured data bases)
- No consistent consideration given to:
  - Number of (monitored) piles in group
  - Combinations of different monitoring and prediction methods (individual method errors)
  - Heterogeneity of site (spatial variability)
  - Geometric configuration of (monitored) piles

Current FDOT Practice

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Table 1-1. AASHTO 10.5.5.2.3-1 (2009)

Condition/Resistance Determination Method	Resistance Factor
Static load test of at least one pile Dynamic testing of at least two piles (no less than 2% of the production piles)	**0.8**
Static load test of at least one pile No dynamic testing	**0.75**
Dynamic testing on 100% of production piles	**0.75**
Dynamic test w/ signal matching (BOR) of at least one production pile p/ pier	**0.65**
Wave equation analysis (EOD) No pile dynamic measurements or load test	**0.4**
FHWA-modified Gates dynamic pile formula (EOD)	**0.4**
ENR dynamic pile formula (EOD)	**0.1**

Bias and Uncertainty

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- **BIAS**
  - Systematic over / under estimation
  - May be corrected for deterministically (by an equation)
- **UNCERTAINTY**
  - Random prediction error after bias correction
  - May be accounted for as error variance $\boldsymbol{\sigma^2_\varepsilon}$ or error coefficient of variation $\mathbf{CV_\varepsilon}$ of prediction method

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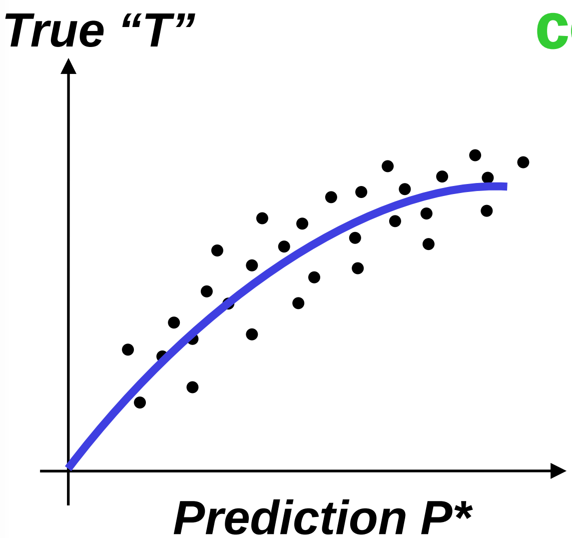
Bias and Uncertainty



Bias correction

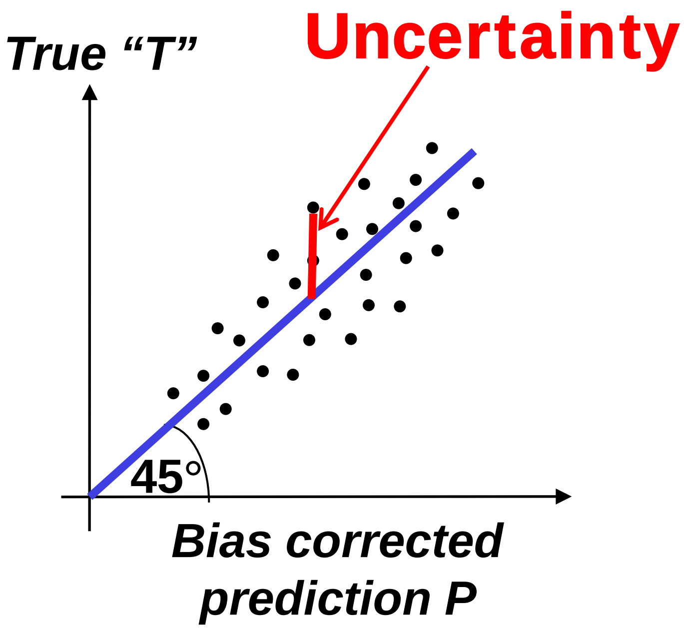
E.g.:

$P = a + bP^*$

$P = aP^{*b}$

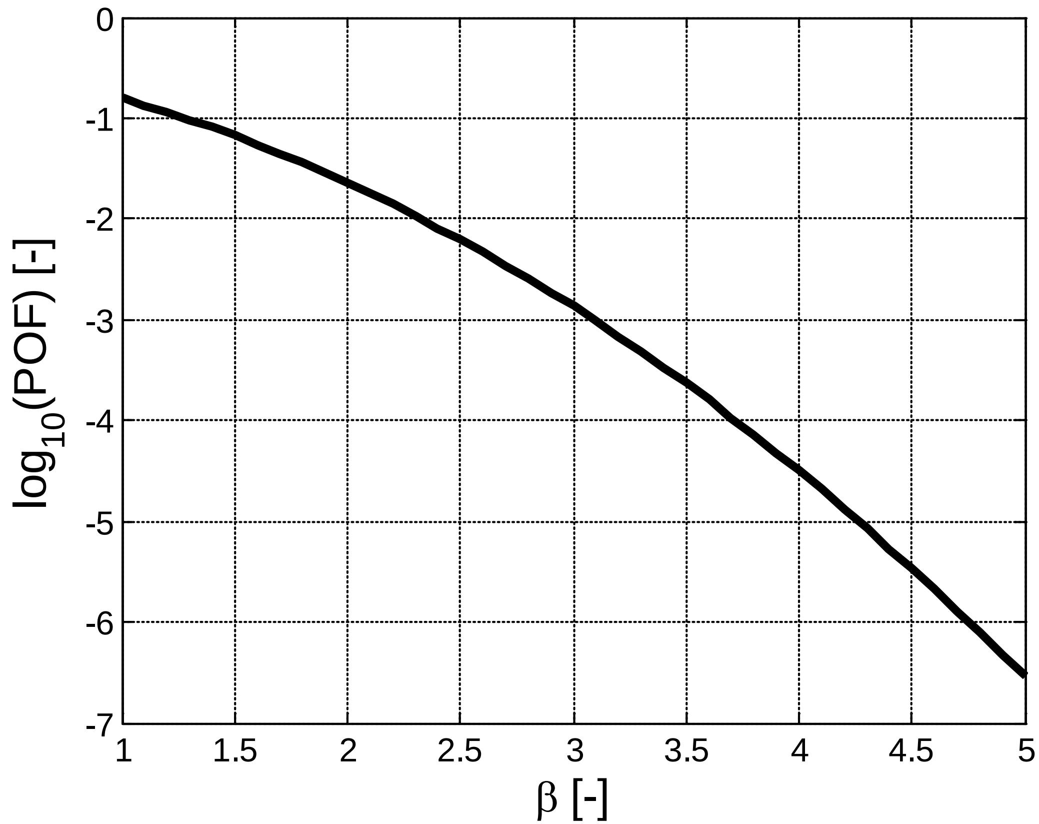
$P = \log(P^*)$

⋮



Probability of Failure (POF)

- LRFD reliability index **β** is directly related to POF



Probability of Failure (POF)

- A prescribed POF always refers to a certain structural unit (e.g., single pile, pier or whole bridge)

Example:

- If a pier consists of 4 piles, where each has a **POF_{pile} = 0.001**, then the pier has a **POF_{pier}** $= 0.001^4$ **$= 10^{-12}$** if all piles have to fail for the pier to fail (i.e., **full redundancy** due to a rigid pile cap, for example)
- It the pier fails with failure of only a single pile (**zero redundancy**) then **POF_{pier}** $= 1 - (1-0.001)^4$ **$\approx 0.004 > 0.001$**

Probability of Failure (POF)

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- The more elements are combined fully redundant, the smaller POF (all elements have to fail)
- The more elements are combined without redundancy, the larger POF (only one of many element needs to fail)
- POF's of piles, piers and bridge are not the same!
- **WE USE POF AT PIER LEVEL AND ASSUME FULL REDUNDANCY OF PILES IN A PIER**
- **POF OF BRIDGE THEN DEPENDS ON NUMBER OF PIERS AND SUPERSTRUCTURE PROPERTIES** (i.e., load redistribution, pier redundancy)

