# *Workbook*

# LRFD Workshop on Bridge Foundations Consisting of Driven Piles in Iowa

**October 30, 2012**

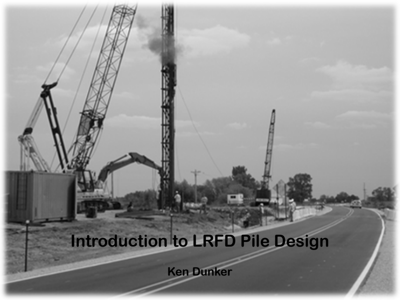
Iowa State University Institute for Transportation | Baker | Bridge Engineering Center | IHRB Iowa Highway Research Board | Iowa Department of Transportation Research and Technology Bureau

# LRFD Workshop on Bridge Foundations Consisting of Driven Piles in Iowa

**East/West Materials Conference Room, Iowa DOT, Ames**
**Date: October 30, 2012; repeated on Oct. 31, 2012**

## Agenda

| | |
|---|---|
| **Registration** | |
| 8:30 am to 9:00 am | Registration |
| **Morning Session** | |
| 9:00 am to 9:20 am | Opening Remarks:<br>**Sri Sritharan (Iowa State University) and Ken Dunker (Iowa DOT)** |
| 9:20 am to 9:50 am | PILOT Database and Field Testing of Piles:<br>**Sri Sritharan (Iowa State University)** |
| 9:50 am to 10:20 am | LRFD Calibration Process:<br>**Kam Ng (Iowa State University)** |
| 10:20 am to 10:30 am | Break |
| 10:30 am to 11:00 am | Construction Control (Modified Iowa ENR and WEAP Analysis)<br>**Kam Ng (Iowa State University)** |
| 11:00 am to 11:30 am | Development of Design Guide:<br>**Don Green (Baker)** |
| 11:30 am to 12:30 pm | Track 2 and Example: Design and Construction Stages<br>**Kam Ng (Iowa State University)** |
| **Afternoon Session** | |
| 12:30 pm to 1:30 pm | Lunch Break |
| 1:30 pm to 2:30 pm | Track 1 and Example: Design Stage<br>**Don Green (Baker)** |
| 2:30 pm to 2:50 pm | Track 1 and Example: Construction Stage<br>**Don Green (Baker)** |
| 2:50 pm to 3:00 pm | Comparison between Track 1 and Track 2<br>**Kam Ng (Iowa State University)** |
| 3:00 pm to 3:15 pm | Break |
| 3:15 pm to 3:30 pm | Track 3 and Examples<br>**Kam Ng (Iowa State University)** |
| 3:30 pm to 3:45 pm | Other Pile Types:<br>**Ken Dunker (Iowa DOT)** |
| 3:45 pm to 4:15 pm | Design using spreadsheet<br>**Michael Nop (Iowa DOT)** |
| 4:15 pm to 4:30 pm | Feedback and Discussion<br>**Sri Sritharan (Iowa State University)** |




## Overview - 1

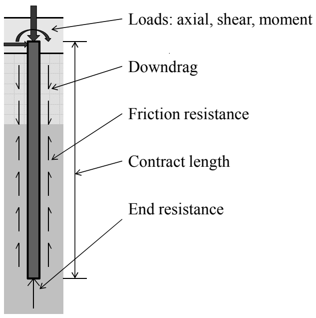
- Pile design has three aspects:
  - Structural
  - Geotechnical
  - Driving target
- The Bridge Design Manual has structural simplifications for typical design cases.
  - Integral abutments
  - Pile bents
  - Lateral loads
  - Scour below pier foundations

## Overview - 2

- ISU research focused on geotechnical and driving target aspects of design.
  - Database of Iowa DOT pile tests
  - Field testing
  - Statistical calibration
  - Design guidelines
    - Contract length related to construction control and soil classification
    - Driving target related to construction control and soil classification

## Overview - 3

### Design

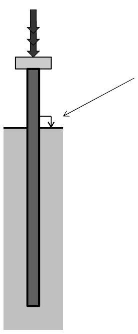



**ALSO**

- Scour
- Minimum embedment
- Uplift
- Maximum height above ground

## Overview - 4

### Construction



Driving target: minimum blows/foot at End of Drive (EOD) determined by wave equation (WEAP), Iowa DOT formula, or alternate construction control.

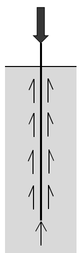
Drive entire contract length unless pile reaches refusal (160 blows/foot).

If minimum blows/foot are not achieved, retap the pile at least one day later or add a pile extension.

## Overview - 5

- Anomalies in new policy are being resolved.
- Special provision may be required (to explain larger driving targets).
- Standards may require modification until they are revised.
- Office/consultant policies are changing—check with the office for specific projects.

## Geotechnical Design History - 1



**Allowable Stress Design (ASD) [to 2007]**

- Q = service load
- Blue Book friction and end bearing values (FS $\geq$ 2)
- Q = driving target, ___ blows/foot (WEAP with 2.2 factor or Iowa ENR formula with 4.0 safety factor)

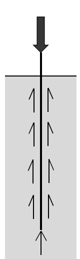
## Geotechnical Design History - 2

Basic LRFD relationship:

$$\Sigma \eta \gamma Q \leq \varphi R_n$$

(In general for the presentations today Q will indicate geotechnical or target driving values and P will indicate structural values.)

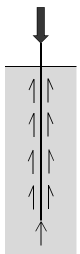
## Geotechnical Design History - 3



**Interim Load and Resistance Factor Design (LRFD) [2007-2012]**

- $Q_u$ = AASHTO factored load
- Blue Book friction and end bearing resistances (FS = 1)
- $\varphi$ = 0.725 (assumed $\gamma_{average}$ = 1.45 for calibration)
- Q = driving target, ___ blows/foot (WEAP with 2.2 factor or Iowa ENR formula with 4.0 safety factor: same as ASD)

## Geotechnical Design History - 4



**Future Load and Resistance Factor Design (LRFD) [2013 and beyond]**

- $Q_u$ = AASHTO factored load
- Blue Book friction and end bearing resistances (FS = 1)
- φ calibrated for site soil & const. ctrl.
- $R_{ndr-T}$ = driving target, ___ blows/foot (WEAP with 1.0 factor or Iowa ENR formula without safety factor)
- $\varphi_{TAR}$ calibrated for site soil & const. ctrl.

## Implementation - 1

- In-house design for new bridges to be let after 1 October 2012
- Consultant and county training on 30 & 31 October 2012
- Future dates…next slide…

## Implementation - 2

- Updated Bridge Design Manual and Revised Vol. IV Examples in January 2013
- Release of updated H-, J-, and RS- standards in April 2013
- Consultant design for new bridges to be let in July 2013
- Proposed sunset of Iowa DOT ENR Formulas in 2017

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# PILOT Database and Field Testing of Piles

Sri Sritharan and Kam Ng

## Acknowledgements

1) Iowa Highway Research Board
2) Research and Technology Bureau
3) Technical Advisory Committee: Ken Dunker; Gary Novey; Ahmad Abu-Hawash; Michael Nop; Dean Bierwagen; Bob Stanley; Steve Megivern; Kyle Frame; Curtis Monk; John Rasmussen; and Lyle Brehm
4) Several Contractors
5) GSI and Team Services
6) Kyle Frame, Ken Dunker, Michael Nop and Ahmad Abu-Hawash from Iowa DOT

## Learning Outcomes

1) Scope and research objectives
2) National and local survey
3) PILOT database
4) Full-scale field testing of piles
5) Pile setup quantification

## Research Scope

1) Perform literature review
2) Conduct national and local surveys
3) Develop a user-friendly electronic PIle LOad Test (PILOT) database
4) Conduct 10 full-scale field tests
5) Data collection and analysis
6) Calibrate LRFD resistance factors
7) Recommend LRFD pile design and construction procedures

## Research Objective-1

1) Examine the current pile design and construction procedures in Iowa
2) Recommend changes and improvements that are consistent with available pile load test data and LRFD bridge design practice
3) Install and load test piles in the field
4) Collect complete data
5) Improve design of piles in accordance with LRFD

## Research Objective-2

6) Develop regionally-calibrated LRFD resistance factors for bridge pile foundations in Iowa
7) Disseminate research outcomes

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## Research Reports

- Volume I – PILOT Database
- Volume II – Field Testing of Piles
- Volume III – LRFD Calibration
- Volume IV – Design Guide and Examples

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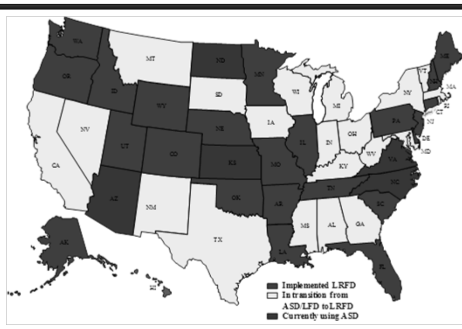
## National Survey

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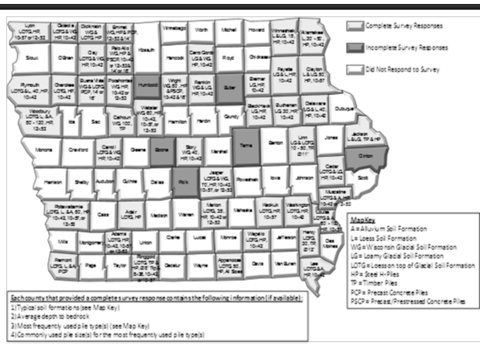
## Local Survey