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Overview

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- Presentation of three different approaches with evaluation of underlying assumptions, advantages and disadvantages:

  1. Adding spatial uncertainty to FB-Deep method (SPT/CPT) for single piles
  2. Geostatistical approach for pile groups
  3. Regression approach for pile groups

- Practical example

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FB-Deep Method

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- Uses SPT/CPT data **N** to predict total (side + tip) pile resistances for given ground conditions (e.g., sand, clay, layering, etc.) as a weighted sum
- We assume random pile location at a site
- Vertical correlation length $\mathbf{a_v}$ of **N** is known from variogram analysis of depth profiles
- Uncertainty $\mathbf{CV_R}$ in pile resistance due to spatial variability is equal to $\boldsymbol{\alpha^{1/2} CV_N}$
- **α** is a variance reduction factor depending on $\mathbf{L' = L/a_v}$ and $\mathbf{D' = D/a_v}$ obtained from geostatistics

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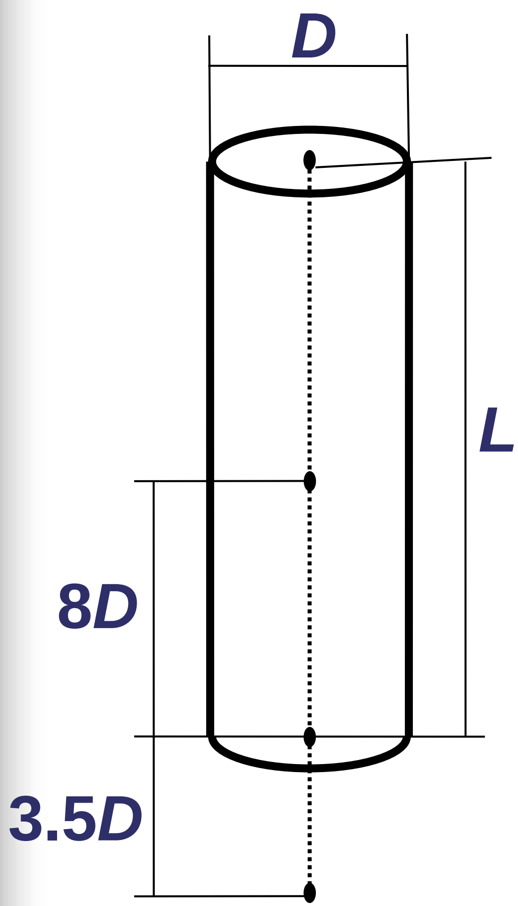
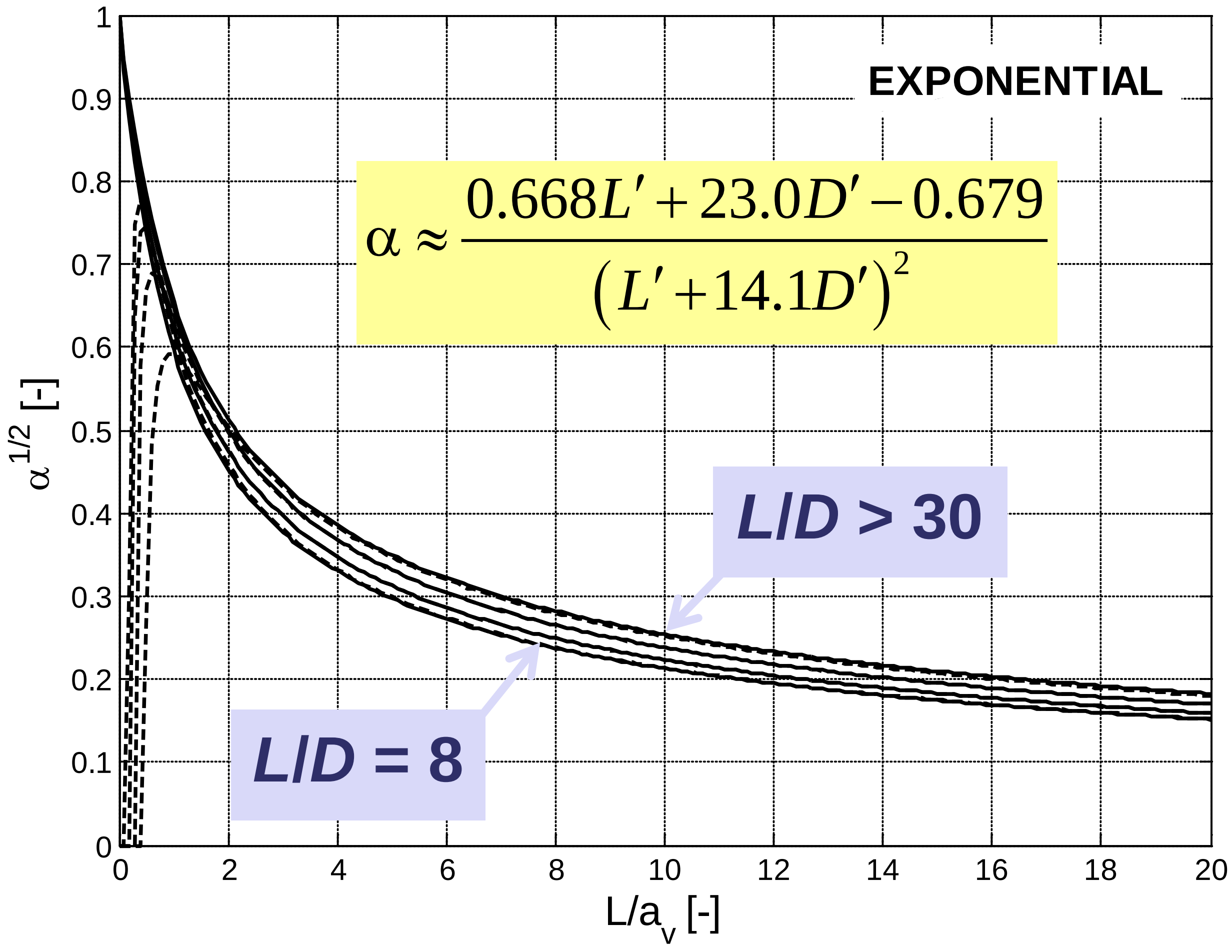
FB-Deep Method - Sand





FB-Deep Method

- Results do not include method error (of FB-Deep equations)
- Valid only for single piles and linear FB-Deep equations (e.g., for sand)
- Further approximations required for non-linear FB-Deep equations (e.g., quadratic for clay)
- Solution becomes more complex for more than a single layer
- No accounting for “nearby” data

Geostatistical Approach for Pile Groups

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- Two scenarios are considered depending on the type of data available:

  1. **Local unit side friction data (design neglecting end bearing)**
  2. **Total (side + tip) pile resistance data, e.g., from pile monitoring during installation**

- Both scenarios account for uncertainty reduction due to nearby data (spatial correlation between observed and predicted resistances)

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Geostatistical Approach: **Scenario 1**

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- Three dimensional problem using a simplified form of ordinary block kriging
- Nominal unit side friction in a pile group is equal to a weighted average of unit side friction observed at the nearest data location and of mean unit side friction over the site (geostatistically homogeneous sub-zone)
- Uncertainty $\mathbf{CV_R}$ decreases and LRFD resistance factor $\mathbf{\Phi}$ increases with the amount of data available and with spatial correlation between data and prediction locations

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Geostatistical Approach: **Scenario 1**

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- Approach suitable for arbitrary pile lengths within vertical range of data

- Conservative worst case scenarios may be found for unknown horizontal correlation length $\mathbf{a_v}$

  1. Numerical minimization of $\mathbf{Q_{design} = \Phi R_n}$

  2. Equations for minimizing $\mathbf{\Phi}$ and $\mathbf{R_n}$ separately (simpler, but even more conservative)

- Only unit side friction is considered
  → **NO END BEARING**

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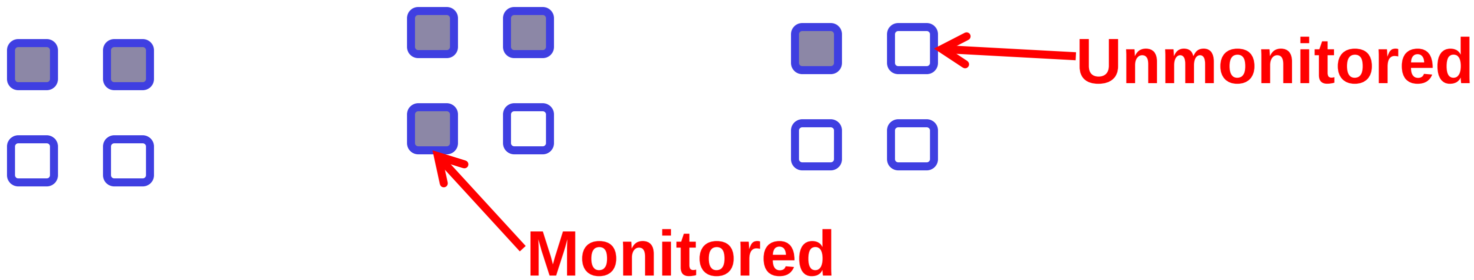
Geostatistical Approach: **Scenario 2**

- Total (side + tip) resistance is considered a spatially correlated random variable in the horizontal plane (no more vertical direction); for example:



- Resistance data available from pile monitoring methods during installation (e.g., EDC, PDA)
- Similar to scenario 1, a simplified ordinary kriging approach is adopted

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Geostatistical Approach: **Scenario 2**

- Mean nominal pile resistance in a group is predicted as a weighted average between mean monitored pile resistance in that group and mean monitored pile resistance over site (homogeneous sub-zone)
- Uncertainty $\mathbf{CV_R}$ decreases and LRFD resistance factor $\boldsymbol{\Phi}$ increases with the degree of monitoring
- If all piles in a group are monitored, then $\mathbf{CV_R}$ only depends on the uncertainty (random error) of the prediction method, i.e., no more spatial uncertainty

Geostatistical Approach: **Scenario 2**

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- Results depend on the number AND geometric arrangement of monitored and unmonitored piles in a group
- No simple general expressions or charts could be generated for practical application
- **Conceptual limitations** of viewing pile resistance as a spatially correlated random function:
  - All piles (monitored and unmonitored) need to share some common characteristic (e.g., final blow count or embedment depth)
  - This is not generally the case in practice

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Regression Approach for Pile Groups

- All previous approaches involve spatial correlation and have one or more limitations:
  - Valid for single piles only
  - Does not account for end bearing
  - Complex representation / application of results
  - Divergence between conceptual assumptions and design / construction practice

Regression Approach for Pile Groups

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- “Regression approach” explores correlation between blow count data and pile resistances rather than spatial correlation between pile resistances (or SPT/CPT data)
- Motivation:
  - Does not rely on generally unknown $\mathbf{a_h}$
  - **Blow count data is available for EVERY pile**
  - **Correlation (prediction quality) between blow counts and pile resistances has been used in past (GATES, ENR, etc)**

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Blow Counts **N** vs. Monitored Pile Resistances $\mathbf{R_m}$

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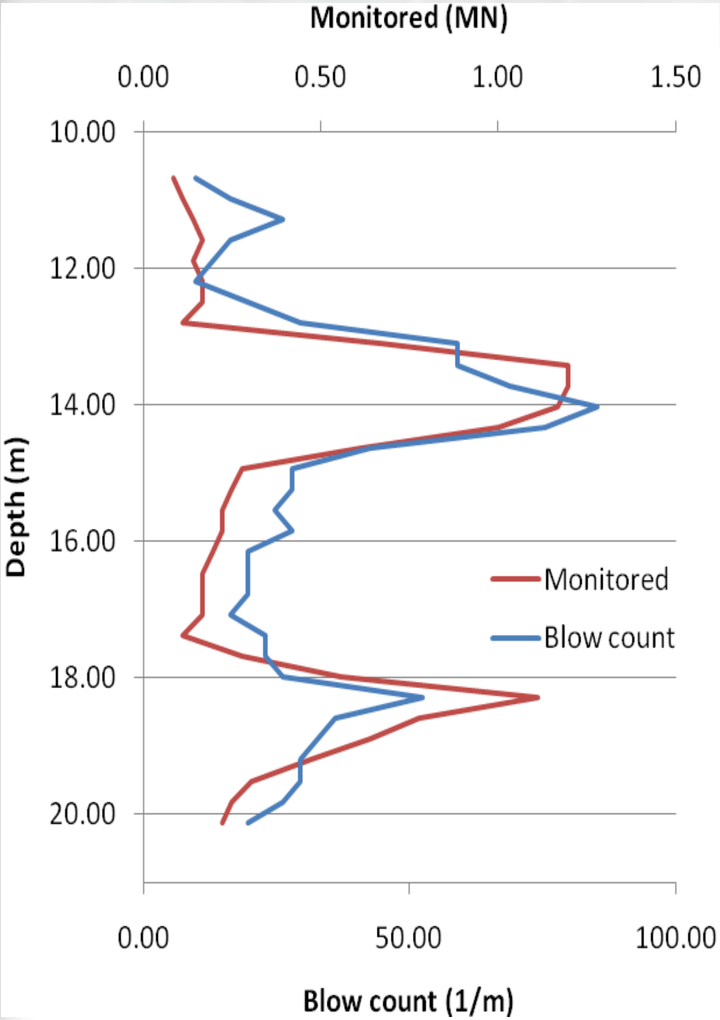

- Ex.: Depth profiles of Caminida pile 7
  - Good correlation between **N** and $\mathbf{R_m}$
  - Different layers are directly handled
- What's the best relationship between **N** and $\mathbf{R_m}$?

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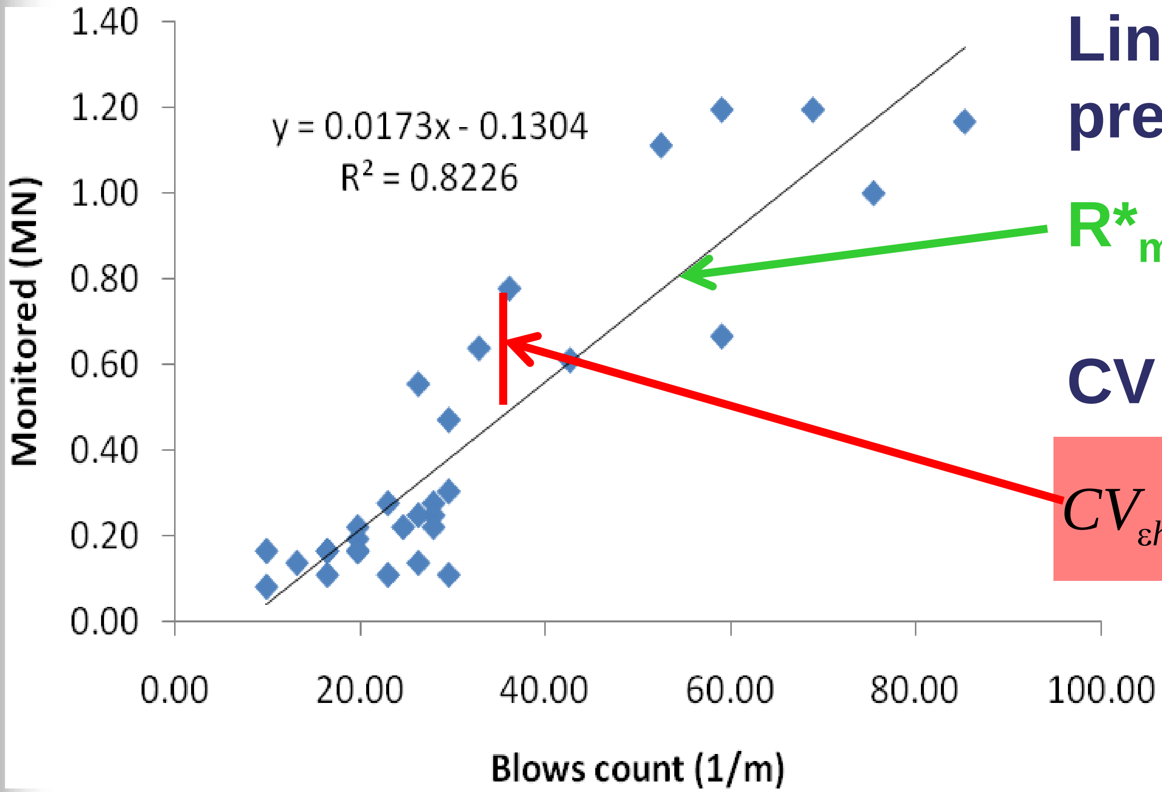
Blow Counts **N** vs. Monitored Pile Resistances $\mathbf{R_m}$