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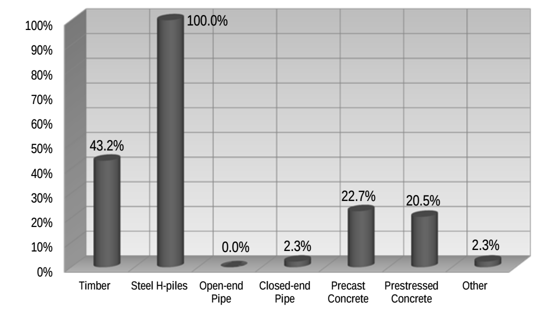
# Local Survey Outcome-1

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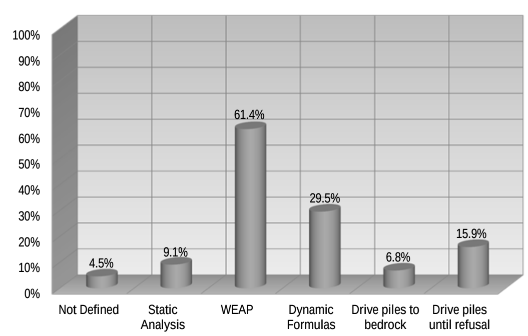
# Local Survey Outcome-2

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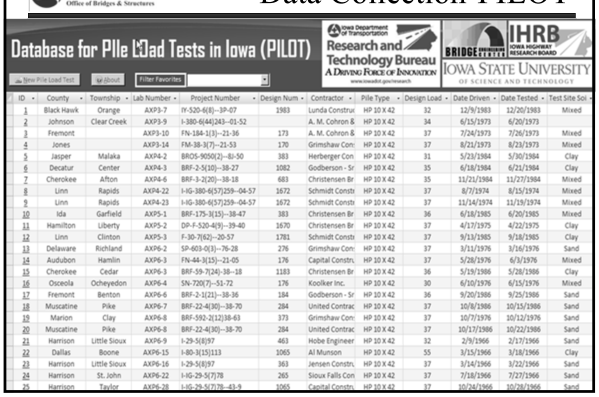
# Data Collection-PILOT




| ID | County | Township | Lab Number | Project Number | Design Num | Contractor | Pile Type | Design Load | Date Driven | Date Tested | Test Site Soi |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Black Hawk | Orange | AXP3-7 | IY-520-6(8)--3P-07 | 1983 | Lunda Construc | HP 10 X 42 | 32 | 12/9/1983 | 12/20/1983 | Mixed |
| 2 | Johnson | Clear Creek | AXP3-9 | I-380-6(44)243--01-52 | | A. M. Cohron & | HP 10 X 42 | 34 | 6/15/1973 | 6/20/1973 | |
| 3 | Fremont | | AXP3-10 | FN-184-1(3)--21-36 | 173 | A. M. Cohron & | HP 10 X 42 | 37 | 7/24/1973 | 7/26/1973 | Mixed |
| 4 | Jones | | AXP3-14 | FM-38-3(7)--21-53 | 170 | Grimshaw Con: | HP 10 X 42 | 37 | 8/21/1973 | 8/23/1973 | Mixed |
| 5 | Jasper | Malaka | AXP4-2 | BROS-9050(2)--8J-50 | 383 | Herberger Con | HP 10 X 42 | 31 | 5/23/1984 | 5/30/1984 | Clay |
| 6 | Decatur | Center | AXP4-3 | BRF-2-5(10)--38-27 | 1082 | Godberson - Sr | HP 10 X 42 | 35 | 6/18/1984 | 6/21/1984 | Clay |
| 7 | Cherokee | Afton | AXP4-6 | BRF-3-2(20)--38-18 | 683 | Christensen Br | HP 10 X 42 | 35 | 11/21/1984 | 11/27/1984 | Mixed |
| 8 | Linn | Rapids | AXP4-22 | I-IG-380-6(57)259--04-57 | 1672 | Schmidt Constr | HP 10 X 42 | 37 | 8/7/1974 | 8/15/1974 | Mixed |
| 9 | Linn | Rapids | AXP4-23 | I-IG-380-6(57)259--04-57 | 1672 | Schmidt Constr | HP 10 X 42 | 37 | 11/14/1974 | 11/19/1974 | Mixed |
| 10 | Ida | Garfield | AXP5-1 | BRF-175-3(15)--38-47 | 383 | Christensen Br | HP 10 X 42 | 36 | 6/18/1985 | 6/20/1985 | Mixed |
| 11 | Hamilton | Liberty | AXP5-2 | DP-F-520-4(9)--39-40 | 1670 | Christensen Br | HP 10 X 42 | 37 | 4/17/1975 | 4/22/1975 | Clay |
| 12 | Linn | Clinton | AXP5-3 | F-30-7(62)--20-57 | 1781 | Schmidt Constr | HP 10 X 42 | 37 | 9/13/1985 | 9/18/1985 | Clay |
| 13 | Delaware | Richland | AXP6-2 | SP-603-0(3)--76-28 | 276 | Grimshaw Con: | HP 10 X 42 | 37 | 3/11/1976 | 3/16/1976 | Sand |
| 14 | Audubon | Hamlin | AXP6-3 | FN-44-3(15)--21-05 | 176 | Capital Constru | HP 10 X 42 | 37 | 5/28/1976 | 6/3/1976 | Mixed |
| 15 | Cherokee | Cedar | AXP6-3 | BRF-59-7(24)-38--18 | 1183 | Christensen Br | HP 10 X 42 | 36 | 5/19/1986 | 5/28/1986 | Clay |
| 16 | Osceola | Ocheyedon | AXP6-4 | SN-720(7)--51-72 | 176 | Koolker Inc. | HP 10 X 42 | 30 | 6/10/1976 | 6/15/1976 | Mixed |
| 17 | Fremont | Benton | AXP6-6 | BRF-2-1(21)--38-36 | 184 | Godberson - Sr | HP 10 X 42 | 36 | 9/20/1986 | 9/25/1986 | Sand |
| 18 | Muscatine | Pike | AXP6-7 | BRF-22-4(30)--38-70 | 284 | United Contrac | HP 10 X 42 | 37 | 10/8/1986 | 10/15/1986 | Sand |
| 19 | Marion | Clay | AXP6-8 | BRF-592-2(12)38-63 | 373 | Grimshaw Con: | HP 10 X 42 | 37 | 10/7/1976 | 10/12/1976 | Sand |
| 20 | Muscatine | Pike | AXP6-8 | BRF-22-4(30)--38-70 | 284 | United Contrac | HP 10 X 42 | 37 | 10/17/1986 | 10/22/1986 | Sand |
| 21 | Harrison | Little Sioux | AXP6-9 | I-29-5(8)97 | 463 | Hobe Engineer | HP 10 X 42 | 32 | 2/9/1966 | 2/17/1966 | Sand |
| 22 | Dallas | Boone | AXP6-15 | I-80-3(15)113 | 1065 | Al Munson | HP 10 X 42 | 55 | 3/15/1966 | 3/18/1966 | Clay |
| 23 | Harrison | Little Sioux | AXP6-16 | I-29-5(8)97 | 363 | Jensen Constru | HP 10 X 42 | 37 | 3/14/1966 | 3/22/1966 | Sand |
| 24 | Harrison | St. John | AXP6-22 | I-IG-29-5(7)78 | 265 | Sioux Falls Con | HP 10 X 42 | 37 | 7/18/1966 | 7/27/1966 | Sand |
| 25 | Harrison | Taylor | AXP6-28 | I-IG-29-5(7)78--43-9 | 1065 | Capital Constru | HP 10 X 42 | 37 | 10/24/1966 | 10/28/1966 | Sand |

## Soil Profile-70% Rule

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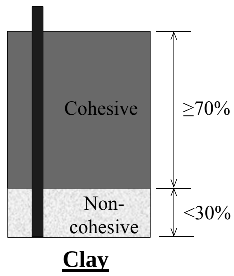
| Generalized Soil Category | Soil Classification Method: AASHTO | USDA Textural | BDM 6.2.7 Geotechnical Resistance Chart | |
|---|---|---|---|---|
| Cohesive | A-4, A-5, A-6 and A-7 | Clay<br>Silty clay<br>Silty clay loam<br>Silt<br>Clay loam<br>Silt loam<br>Loam<br>Sandy clay | Loess | Very soft silty clay |
| | | | | Soft silty clay |
| | | | | Stiff silty clay |
| | | | | Firm silty clay |
| | | | | Stiff silt |
| | | | | Stiff sandy clay |
| | | | Glacial Clay | Firm silty glacial clay |
| | | | | Firm clay (gumbotil) |
| | | | | Firm glacial clay |
| | | | | Firm sandy glacial clay |
| | | | | Firm-very firm glacial clay |
| | | | | Very firm glacial clay |
| | | | | Very firm sandy glacial clay |
| | | | | Cohesive or glacial material |
| Non-Cohesive | A-1, A-2 and A-3 | Sandy clay loam<br>Sandy loam<br>Loamy sand<br>Sand | Alluvium Or Loess | Stiff sandy silt |
| | | | | Silty sand |
| | | | | Clayey sand |
| | | | | Fine sand |
| | | | | Coarse sand |
| | | | | Gravely sand |
| | | | | Granular material (N>40) |




## Soil Profile-70% Rule

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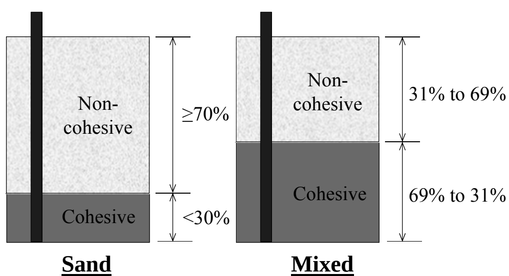


## PILOT Historical Data Summary

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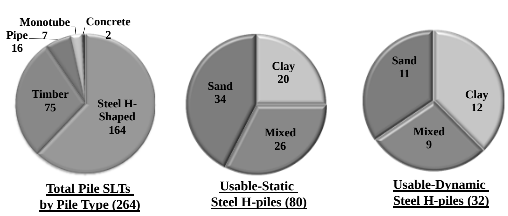

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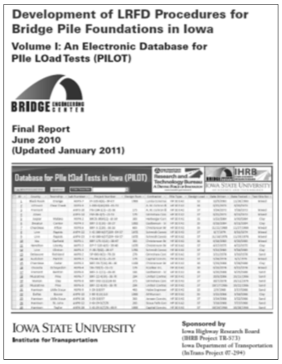
## LRFD Report Volume I


Development of LRFD Procedures for Bridge Pile Foundations in Iowa

Volume I: An Electronic Database for PIle LOad Tests (PILOT)

BRIDGE ENGINEERING CENTER

Final Report
June 2010
(Updated January 2011)

Database for PIle LOad Tests in Iowa (PILOT)

IOWA STATE UNIVERSITY
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Sponsored by
Iowa Highway Research Board
(IHRB Project TR-573)
Iowa Department of Transportation
(InTrans Project 07-294)

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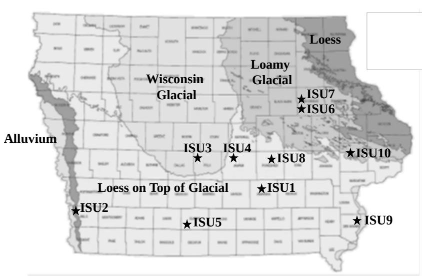
## Ten Full-Scale Field Tests




| Test Site | Soil Profile |
|---|---|
| ISU1, ISU7 & ISU8 | Mixed |
| ISU2, ISU3, ISU4, ISU5 & ISU6 | Clay |
| ISU9 & ISU10 | Sand |

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## Subsurface Investigations


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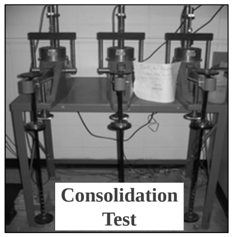
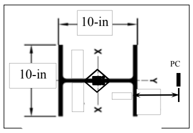
## Subsurface Investigations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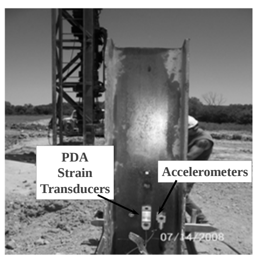
## Pile Testing


**Steel H-Pile Instrumentation**

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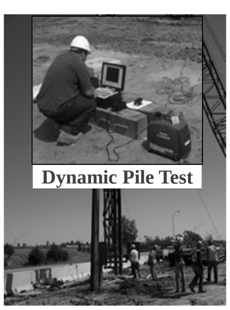
## Pile Testing




**Driving & Restrikes**

**Static Load Test**

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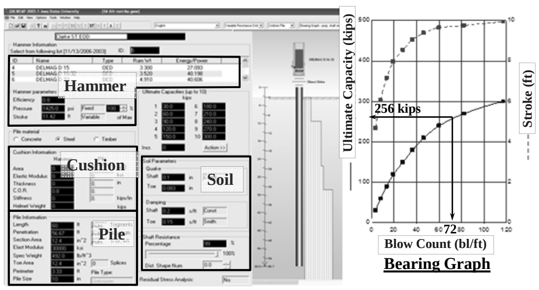
## Estimated Pile Capacity-WEAP

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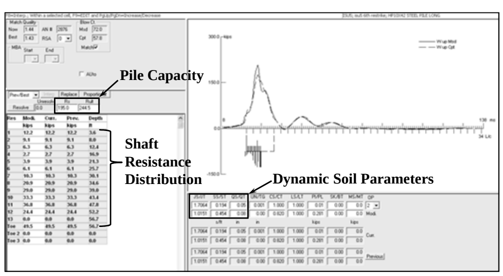
## Estimated Capacity-PDA/CAPWAP

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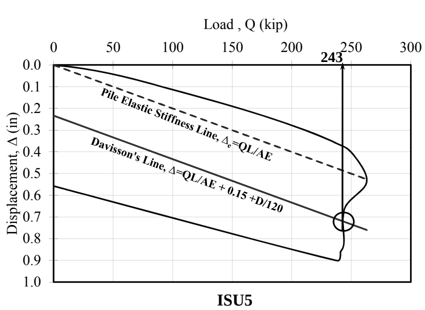
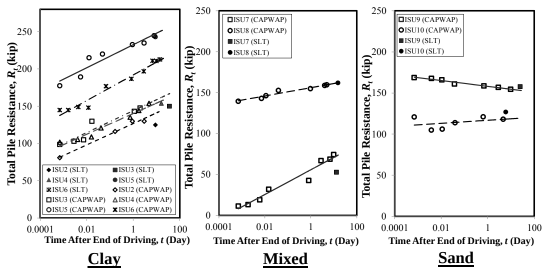
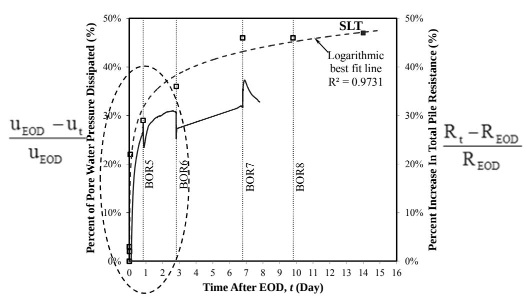
## Measured Pile Capacity-SLT



## Pile Capacity vs Time



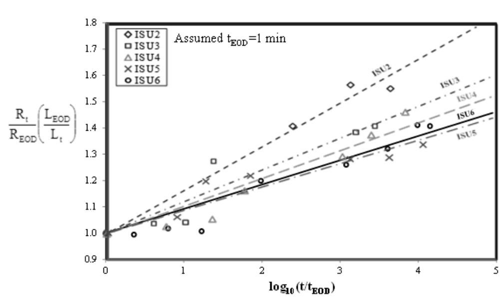

## Pile Setup in Clay (ISU6)




**What is Pile Setup?**

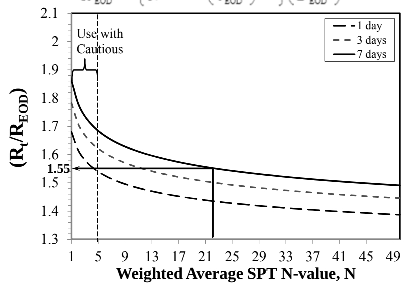
- Increase in pile capacity as a function of time due to healing of remolded soil and consolidation of clay soil

## Pile Setup Rate



## Pile Setup Quantification

$$\frac{R_t}{R_{EOD}} = \left\{\frac{a}{N^b}\log_{10}\left(\frac{t}{t_{EOD}}\right)+1\right\}\left(\frac{L_t}{L_{EOD}}\right)$$




## Pile Setup-Anticipated Errors

| Confidence Level (%) | Anticipated Errors for $R_t$ (%) | |
|---|---|---|
| | Construction Control Method for $R_{EOD}$ | |
| | CAPWAP | WEAP-Iowa Blue Book |
| **80** | -4% to 2.8% | -12.2% to -1.8% |
| **90 (Pile Group)** | -4.9% to 3.8% | -13.9% to -0.5% |
| **98 (Single Pile)** | -7% to 5.3% | -17.2% to 1.9% |

## LRFD Report Volume II


Development of LRFD Procedures for Bridge Pile Foundations in Iowa

Volume II: Field Testing of Steel Piles in Clay, Sand, and Mixed Soils and Data Analysis

Final Report
September 2011

IOWA STATE UNIVERSITY
Institute for Transportation

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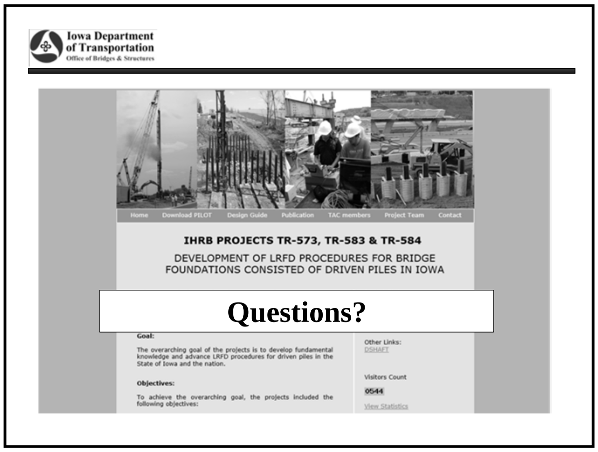
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Publication
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Project Team
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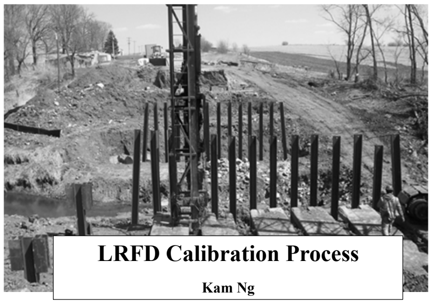
IHRB PROJECTS TR-573, TR-583 & TR-584
DEVELOPMENT OF LRFD PROCEDURES FOR BRIDGE FOUNDATIONS CONSISTED OF DRIVEN PILES IN IOWA
Questions?
Goal:
The overarching goal of the projects is to develop fundamental knowledge and advance LRFD procedures for driven piles in the State of Iowa and the nation.
Objectives:
To achieve the overarching goal, the projects included the following objectives:
Other Links:
DSHAFT
Visitors Count
0544
View Statistics