- Scatter plot of **N** vs. $\mathbf{R_m}$ for Caminida pile 7:



Linear regression prediction of $\mathbf{R_m}$:

$R^*_m = a + bN$

CV of prediction error:

$$CV_{\varepsilon h} = \sqrt{\exp\left[\sigma^2_{\ln m}\left(1 - R^2_{\ln}\right)\right] - 1}$$

Blow Counts **N** vs. Monitored Pile Resistances $\mathbf{R_m}$

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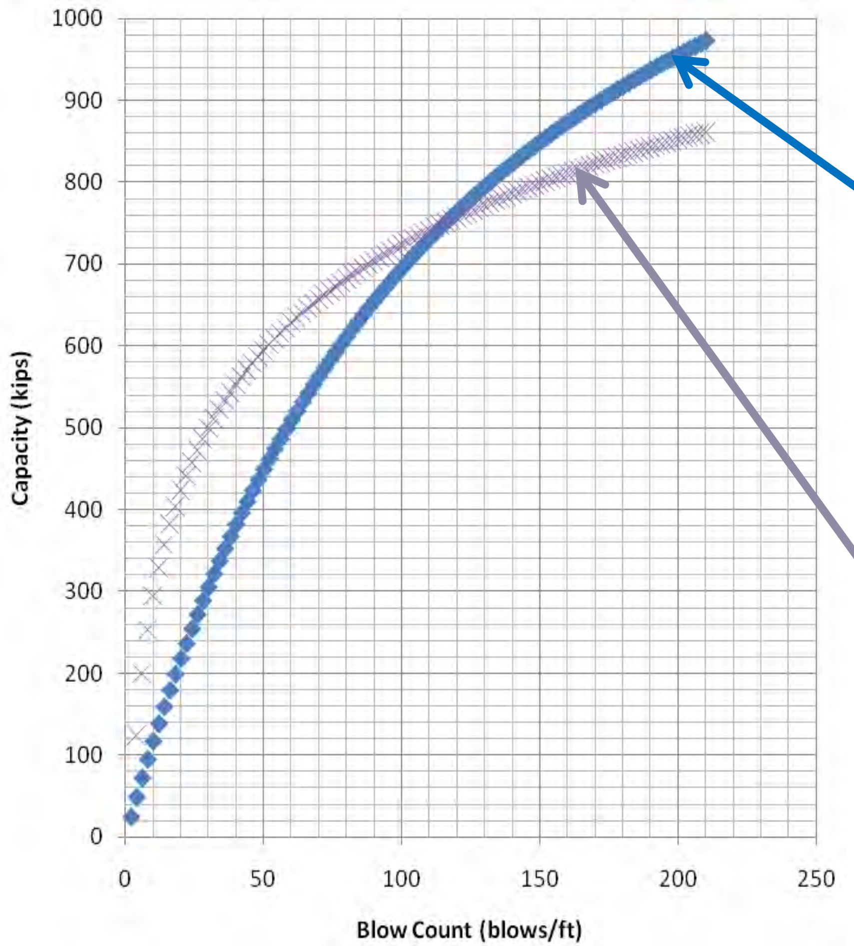
- Alternative (non-linear) relationships are also possible:



ENR:

$$R_m* = \frac{e_h W_H H}{FS(s + C)}$$

FHWA-Gates:

$$R_m* = 1.75\sqrt{W_H H}\log(10N) - 100$$

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Predicted Pile Group Resistance $\mathbf{R_g}$

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- Sum of monitored and unmonitored pile resistances

$$R_g = \sum_{i=1}^{n_m} R_{mi} + \sum_{i=n_m+1}^{n_p} (a + bN)$$

$\mathbf{n_m}$ ... number of monitored piles in a group

$\mathbf{n_p}$ ... total number of piles in a group

- $\mathbf{R_g}$ possesses prediction uncertainty $\mathbf{CV_g}$

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Pile Group Resistance Uncertainty $\mathbf{CV_g}$

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- Summing error variances of all piles in a group gives

$$CV_g = \sqrt{\frac{1}{n_p}\left[CV_{\varepsilon m}^2 + \left(1 - \frac{n_m}{n_p}\right)CV_{\varepsilon h}^2\right]}$$

$\mathbf{CV_{\varepsilon m}}$ ... error CV of monitoring method known from existing data bases of monitored vs. load test results

$\mathbf{CV_{\varepsilon h}}$ ... error CV of prediction between **N** and $\mathbf{R_m}$ known from regression model based on depth profiles

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LRFD Φ

- From AASHTO (2004):

$$\Phi = k\sqrt{\frac{1+CV_Q^2}{1+CV_g^2}}\exp\left\{-\beta\sqrt{\ln\left[\left(1+CV_g^2\right)\left(1+CV_Q^2\right)\right]}\right\}$$

k ... constant depending on load characteristics

CV_Q ... CV of random load

β … reliability index (e.g., 2.5, 3, etc.)