## LRFD Calibration Process

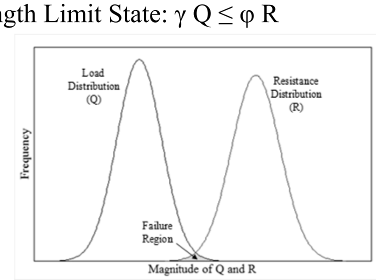
Kam Ng

## Learning Outcomes

1) LRFD calibration process
2) Integration of pile setup into LRFD
3) Construction control consideration
4) Resistance factors for design and construction

## LRFD Philosophy

Strength Limit State: $\gamma Q \leq \varphi R$



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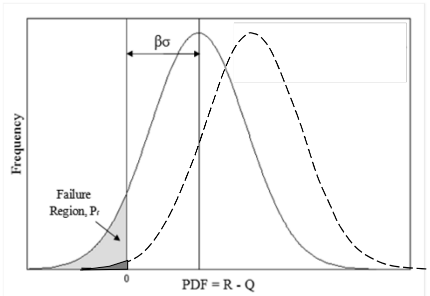
## Reliability Theory

NCHRP-507 Guidelines + Local Practices

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## FOSM

Barker et al. (1991):

$$\varphi_R = \frac{\lambda_R\left(\frac{\gamma_{DL} Q_{DL}}{Q_{LL}} + \gamma_{LL}\right)\sqrt{\frac{(1 + COV^2_{Q_{DL}} + COV^2_{Q_{LL}})}{(1 + COV_R^2)}}}{\left(\frac{\lambda_{Q_{DL}} Q_{DL}}{Q_{LL}} + \lambda_{Q_{LL}}\right)\exp\left\{\beta_T\sqrt{\ln[(1 + COV_R^2)(1 + COV^2_{Q_{DL}} + COV^2_{Q_{LL}})]}\right\}}$$

where,

$\varphi_R$ = Resistance factor

**Follow AASHTO:**

$\gamma_{DL}$ = Load factor for dead loads (DL) = 1.25 (Strength I)
$\gamma_{LL}$ = Load factor for live loads (LL) = 1.75 (Strength I)
$\lambda_{QDL}$ = Dead load bias = 1.05
$\lambda_{QLL}$ = Live load bias = 1.15
$COV_{QDL}$ = Coefficient of variation for dead load = 0.1
$COV_{QLL}$ = Coefficient of variation for live load = 0.2
$Q_{DL}/Q_{LL}$ = Dead load to live load ratio = 2.0
$\beta_T$ = Target reliability index (2.33 for redundant pile group and 3.0 for non-redundant pile group)

**Iowa:**

$\lambda_R$ = Resistance bias
$COV_R$ = Coefficient of variation for resistance

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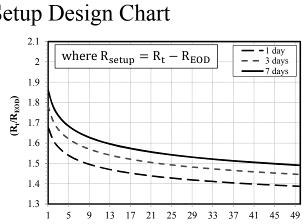
## Pile Setup in LRFD

Strength Limit State: $\gamma Q \leq \varphi_{EOD} R_{EOD} + \varphi_{setup} R_{setup}$

- $R_{EOD}$ : WEAP or PDA/CAPWAP
- $R_{setup}$ : Setup Design Chart



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## Resistance Factor Calculations

$\varphi_{EOD}$: FOSM

$\varphi_{setup}$: Modified FOSM (LRFD Report Volume II)

$$\varphi_{setup} = \frac{\lambda_{setup}\left[\frac{\gamma_D\left(\frac{Q_D}{Q_L}\right)+\gamma_L}{1+\left(\frac{Q_D}{Q_L}\right)} - \varphi_{EOD}\,\alpha\right]}{\frac{\left(\frac{\lambda_D\left(\frac{Q_D}{Q_L}\right)+\lambda_L}{1+\left(\frac{Q_D}{Q_L}\right)}\right)e^{\beta_T\sqrt{\ln\left[\left(1+COV^2_{R_{EOD}}+COV^2_{R_{setup}}\right)\left(1+COV^2_{Q_D}+COV^2_{Q_L}\right)\right]}}}{\sqrt{\frac{\left(1+COV^2_{Q_D}+COV^2_{Q_L}\right)}{\left(1+COV^2_{R_{EOD}}+COV^2_{R_{setup}}\right)}}} - \lambda_{EOD}\,\alpha}$$

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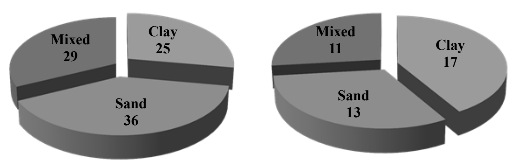
## Total Data for Calibration




**Static Analysis Methods (90)**

**Construction Control Methods (41)**

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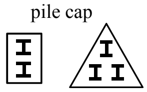
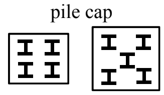
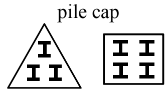
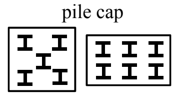
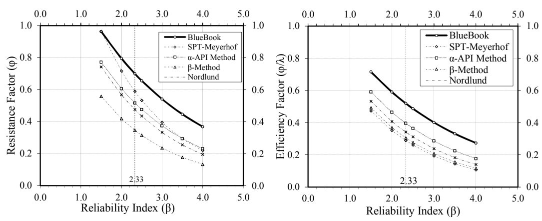
## Reliability Index (β)

| **Type** | **Nonredundant Piles ($\beta$=3.00)** | **Redundant Piles ($\beta$=2.33)** |
|---|---|---|
| Abutment | 3 or fewer piles per pile cap  | 4 or more piles per pile cap  |
| Others | 4 or fewer piles per pile cap  | 5 or more piles per pile cap  |

## Resistance and Efficiency Factors

Static Analysis Methods for Clay Soils




## Recommendations

1) Design Stage (For Contract Length):
   - ❑ Iowa Blue Book [BDM 6.2.7]
2) Construction Stage:
   - ❑ Iowa DOT Modified ENR Formula
   - ❑ WEAP [Iowa Blue Book for Unit Soil Resistance]
   - ❑ PDA/CAPWAP
   - ❑ Static Load Test

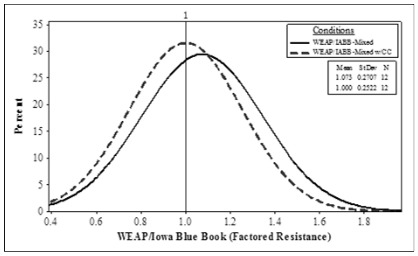
## Construction Control Analysis

To minimize discrepancy in pile capacity obtained from design and construction stages

| Construction Control Method | Soil Profile | Condition | Original φ for Iowa Blue Book | Revised φ for Iowa Blue Book | % Gain |
|---|---|---|---|---|---|
| WEAP | Clay | EOD+setup | 0.63 | 0.63 | 0% |
| | Mixed | EOD | 0.60 | 0.64 | 7% |
| | Sand | EOD | 0.55 | 0.55 | 0% |
| CAPWAP | Clay | EOD+setup | 0.63 | 0.68 | 8% |
| | | BOR | 0.63 | 0.80 | 27% |
| | Mixed | EOD | 0.60 | 0.80 | 33% |
| | | BOR | 0.60 | 0.71 | 18% |
| | Sand | EOD | 0.55 | 0.69 | 25% |
| | | BOR | 0.55 | 0.58 | 6% |
| Iowa DOT ENR Formula | Clay | EOD | 0.63 | 0.63 | 0% |
| | Mixed | EOD | 0.60 | 0.70 | 17% |
| | Sand | EOD | 0.55 | 0.55 | 0% |

## Construction Control Analysis

For Iowa Blue Book and Mixed Soils based on WEAP as Construction Control Method:




## Recommended φ for Design

Pile in Axial Compression

| Theo. Analysis | Construction Control (Field Verification) | | | | | Resistance Factor (φ) for β=2.33 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Driving Criteria Basis | | PDA/ CAP WAP | Restrike Test after EOD | Static Pile Load Test | Cohesive | | | Mixed | Non-cohesive |
| | Iowa DOT ENR | WEAP | | | | φ | $\varphi_{EOD}$ | $\varphi_{setup}$ | φ | φ |
| Iowa Blue Book | Yes | - | - | - | - | 0.60 | - | - | 0.60 | 0.50 |
| | No | Yes | - | - | - | 0.65 | - | - | 0.65 | 0.55 |
| | | | Yes | - | - | 0.70 | - | - | 0.70 | 0.60 |
| | | | | Yes | - | 0.80 | - | - | 0.70 | |
| | | | - | - | Yes | 0.80 | - | - | 0.80 | 0.80 |

## Recommended φ for Design

Pile in Axial Tension

| Theo. Analysis | Construction control (Field Verification) | | | | | Resistance Factor (φ) for β=2.33 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Driving Criteria Basis | | PDA/ CAP WAP | Restrike Test after EOD | Static Pile Load Test | Cohesive | | | Mixed | Non-cohesive |
| | Iowa DOT ENR | WEAP | | | | φ | $\varphi_{EOD}$ | $\varphi_{setup}$ | φ | φ |
| Iowa Blue Book | Yes | - | - | - | - | 0.45 | - | - | 0.45 | 0.40 |
| | No | Yes | - | - | - | 0.50 | - | - | 0.50 | 0.40 |
| | | | Yes | - | - | 0.55 | - | - | 0.55 | 0.45 |
| | | | | Yes | - | 0.60 | - | - | 0.55 | 0.45 |
| | | | - | - | Yes | 0.80 | - | - | 0.80 | 0.80 |

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## Recommended φ for Construction

| Theo. Analysis | Construction control (Field Verification) | | | | | Resistance Factor (φ) for β=2.33 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Driving Criteria Basis | | PDA/ CAP WAP | Restrike Test after EOD | Static Pile Load Test | Cohesive | | | Mixed | Non-cohesive |
| | Iowa DOT ENR | WEAP | | | | $\varphi$ | $\varphi_{EOD}$ | $\varphi_{setup}$ | $\varphi$ | $\varphi$ |
| Iowa Blue Book | Yes | - | - | - | - | 0.55 | - | - | 0.55 | 0.50 |
| | No | Yes | - | - | - | - | 0.65 | 0.20 | 0.65 | 0.55 |
| | | | - | Yes | - | 0.70 | - | - | | |
| | | | Yes | - | - | - | 0.75 | 0.40 | 0.70 | 0.70 |
| | | | | Yes | - | 0.80 | - | - | | |
| | | | - | - | Yes | 0.80 | - | - | 0.80 | 0.80 |

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## LRFD Report Volume III


Development of LRFD Procedures for Bridge Pile Foundations in Iowa

Volume III: Recommended Resistance Factors with Consideration of Construction Control and Setup

BRIDGE ENGINEERING CENTER

Final Report
February 2012

IOWA STATE UNIVERSITY
Institute for Transportation

Sponsored by
Iowa Highway Research Board
(IHRB Project TR-584)
Iowa Department of Transportation
(InTrans Project 08-313)

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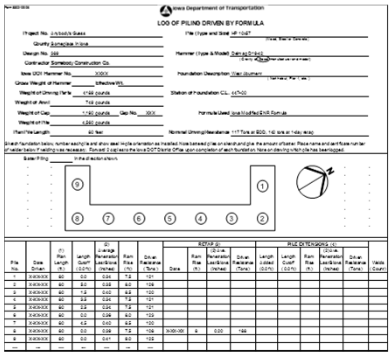
## Construction Control–Kam Ng



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## Learning Outcomes

A. Recognize the changes in the Modified Iowa ENR formula from Interim LRFD to LRFD.
B. Recognize the changes in the WEAP analysis from Interim LRFD to LRFD.
C. Learn the step by step LRFD procedure of the WEAP analysis

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## Modified Iowa ENR

| **Interim LRFD** | **LRFD** |
| --- | --- |
| For gravity hammers with wood, steel H, or steel pipe piles | |
| • Bearing value (P)<br>• $P = \frac{3WH}{S+0.35} \times \frac{W}{W+M}$ (English)<br>• $P = \frac{2.5WH}{S+8.9} \times \frac{W}{W+M}$ (Metric) | • Nominal bearing resistance ($R_n$)<br>• $R_n = \frac{12WH}{S+0.35} \times \frac{W}{W+M}$ (English)<br>• $R_n = \frac{10WH}{S+8.9} \times \frac{W}{W+M}$ (Metric) |
| W = weight of the gravity hammer in tons (kg)<br>H = height of free fall in feet (meters)<br>M = weight of the pile plus weight of cap in tons (kg)<br>S = average penetration in inches (mm) of the pile per blow for the last 5 blows | |

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## Modified Iowa ENR

| Interim LRFD | LRFD |
|---|---|
| For gravity hammers with concrete piles | |
| • Bearing value (P)<br>• $P = \frac{4.5WH}{S+0.2} \times \frac{W}{W+M}$ (English)<br>• $P = \frac{3.7WH}{S+5.1} \times \frac{W}{W+M}$ (Metric) | • Nominal bearing resistance ($R_n$)<br>• $R_n = \frac{18WH}{S+0.2} \times \frac{W}{W+M}$ (English)<br>• $R_n = \frac{14.8WH}{S+5.1} \times \frac{W}{W+M}$ (Metric) |

W = weight of the gravity hammer in tons (kg)
H = height of free fall in feet (meters)
M = weight of the pile plus weight of cap in tons (kg)
S = average penetration in inches (mm) of the pile per blow for the last 5 blows

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## Modified Iowa ENR

| Interim LRFD | LRFD |
|---|---|
| For diesel hammers with wood, steel H, or steel pipe piles and steam hammers for all piles | |
| • Bearing value (P)<br>• $P = \frac{3E}{S+0.1} \times \frac{W}{W+M}$ (English)<br>• $P = \frac{0.25E}{S+2.5} \times \frac{W}{W+M}$ (Metric) | • Nominal bearing resistance ($R_n$)<br>• $R_n = \frac{12E}{S+0.1} \times \frac{W}{W+M}$ (English)<br>• $R_n = \frac{E}{S+2.5} \times \frac{W}{W+M}$ (Metric) |

W = weight of the ram of a diesel hammer in tons (kg)
H = height of free fall of ram in feet (meters)
M = weight of the pile plus weight of cap plus weight of anvil in tons (kg)
E = energy per blow in foot-tons (joules)
S = average penetration in inches (mm) of pile per blow for the last 10 blows

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## Modified Iowa ENR

| Interim LRFD | LRFD |
|---|---|
| For diesel hammers with concrete piles | |
| • Bearing value (P)<br>• $P = \frac{7E}{S+0.1} \times \frac{W}{W+M}$ (English)<br>• $P = \frac{0.58E}{S+2.5} \times \frac{W}{W+M}$ (Metric) | • Nominal bearing resistance ($R_n$)<br>• $R_n = \frac{28E}{S+0.1} \times \frac{W}{W+M}$ (English)<br>• $R_n = \frac{2.32E}{S+2.5} \times \frac{W}{W+M}$ (Metric) |

W = weight of the ram of a diesel hammer in tons (kg)
H = height of free fall of ram in feet (meters)
M = weight of the pile plus weight of cap plus weight of anvil in tons (kg)
E = energy per blow in foot-tons (joules)
S = average penetration in inches (mm) of pile per blow for the last 10 blows

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## WEAP

| Interim LRFD | LRFD |
|---|---|
| • Bearing capacity<br>• Bearing graph with safety factor of 2.2<br>• Pile is accepted if the measured driving resistance ≥ the plan design bearing<br>• No driveability analysis<br>• Use SPT N-value<br>• Variable soil parameters | • Nominal bearing resistance ($R_n$)<br>• Bearing graph in terms of nominal resistance<br>• Pile is accepted if the nominal measured driving resistance ≥ the target nominal driving resistance<br>• No driveability analysis except SRL-3<br>• Use unit resistance from modified Iowa Design Charts<br>• Simple soil parameters |

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## Modified Iowa Design Chart for Friction

**LRFD Report Volume II (Ng et al. 2010)**

**Table 4.17. Revised Iowa pile design chart used in WEAP for friction bearing Grade 50 steel H-piles**

| SOIL DESCRIPTION | LRFD DRIVEN PILE FOUNDATION GEOTECHNICAL RESISTANCE CHART, ENGLISH UNITS | | | | |
|---|---|---|---|---|---|
| | SPT N-VALUE | | ESTIMATED NOMINAL RESISTANCE VALUES FOR FRICTION PILE IN KIPS PER SQUARE FOOT (KSF) | | |
| **Alluvium or Loess** | **MEAN** | **RANGE** | **HP 10** | **HP 12** | **HP 14** |
| Very soft silty clay | 1 | 0 - 1 | 0.12 | 0.20 | 0.17 |
| Soft silty clay | 3 | 2 - 4 | 0.24 | 0.30 | 0.26 |
| Stiff silty clay | 6 | 4 - 8 | 0.36 | 0.40 | 0.43 |
| Firm silty clay | 11 | 7 - 15 | 0.60 | 0.60 | 0.60 |
| Stiff silt | 6 | 3 - 7 | 0.36 | 0.40 | 0.34 |
| Stiff sandy silt | 6 | 4 - 8 | 0.36 | 0.40 | 0.34 |
| Stiff sandy clay | 6 | 4 - 8 | 0.36 | 0.40 | 0.43 |
| Silty sand | 8 | 3 - 13 | 0.25 | 0.21 | 0.23 |
| Clayey sand | 13 | 6 - 20 | 0.33 | 0.34 | 0.40 |
| Fine sand | 15 | 8 - 22 | 0.41 | 0.41 | 0.40 |
| Coarse sand | 20 | 12 - 28 | 0.58 | 0.55 | 0.52 |
| Gravely sand | 21 | 11 - 31 | 0.58 | 0.55 | 0.52 |
| Granular material | > 40 | - | 0.83 | 0.82 | 0.80 |
| **Glacial Clay** | **MEAN** | **RANGE** | **HP 10** | **HP 12** | **HP 14** |
| Firm silty glacial clay | 11 | 7 - 15 | 0.72 | 0.70 | 0.69 |
| Firm clay (gumbotil) | 12 | 9 - 15 | 0.72 | 0.70 | 0.69 |
| Firm glacial clay(1) | 11 | 7 - 15 | 0.84<br>[0.96] | 0.80<br>[1.00] | 0.77<br>[0.94] |
| Firm sandy glacial clay(1) | 13 | 9 - 15 | 0.84<br>[0.96] | 0.80<br>[1.00] | 0.77<br>[0.94] |
| Firm-very firm glacial clay(1) | 14 | 11 - 17 | 0.84<br>[1.20] | 0.80<br>[1.20] | 0.77<br>[1.20] |
| Very firm glacial clay(1) | 24 | 17 - 30 | 0.84<br>[1.20] | 0.80<br>[1.20] | 0.77<br>[1.20] |
| Very firm sandy glacial clay(1) | 25 | 15 - 30 | 0.84<br>[1.20] | 0.80<br>[1.20] | 0.77<br>[1.20] |
| Cohesive or glacial material(1) | > 35 | - | 0.84<br>[1.20] | 0.80<br>[1.20] | 0.77<br>[1.20] |

(1) - For double entries the upper value is for an embedded pile within 30 feet of the natural ground elevation, and the lower value [ ] is for pile depths more than 30 feet below the natural ground elevation.