Simple Approximation for LRFD Φ

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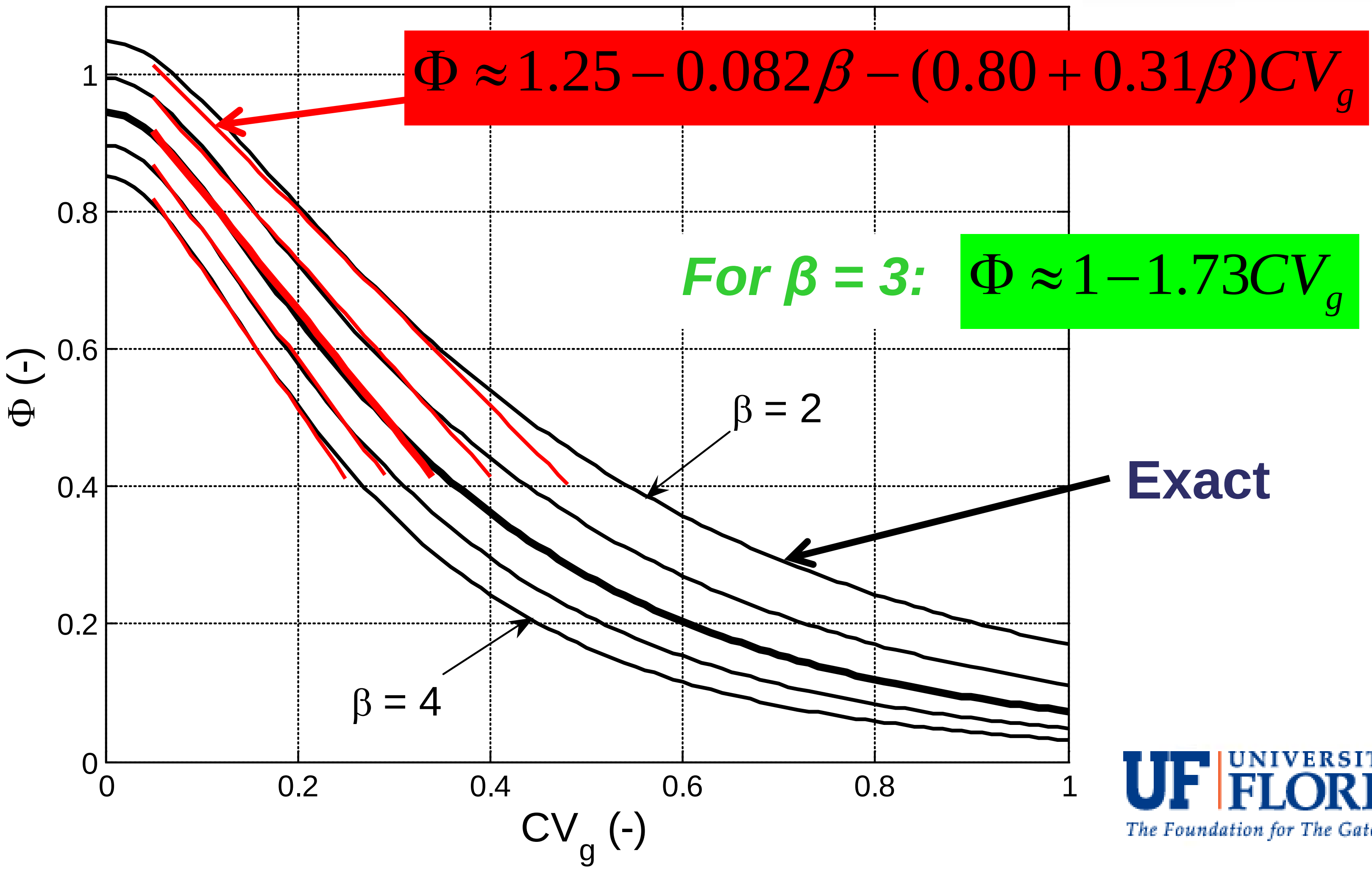

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Simple Approximation for LRFD Φ

- Final design equation (e.g., for **β** = 3)

$$\Phi \approx 1 - 1.73\sqrt{\frac{1}{n_p}\left[CV_{\varepsilon m}^2 + \left(1 - \frac{n_m}{n_p}\right)CV_{\varepsilon h}^2\right]}$$

- Depends on
  - Number $\mathbf{n_p}$ of piles in group
  - Degree of monitoring $\mathbf{n_m/n_p}$
  - Prediction uncertainties $\mathbf{CV_{\varepsilon m}}$ and $\mathbf{CV_{\varepsilon h}}$

Simple Approximation for LRFD Φ

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- Equation valid if nominal resistance is evenly distributed between all piles in a group
- This means:
  - All monitored piles are driven until $\mathbf{R_m = \Phi Q_{design} / n_p}$ is reached
  - All unmonitored piles are driven until $\mathbf{N = (R_m - a) / b}$ is reached (i.e., blow count, for which predicted resistance is again equal to $\mathbf{R_m}$)

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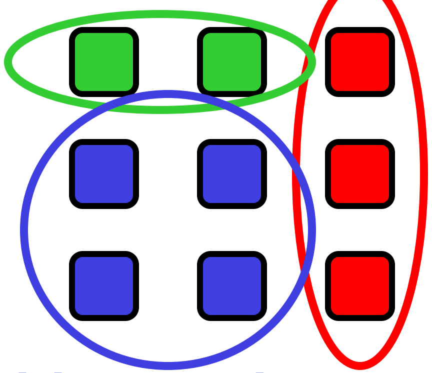
Uneven Resistance Distribution between Piles in a Group

- One or more piles of a group are monitored test piles installed prior to final group design
- For example:
  - $\mathbf{n_p = 9}$ (total)
  - **$n_0 = 2$ (previously driven)**
  - $\mathbf{n_m = 6}$ (**blue** + **green**) (total monitored: previously driven plus to be driven)



Uneven Resistance Distribution between Piles in a Group

- Predicted resistance $\mathbf{R_0}$ of all $\mathbf{n_0}$ test piles together

$$R_0 = \sum_{i=1}^{n_0} R_{mi}$$

- Uncertainty about $\mathbf{R_0}$

$$CV_0 = \frac{\sqrt{\sum_{i=1}^{n_0} \left(CV_{\varepsilon m} R_{mi}\right)^2}}{R_0}$$

- For the remaining piles of a group the evenly distributed nominal resistance $\mathbf{R_p}$ is sought

Uneven Resistance Distribution between Piles in a Group

- Predicted pile group resistance (summing pile resistances)

$$R_g = R_0 + (n_p - n_0)R_p$$

previously installed (R_0) **not yet installed** ($(n_p - n_0)R_p$)

- Uncertainty about $\mathbf{R_g}$ (summing pile resistance variances)

$$CV_g = \frac{\sqrt{CV_0^2 R_0^2 + \left[(n_p - n_0)CV_{\varepsilon m}^2 + (n_p - n_m)CV_{\varepsilon h}^2\right] R_p^2}}{R_g = R_0 + (n_p - n_0)R_p}$$

Uneven Resistance Distribution between Piles in a Group

- **CV_g** now depends on unknown **R_p**
- Previously, for **R_0 = 0** it dropped out ($R_m = R_p$)
- Iterative solution is required, **OR**
- Using the linear approximation developed for **Φ**, **R_p** may be directly found by solving a quadratic equation
- **Φ is for the whole group** defined as

$$\Phi = \frac{Q_{design}}{R_g} = \frac{Q_{design}}{R_0 + (n_p - n_0)R_p}$$

Uneven Resistance Distribution between Piles in a Group

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- Solution of the quadratic equation for **β = 3**

$$R_p = \frac{Q_{design} - R_0}{(n_p - n_0)(1-K)}\left[1 + \sqrt{K + 3(1-K)\left(\frac{CV_0 R_0}{Q_{design} - R_0}\right)^2}\,\right]$$

with

$$K = \frac{3}{n_p - n_0}\left(CV_{\varepsilon m}^2 + \frac{n_p - n_m}{n_p - n_0} CV_{\varepsilon h}^2\right)$$

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Uneven Resistance Distribution between Piles in a Group

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- **For the remaining piles still to be driven** we obtain a $\mathbf{\Phi_{rem}}$ as

$$\Phi_{rem} = \frac{Q_{design} - R_0}{(n_p - n_0)R_p} = \Phi^* \frac{2 - \Phi^*}{1 + \sqrt{\left(1 - \Phi^*\right)^2 + 3\Phi^*\left(2 - \Phi^*\right)\left(\frac{CV_0 R_0}{Q_{design} - R_0}\right)^2}}$$

where $\mathbf{\Phi^*}$ is equal to $\mathbf{\Phi}$ from before, but where $\mathbf{n_p - n_0}$ is used instead of $\mathbf{n_p}$ and $\mathbf{n_m - n_0}$ instead of $\mathbf{n_m}$

$$\Phi^* \approx 1 - 1.73\sqrt{\frac{1}{\left(n_p - n_0\right)}\left[CV_{\varepsilon m}^2 + \left(1 - \frac{\left(n_m - n_0\right)}{\left(n_p - n_0\right)}\right)CV_{\varepsilon h}^2\right]}$$

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Uneven Resistance Distribution between Piles in a Group