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## Modified Iowa Design Chart for End Bearing

**LRFD Report Volume II (Ng et al. 2010)**

**Table 4.18. Revised Iowa pile design chart used in WEAP for end bearing Grade 50 steel H-piles**

| SOIL DESCRIPTION | LRFD DRIVEN PILE FOUNDATION GEOTECHNICAL RESISTANCE CHART, ENGLISH UNITS | | | | |
|---|---|---|---|---|---|
| | SPT N-VALUE | | ESTIMATED NOMINAL RESISTANCE VALUES FOR END BEARING PILE IN KIPS | | |
| | MEAN | RANGE | HP 10 | HP 12 | HP 14 |
| Granular material | < 15 | - | Do not consider end bearing | | |
| Fine or medium sand | 15 | - | | | |
| Coarse sand | 20 | - | | | |
| Gravely sand | 21 | - | | | |
| Granular material | 25 | - | | | |
| | - | 25 - 50 | 24.8-49.6 | 31-62 | 42.8-85.6 |
| | - | 50 - 100 | 49.6-99.2 | 62-124 | 85.6-171.2 |
| | - | 100 - 300 | 99.2-198.4 | 124-248 | 171.2-385.2 |
| | - | > 300 | 223.2 | 279 | 385.2 |
| Bedrock | - | 100 - 200 | 148.8 | 186 | 256.8 |
| | - | > 200 | 223.2 | 279 | 385.2 |
| Cohesive material | 12 | 10 - 50 | Do not consider end bearing | | |
| | 20 | - | 12.4 | 15.5 | 21.4 |
| | 25 | - | 24.8 | 31 | 42.8 |
| | 50 | - | 49.6 | 62 | 85.6 |
| | 100 | - | 86.8 | 108.5 | 149.8 |

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## Soil Parameters

**LRFD Report Volume II (Ng et al. 2010)**

LRFD →

**Table 4.19. WEAP recommended soil quake values (Pile Dynamics, Inc., 2005)**

| Soil Type (Pile Type) | Shaft Quake (in) | Toe Quake (in) |
|---|---|---|
| All soil types, soft rock (Non-displacement piles) | 0.10 | 0.10 |
| Very dense or hard soils (Displacement piles of diameter or width D) | 0.10 | D/120 |
| Loose or soft soils (Displacement piles of diameter or width D) | 0.10 | D/60 |
| Hard rock (All pile types) | 0.10 | 0.04 |

**Table 4.20. WEAP recommended Smith's damping factors used in ST, SA, Driven and Iowa Blue Book (Pile Dynamics, Inc., 2005)**

| Soil Types | Smith's Shaft Damping Factor (s/ft) | Smith's Toe Damping Factor (s/ft) |
|---|---|---|
| Non-cohesive soils | 0.05 | 0.15 |
| Cohesive soils | 0.20 | 0.15 |

Interim LRFD →

**Table 4.21. Damping factors used in the Iowa DOT method**

| Soil Types | Shaft Damping Factor (s/ft) | Toe Damping Factor (s/ft) |
|---|---|---|
| Rock | 0.05 | 0.05 |
| Boulder & Gravel or Gravel Sand | 0.10 | 0.05 |
| Medium Sand or Fine Sand | 0.10 | 0.10 |
| Packed Sand | 0.10 | 0.05 |
| Silt | 0.15 | 0.12 |
| Silty Clay, Silty Clay, Sandy Clay or Firm Sandy Glacial Clay | 0.12 | 0.12 |
| Firm Clay | 0.15 | 0.12 |
| Firm Glacial Clay or Firm Silty Glacial Clay | 0.15 | 0.15 |

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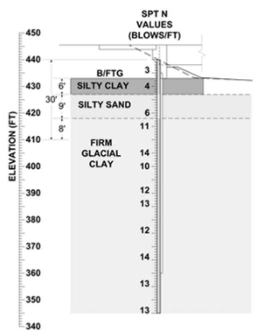
## WEAP-Video

**Project Information**

- HP 10 × 57 Piles
- 75 ft Contract Length
- 73 ft Embedded
- Delmag D19-42
- Assumed 7 ft Hammer Stroke
- Assumed a nominal resistance of 200 kips for Inspector's Chart Analysis
- LRFD Procedure

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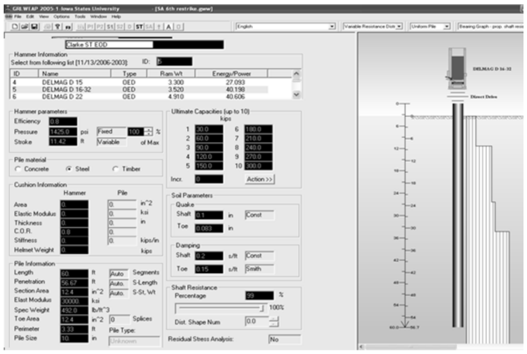
## Questions? – Kam Ng



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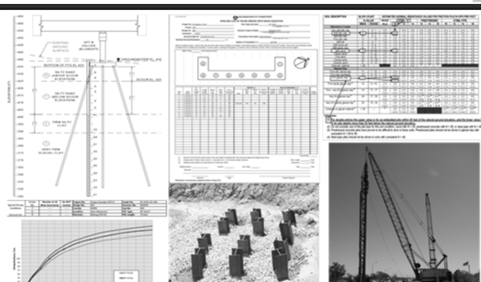
Baker



## Development of Design Guide

Don Green and Kam Ng

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## Learning Outcomes

1) New LRFD procedure for bridge foundations consisting of driven piles in Iowa
2) Three track examples cover various pile types, soil profiles and special design considerations
3) Geotechnical design of pile foundations using Iowa Blue Book
4) Establish pile driving criteria using WEAP, Iowa ENR formula and PDA/CAPWAP

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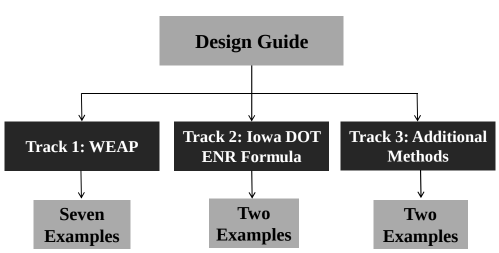
## Three Track Approach

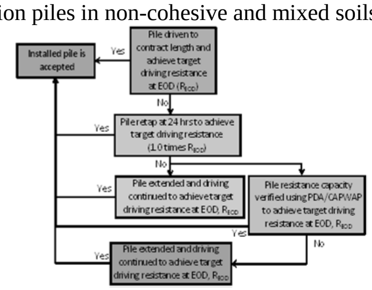


## Design Process

| Design Step | |
|---|---|
| **Step 1** | Develop bridge situation plan (or TS&L, Type, Size, and Location) (1) |
| **Step 2** | Develop soils package, including soil borings and foundation recommendations (1) |
| **Step 3** | Determine pile arrangement, pile loads, and other design requirements (1) |
| **Step 4** | Estimate the nominal geotechnical resistance per foot of pile embedment (2) |
| **Step 5** | Select resistance factor(s) to estimate pile length based on the soil profile and construction control (2) |
| **Step 6** | Calculate the required nominal pile resistance, $R_n$ (2) |
| **Step 7** | Estimate contract pile length, L (2) |
| **Step 8** | Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$ (2) |
| **Step 9** | Prepare CADD note for bridge plans |
| **Step 10** | Check the design (3) |
| **Construction Step** | |
| **Step 11** | Prepare bearing graph |
| **Step 12** | Observe construction, record driven resistance, and resolve any construction issues |

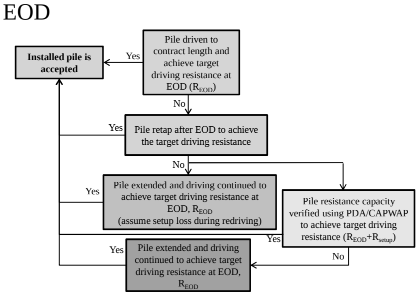
## Construction Control-1

- End bearing piles
- Friction piles in non-cohesive and mixed soils




## Construction Control-2

- Friction piles in cohesive soils and retap performed after EOD



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# Design Examples

| Track Number | Pile Type | Example Number | Substructure Type | Soil Type | Special Consider-ations | Construction Controls | |
|---|---|---|---|---|---|---|---|
| | | | | | | Driving Criteria Basis | Planned Retap 3 Days after EOD |
| 1 | H-Pile | 1 | Integral Abutment | Cohesive | --- | Wave Equation | No |
| | | 2 | Pier | Mixed | Scour | | |
| | | 3 | Integral Abutment | Cohesive | Downdrag | | |
| | | 4 | Pier | Non-Cohesive | Uplift | | |
| | | 5 | Integral Abutment | Cohesive | End Bearing in Bedrock | | |
| | Pipe Pile | 6 | Pile Bent | Non-Cohesive | Scour | | |
| | Prestressed Concrete Pile | 7 | Pile Bent | Non-Cohesive | Scour | | |
| 2 | H-Pile | 1 | Integral Abutment | Cohesive | --- | Modified Iowa DOT Formula | |
| | Timber | 2 | Integral Abutment | Non-Cohesive | --- | | |
| 3 | H-Pile | 1 | Integral Abutment | Cohesive | --- | PDA/ CAPWAP and Wave Equation | |
| | | 2 | Integral Abutment | Cohesive | --- | Wave Equation | Yes |

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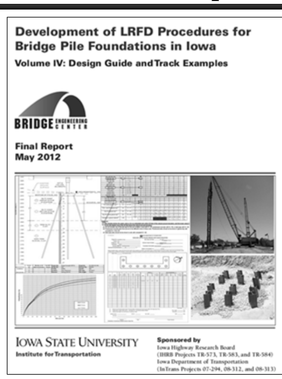
# LRFD Report Volume IV


Development of LRFD Procedures for Bridge Pile Foundations in Iowa
Volume IV: Design Guide and Track Examples
BRIDGE ENGINEERING CENTER
Final Report
May 2012
IOWA STATE UNIVERSITY
Institute for Transportation
Sponsored by
Iowa Highway Research Board
(IHRB Projects TR-573, TR-583, and TR-584)
Iowa Department of Transportation
(InTrans Projects 07-294, 09-312, and 09-313)

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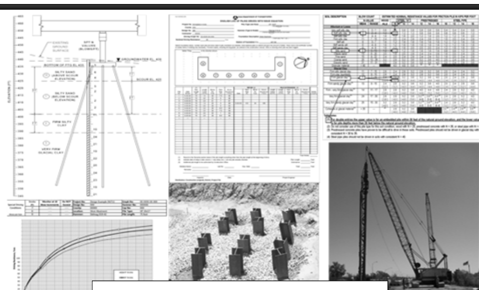


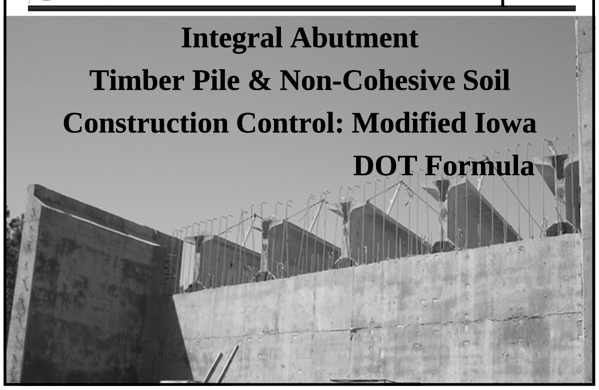
**Questions?**

## Track 2 Example – Kam Ng

## Learning Outcomes

A. Follow the geotechnical design and construction steps to implement Iowa LRFD Pile Design with Modified Iowa DOT Formula construction control.
B. Select a resistance factor to estimate the contract pile length, L.
C. Estimate the target nominal pile driving resistance, $R_{ndr\text{-}T}$.

## Track 2 Example 2



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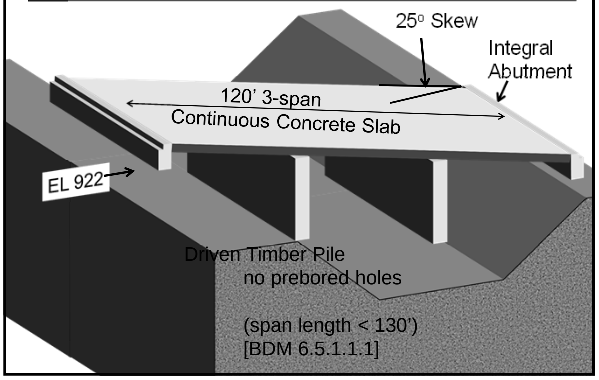
## Step 1. Situation Plan

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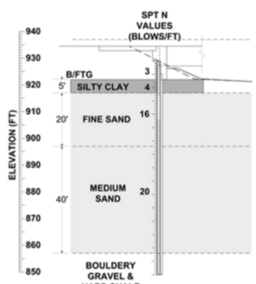
## Step 2. Soils Package

Develop soils package, including soil borings and foundation recommendations

Soils Design Engineer

- 5' soft to stiff silty clay
- 20' fine sand
- 40' medium sand
- bouldery gravel and hard shale

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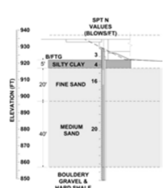
## Step 2. Soils Package



Soils Design Engineer
Develop foundation recommendations

- Timber pile: tip out in medium sand
- Normal driving resistance
- No significant downdrag
- No special site considerations for stability, settlement, or lateral movement

## Step 3. Pile Arrangement

Final Design Engineer

- 12” timber pile
- 54 kips/pile (STR I limit state controls)

  $\varphi Pn = (0.9)(64) = 57.6$ kips/pile > 54

  [BDM 6.2.6.3] OK
- No uplift, downdrag or scour
- Construction Control: Modified Iowa DOT formula
- No need for lateral load or special analysis


## Step 4. Nominal Pile Resistance

| Soil Stratum | Soil Description | Stratum Thickness (ft) | Average SPT N Value (blows/ft) | Estimated Nominal Resistance for Friction Pile (kips/ft) | Cumulative Nominal Friction Resistance at Bottom of Layer (kips) | Estimated Nominal Resistance for End Bearing (kips) |
|---|---|---|---|---|---|---|
| 1 | Soft to Stiff Silty Clay | 5 | 4 | 1.4 | 7.0 | --- |
| 2 | Fine Sand | 20 | 16 | 2.4 | 55.0 | --- |
| 2 | Medium Sand | 40 | 20 | 2.8 | 167.0 | 32 |

## Step 5. Resistance Factor

| Resistance Factor [b] | | | | |
|---|---|---|---|---|
| Cohesive | | | Mixed | Non-Cohesive |
| $\phi$ | $\phi_{EOD}$ | $\phi_{setup}$ | $\phi$ | $\phi$ |
| 0.60 | - | - | 0.60 | **0.50** |
| 0.65 | - | - | 0.65 | 0.55 |

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## Step 5. Resistance Factor

Select resistance factor to estimate pile length

By inspection, piling will be embedded primarily in non-cohesive soil

$\therefore \quad \varphi = 0.50$

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## Step 6. Required Nominal Resistance

The required nominal pile resistance is:

$$R_n = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi} = \frac{54+0}{0.50} = 108 \text{ kips/pile}$$

where: $\sum \eta\gamma Q = \gamma Q = 54\text{kips}$ (Step 3)

$\gamma_{DD} DD = 0$ (no downdrag)

$\varphi = 0.50$ (Step 5)

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## Step 7. Estimate Contract Pile Length

$D_0 = 0$ ft, $R_{n-BB0} = 0$

$D_1 = 5$ ft, $R_{n-BB1} = R_{n-BB0} + (1.4 \text{ klf})(5') = 7.0$ kips

$D_2 = 5 + 20 = 25$ ft, $R_{n-BB2} = R_{n-BB1} + (2.4 \text{ klf})(20')$

$= 7.0 + 48.0 = 55.0$ kips

End bearing in Layer 3 = 32.0 kips,

$R_{n-BB3} = R_{n-BB2} + 32.0 = 87.0$ kips

Required additional length in Layer 3 = (108.0 - 87.0)/2.8 = 7.5', say 8'

$D_4 = 25 + 8 = 33$ feet,

$R_{n\text{-}BB4} = R_{n\text{-}BB3}$ + (2.8 kips/ft) (8 ft) = 87.0 + 22.4 = 109.4 kips > 108 kips

L = 33 + 2 + 1 = 36 feet

Round pile length to nearest 5' increment, $\therefore$ L=35' [BDM 6.2.4.1]

## Step 7. Estimate Pile Length

Check resistance factor:
% non-cohesive soil = [(32-5)/32] (100)
= 84% > 70%  OK

---

istance

Resistance Factor (b)

(f) **Reduce the resistance factor to 0.35 for redundant groups of driven timber pile, if the Iowa DOT formula is used for construction control**. This is based on Iowa historic timber pile test data. For timber pile driven with WEAP, the resistance factor may be taken as 0.40.

| | | |
|---|---|---|
| - | 0.65 | 0.20 |

(e) Use signal matching to determine Nominal Driving Resistance.
(f) **Reduce the resistance factor to 0.35 for redundant groups of driven timber pile, if the Iowa DOT formula is used for construction control**. This is based on Iowa historic timber pile test data. For timber pile driven with WEAP, the resistance factor may be taken as 0.40.