- This is, $\boldsymbol{\Phi}^*$ is a hypothetical $\boldsymbol{\Phi}$ if only the piles in a group still to be driven are considered with design load $\mathbf{Q - R_0}$
- "Hypothetical", because $\boldsymbol{\beta}$ is still applied to entire pile group
- The last big fraction accounts for the difference between $\boldsymbol{\Phi}^*$ and $\boldsymbol{\Phi}_{\mathbf{rem}}$ due to $\mathbf{R_0}$ and $\mathbf{CV_0}$
- For $\mathbf{n_0 = R_0 = 0}$ (no previously driven piles in a group) we get $\boldsymbol{\Phi}_{\mathbf{rem}} = \boldsymbol{\Phi}^* = \boldsymbol{\Phi}$

Uneven Resistance Distribution between Piles in a Group

- This gives the following installation criteria for the remaining piles:
  - All monitored piles are driven until $\mathbf{R_m = R_p}$ is reached
  - All unmonitored piles are driven until $\mathbf{N = (R_p - a) / b}$ is reached (i.e., blow count, for which predicted resistance is again equal to $\mathbf{R_p}$)

Practical Example

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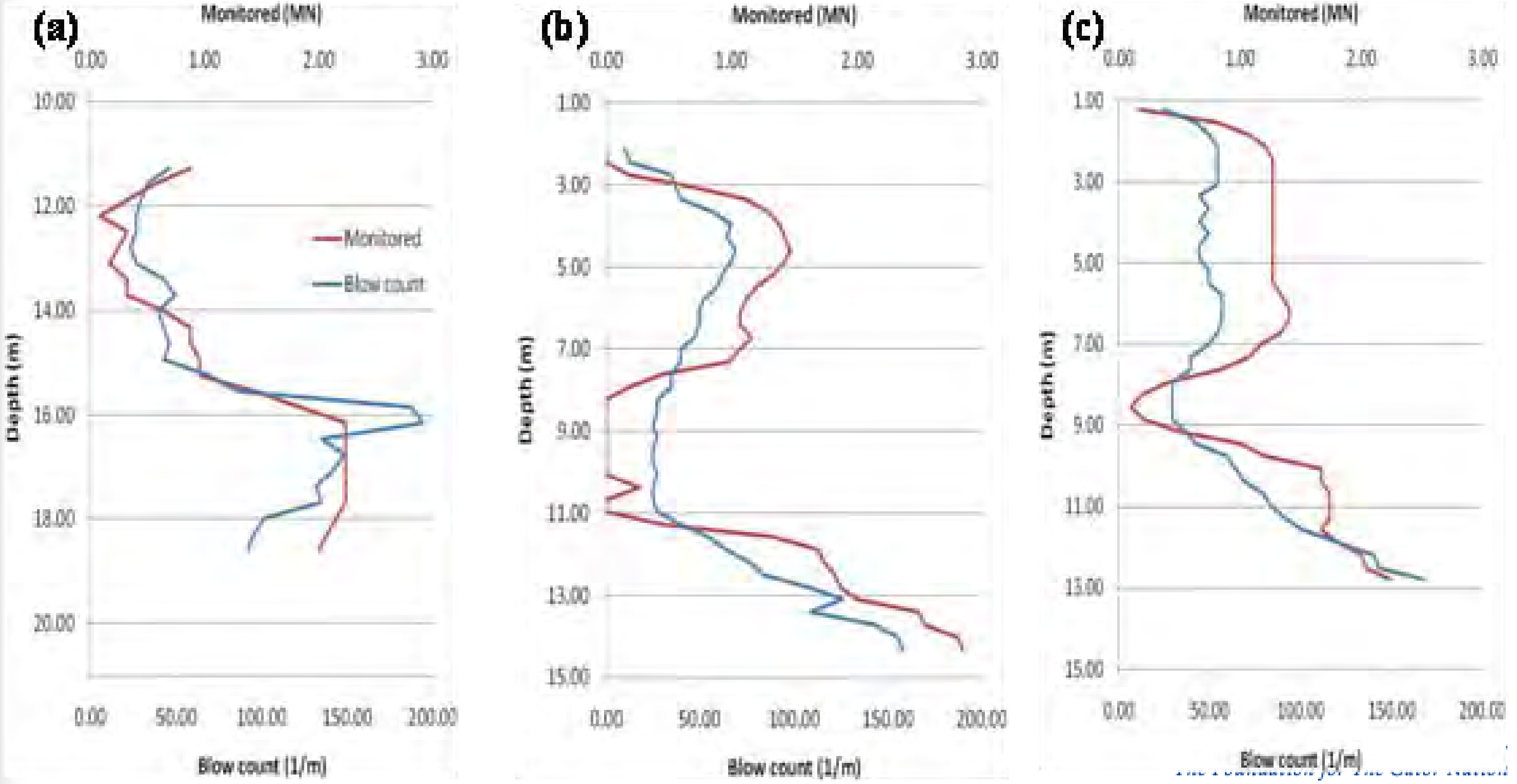
- More field data (Caminida and Dixie):



Practical Example

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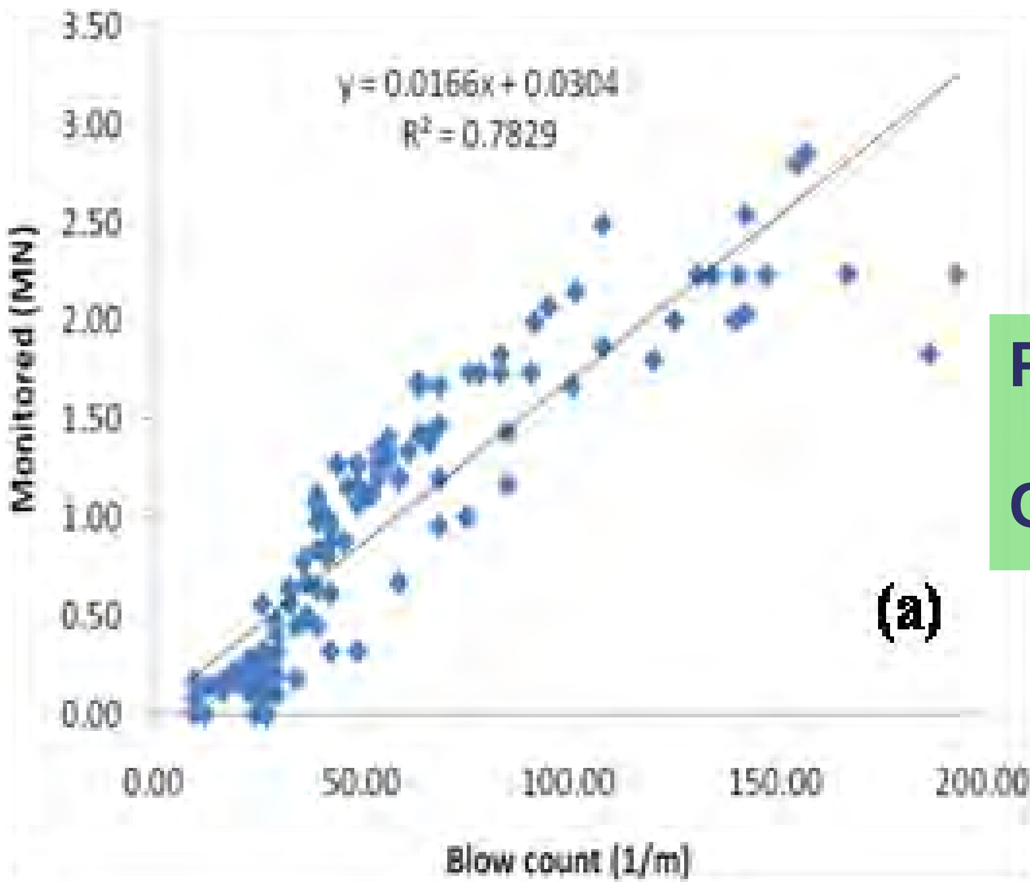
- All four piles together



$R_m^* = 0.03 + 0.017N$

$CV_{\varepsilon h} = 0.48$

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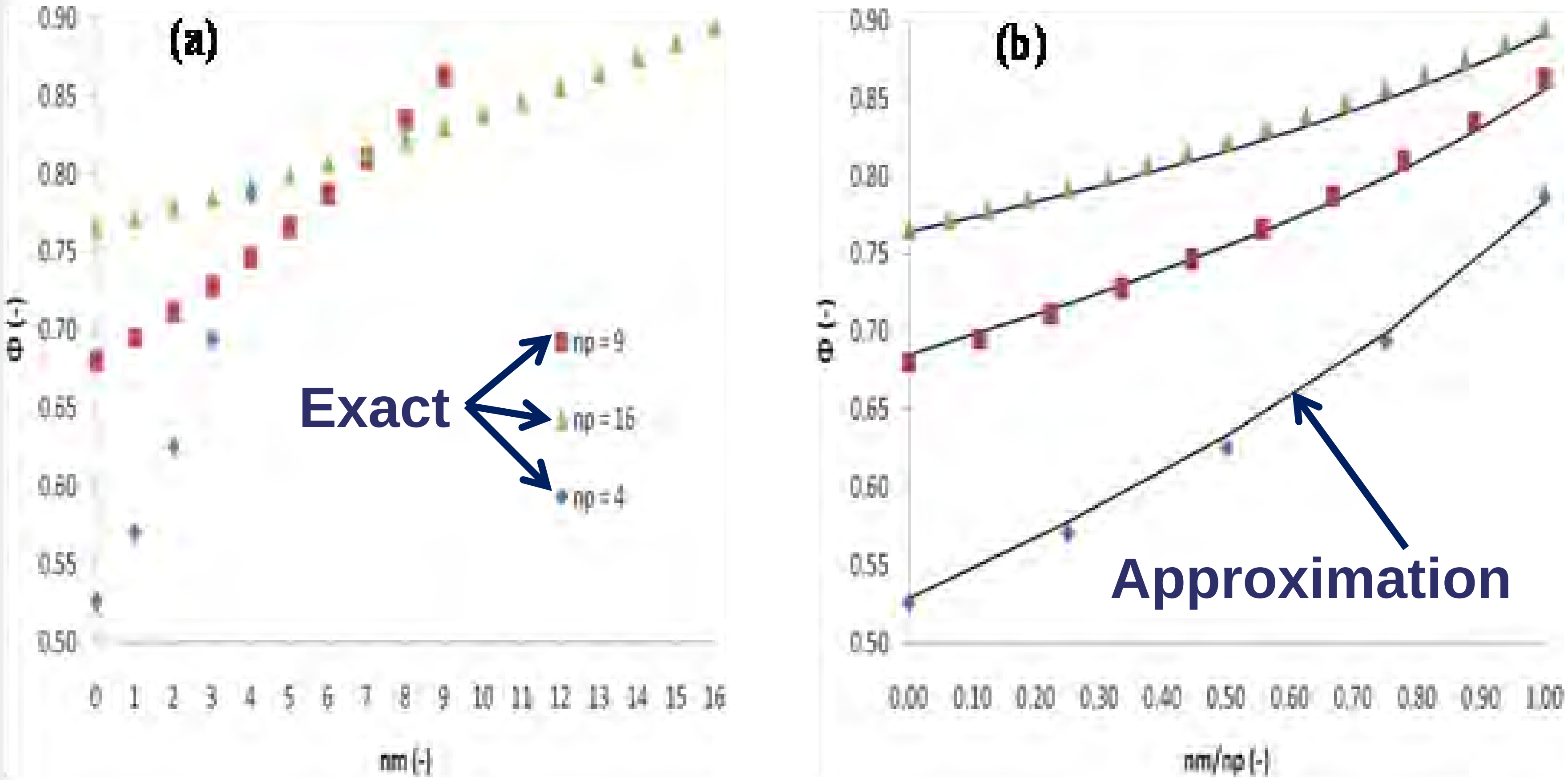
Practical Example

- **Φ** for $\mathbf{n_0 = 0}$, $\mathbf{CV_{\varepsilon m} = 0.25}$, $\mathbf{\beta = 3}$ and different $\mathbf{n_m}$:



Practical Example

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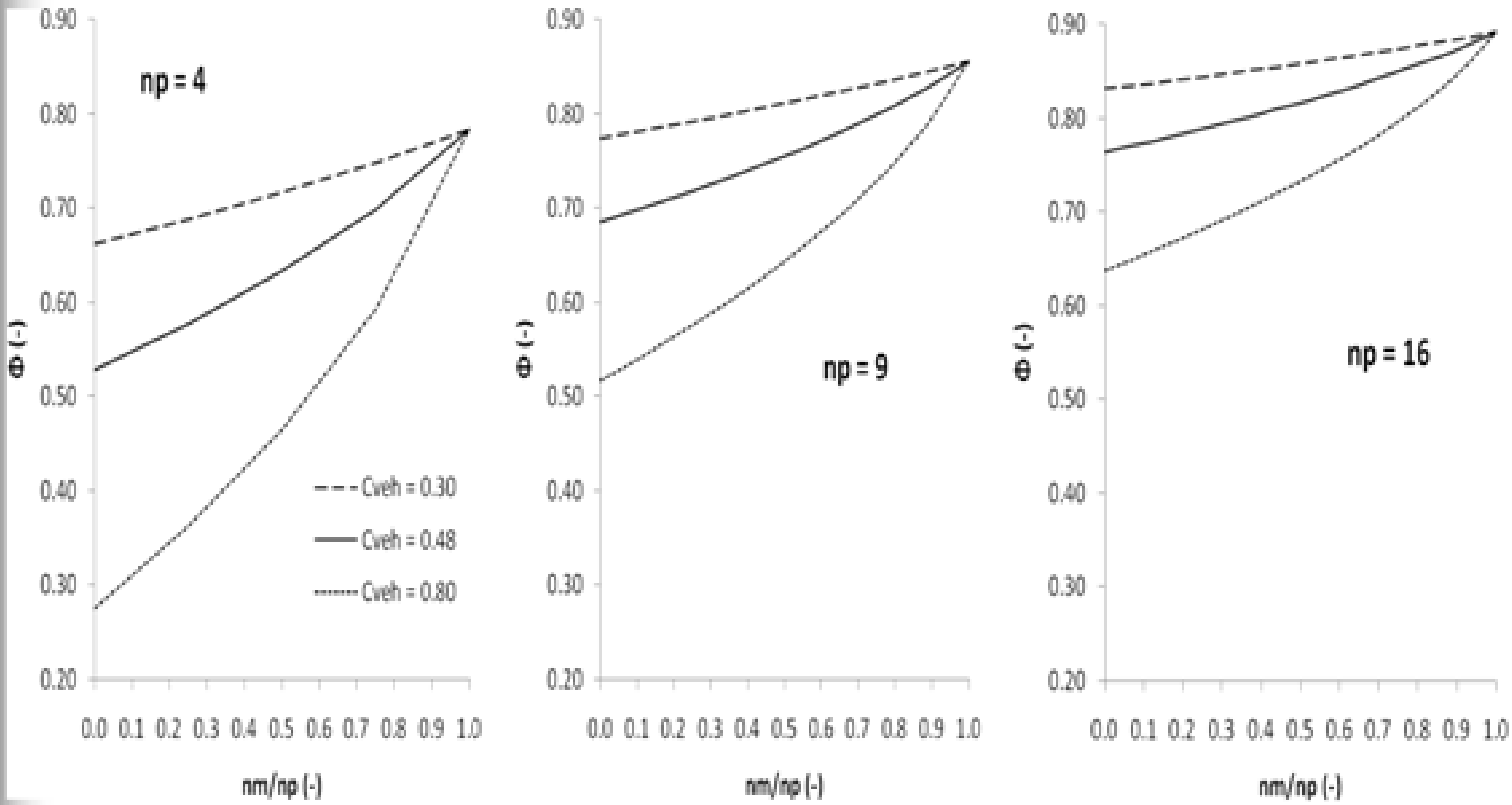
- **Φ** for $\mathbf{n_0 = 0}$, $\mathbf{CV_{\varepsilon m} = 0.25}$, **β = 3** and different $\mathbf{CV_{\varepsilon h}}$:



Practical Example

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- Assumed design situation of a pile group at Caminida or Dixie:
  - $\mathbf{Q_{design} = 15\ MN,\ \beta = 3}$ (for whole group)
  - $\mathbf{n_p = 9,\ n_m = 4,\ n_0 = 0}$ (total, monitored and previously driven piles)
  - $\mathbf{CV_{\varepsilon m} = 0.25}$ (monitoring method error)
  - $\mathbf{CV_{\varepsilon h} = 0.48,\ R_m^* = 0.03 + 0.017N}$

    (from regression analysis)

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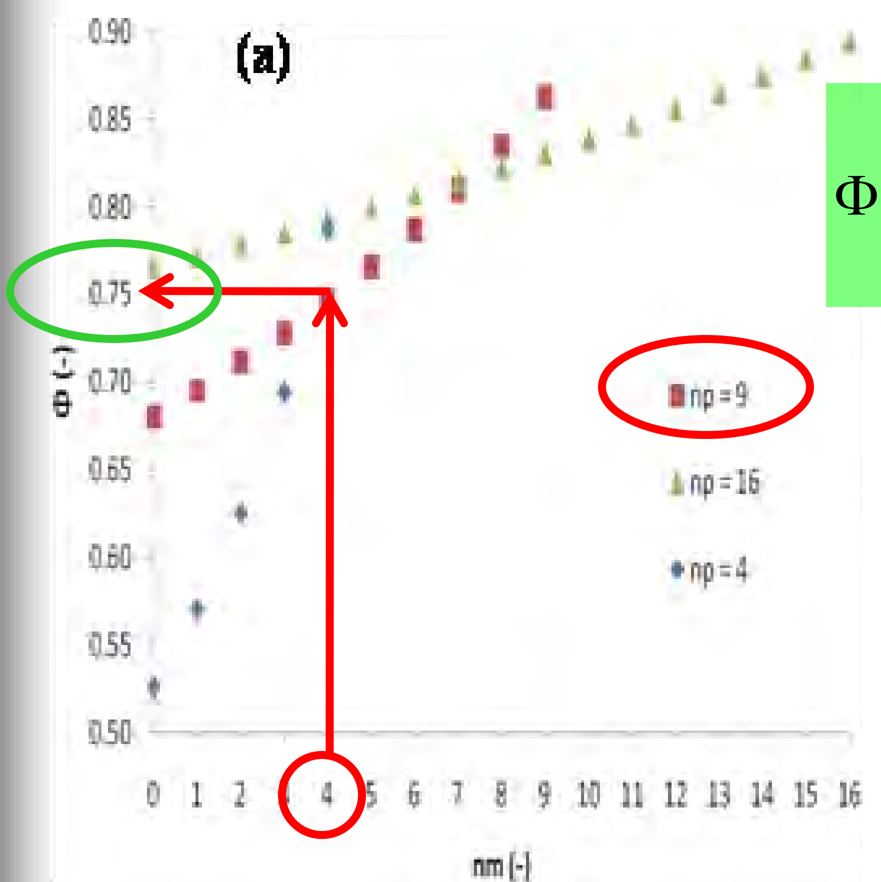
Practical Example

- Using chart or equation:



$$\Phi \approx 1 - 1.73\sqrt{\frac{1}{n_p}\left[CV_{\varepsilon m}^2 + \left(1 - \frac{n_m}{n_p}\right)CV_{\varepsilon h}^2\right]}$$

Φ = 0.75

Practical Example

- With this, nominal group and pile resistances are
  - $\mathbf{R_g = Q_{design}/\Phi = 20\ MN}$
  - $\mathbf{R_p = R_g/n_p = 2.22\ MN}$
- Hence, the four monitored piles are driven until a monitored resistance of $\mathbf{R_m = 2.22\ MN}$ is reached
- The five unmonitored piles are driven until a blow count of **N** = (2.22 – 0.03)/0.017 **= 129 blows/m** is reached

Practical Example

- Further assuming that one pile had been previously driven. i.e., $\mathbf{n_0 = 1}$ ($\mathbf{n_m = 4}$, $\mathbf{n_p = 9}$ remain the same)
- Depending on the respective monitored resistance $\mathbf{R_0}$ the nominal resistance $\mathbf{R_p}$ of the other eight piles still to be driven result as

$$\Phi = \frac{Q_{design}}{R_g}$$

$$\mathbf{Q_{design} = 15\ MN}$$

R_0	R_p	R_g	Φ	Φ^*	Φ_{rem}
3	2.11	19.87	0.75	0.72	0.71
2.22	2.22	20.06	0.75	0.72	0.72
1.5	2.35	20.26	0.74	0.72	0.72

Practical Example

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- $\mathbf{R_p}$ increases as $\mathbf{R_0}$ becomes smaller to compensate
- $\mathbf{R_g}$, $\mathbf{\Phi}$, $\mathbf{\Phi^*}$ and $\mathbf{\Phi_{rem}}$ are also different in all cases, since uncertainty $\mathbf{CV_g}$ is affected by $\mathbf{R_0}$
- The larger $\mathbf{n_0 / n_p}$, the larger is the influence of $\mathbf{R_0}$ and $\mathbf{CV_0}$ on the design of the remaining piles

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Summary

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- Current FDOT practice for design of driven pile groups uses pre-defined values of LRFD **Φ** (e.g., AASHTO)
- This does not account for site heterogeneity, degree of pile monitoring and the combination of different resistance prediction methods in a consistent way
- Prediction methods may be biased (systematic error) and uncertain (random error)
- Bias correction and quantification of uncertainty (variance of CV) are required

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Summary

- Ultimate design goal is to meet a prescribed maximum probability of failure (POF), commonly expressed by reliability index **β**
- POF is generally different for each structural unit (e.g., pile vs. pile group) and depends on degree of redundancy
- In the present work, POF and design load $\mathbf{Q_{design}}$ are considered for a whole pile group (NOT a single pile)

Summary

Civil & Coastal Engineering

- Exploring spatial correlation was found to lead to complex results based on conceptual assumptions, which are not generally valid
- Exploring correlation between blow count data **N** and monitored resistances $\mathbf{R_m}$ result in simple design equations, which remain valid under flexible design / construction scenarios
- High observed correlation between **N** and $\mathbf{R_m}$ leads to good prediction (small uncertainty) and neglecting spatial correlation becomes insignificant

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Summary

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- LRFD **Φ** depends on
  - Number $\mathbf{n_p}$ of piles in group
  - Degree of monitoring $\mathbf{n_m/n_p}$
  - Prediction uncertainties $\mathbf{CV_{\varepsilon m}}$ and $\mathbf{CV_{\varepsilon h}}$
- **Φ** increases as
  - $\mathbf{n_p}$ and $\mathbf{n_m}$ increase
  - $\mathbf{CV_{\varepsilon m}}$ and $\mathbf{CV_{\varepsilon h}}$ decrease

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Summary

- For full monitoring $\mathbf{n_p = n_m}$ and $\mathbf{\Phi}$ purely depends on the monitoring method uncertainty $\mathbf{CV_{\varepsilon m}}$
- Different (possibly non-linear) prediction formulas may be used between **N** and $\mathbf{R_m}$
- Previously driven test piles may be explicitly accounted for in the design process of a respective pile group
- Illustrated by a practical example using data from four piles at Caminida and Dixie