---

## Step 8. Target Nominal Driving Resistance

$\varphi_{TAR}$ = 0.35 for all soil types (timber pile)

The target pile driving resistance is:

$$R_{ndr-T} = \frac{\sum \eta \gamma Q + \gamma_{DD} DD}{\varphi_{TAR}} = \frac{54+0}{0.35} = 154 \text{ kips/pile} = 77 \text{ tons/pile}$$

(using a Modified Iowa DOT Formula construction control)

If construction control = WEAP analysis,

$$\text{then } R_{ndr-T} = \frac{54+0}{0.40} = 135 \text{ kips/pile} = 68 \text{ tons/pile}$$

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## Step 8. Target Nominal Driving Resistance

Structural service load limit = 20 tons for timber pile,
and a driving limit = 40 tons [IDOT SS 2501.03, O, 2, c]

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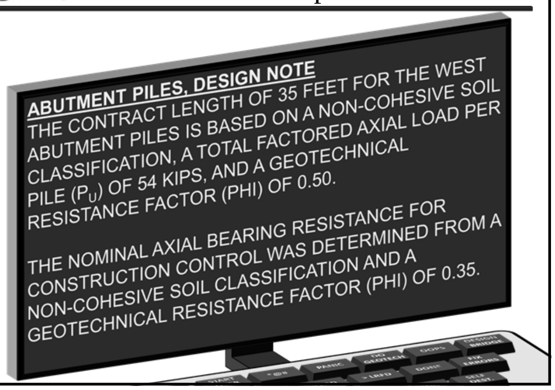
## Step 9. CADD Notes

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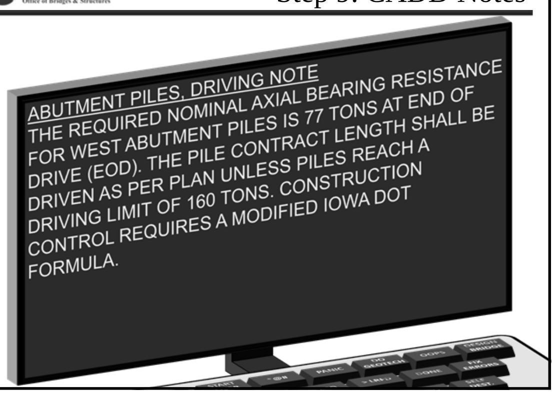
## Step 9. CADD Notes



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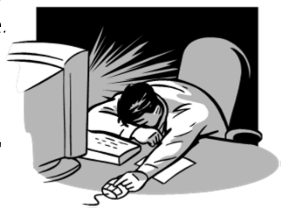
## Step 10. Check the Design

- Independent check of the bridge design, when the final plans are complete.



**END DESIGN PHASE**

| Pile Length (ft.) | Wood Pile | Minimum Energy Requ... Concrete Pile 12" to 14" |
|---|---|---|

| Pile Length (ft.) | Wood Pile | Maximum Energy A... Concrete Pile 12" to 14" |
|---|---|---|
| 25' or less | 24 | 32 |
| 26' to 40' | 24 | 32 |
| 41' to 50' | 33 | 32 |
| 51' to 65' | (a) | (a) |

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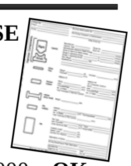
## Step 11. Hammer Data

**BEGIN CONSTRUCTION PHASE**



- Contractor: provide hammer data sheets
- Delmag (APE) D19-42 rated energy:

Minimum 22,721 foot-pounds (setting 1) > 17,000 **OK**
Maximum 31,715 foot-pounds (setting 2) > 24,000 No Good
Maximum 37,868 foot-pounds (setting 3) > 24,000 No Good
Maximum 47,335 foot-pounds (setting 4) > 24,000 No Good

**Accept Delmag D19-42 at Fuel Setting 1 (only)**

## Step 12. Construction Observation

Observe construction, record driven resistance and resolve any construction issues

- Record hammer stroke and number of blows

## Step 12. Construction Observation

$$R_{ndr} = \left(\frac{12E}{S+0.1}\right)\left(\frac{W}{W+M}\right)$$

where:

$R_{ndr}$ = nominal pile driving resistance, in tons

W = weight of ram, in tons (include consideration for hammer efficiency)

M = weight of pile, drive cap (helmet, cushion, striker plate and pile inserts if used), drive anvil and follower (if applicable), in tons

E = W x H = energy per blow, in foot-tons

H = Hammer stroke, in feet

S = average pile penetration, in inches per blow, for the last 10 blows

12 = conversion factor for feet to inches

## Track 2, Example 2

Wrap-up

- Blue Book unit nominal resistance
- Resistance factor = f (Limit State, soil category, & construction control)
- Contract pile length, L = 35 feet
- Construction Control: Modified Iowa DOT Formula
- Resistance factor at EOD = 0.35
- Target driving resistance = 77 tons at EOD

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## Learning Outcomes

A. Follow the geotechnical design and construction steps to implement Iowa LRFD Pile Design with Modified Iowa DOT/ENR Formula construction control.
B. Select a resistance factor to estimate the contract pile length, L.
C. Estimate the target nominal pile driving resistance, $R_{ndr-T}$.

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## Questions? – Kam Ng

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## Track 1 and Example 1

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## Learning Outcomes

A. Follow the geotechnical design and construction steps to implement Iowa LRFD Pile Design.
B. Select a resistance factor to estimate the contract pile length, L.
C. Estimate the target nominal pile driving resistance, $R_{ndr-T}$.
D. Determine the pile setup factor for cohesive soil.

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## Track 1

**Where are we going?**

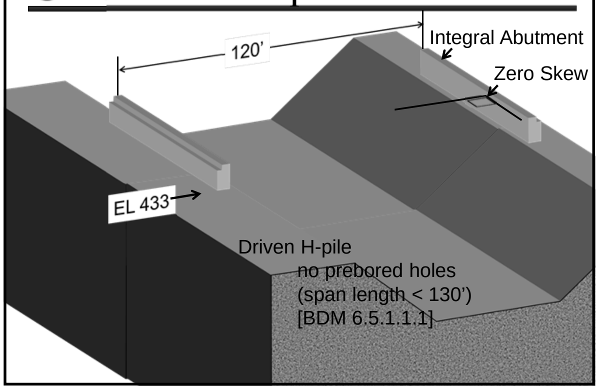
| Design Step | |
|---|---|
| 1 | Preliminary Design Engineer: Develop bridge situation plan (or TS&L, Type, Size, and Location) (1) |
| 2 | Soils Design Engineer: Develop soils package, including borings & foundation recommendations (1) |
| 3 | Final Design Engineer: Determine pile arrangement, pile loads, and other design requirements (1) |
| 4 | Estimate nominal geotechnical resistance per foot of pile embedment |
| 5 | Select resistance factor & estimate pile length, based on soil profile & construction control |
| 6 | Calculate required nominal pile resistance, $R_n$ |
| 7 | Estimate contract pile length, L |
| 8 | Estimate target nominal pile driving resistance, $R_{ndr-T}$ |
| 9 | Prepare CADD note for bridge plans |
| 10 | Check design (2) |
| **Construction Step** | |
| 11 | Prepare bearing graph |
| 12 | Observe construction, record driven resistance, and resolve any construction issues |

Notes: (1) These steps determine the basic information for geotechnical pile design and will vary depending on bridge project and office practice.
(2) Checking will vary depending on bridge project and office practice.

## Track 1 Example 1

**Integral Abutment**
**H-Pile & Cohesive Soil with Setup**
**Construction Control: WEAP**

## Step 1 - Situation Plan

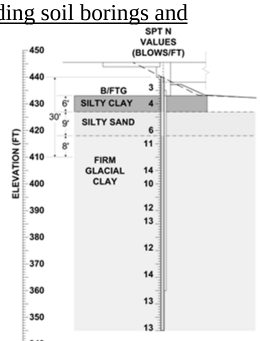



## Step 2. Soils Package

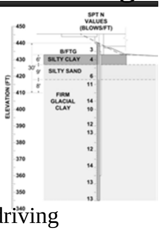
Develop soils package, including soil borings and foundation recommendations

Soils Design Engineer

- 6' soft silty clay
- 9' silty sand
- firm glacial clay



## Step 2. Soils Package



<u>Soils Design Engineer</u>

Develop foundation recommendations

- Friction pile: tip out in firm glacial clay
- Normal driving resistance
- Structural Resistance Level-1, SRL-1 (driving analysis not required by Office of Construction during design) [BDM 6.2.6.1]
- No special site considerations for stability, settlement, or lateral movement

## Step 3 Pile Arrangement



<u>Final Design Engineer</u>

- HP10x57 friction pile
- 128 kips/pile (STR I limit state controls)
- No uplift, downdrag or scour
- Construction Control: WEAP analysis, no planned retap
- No need for lateral load or special analysis

## Step 4 Nominal Pile Resistance

| | N-VALUE MEAN | N-VALUE RANGE | WOOD PILE | STEEL 10 | STEEL 12 |
|---|---|---|---|---|---|
| **Alluvium or Loess** | | | | | |
| Stiff sandy silt | 6 | 4 - 8 | 1.6 | 1.2 | 1.6 |
| Stiff sandy clay | 6 | 4 - 8 | 1.6 | 1.2 | 1.6 |
| Silty sand | 8 | 3 - 13 | 1.2 | 1.2 | 1.2 |
| Clayey sand | 13 | 6 - 20 | 2.0 | 1.6 | 2.0 |
| Firm silty glacial clay | 11 | 7 - 15 | 2.8 | 2.4 | 2.8 |
| Firm clay (gumbotil) | 12 | 9 - 15 | 2.8 | 2.4 | 2.8 |
| Firm glacial clay(1) | 11 | 7 - 15 | 2.4<br>[3.2] | 2.8<br>[3.2] | 3.2<br>[4.0] |
| Firm sandy glacial clay(1) | 13 | 9 - 15 | 2.4 | 2.8 | 3.2 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | [3.6] | [4.0] | [4.8] | [5.6] | [4.8] | [5.6] | [6.4] | [3.2] | [3.6] | [4.0] | [5.2] |
| Very firm sandy glacial clay(1) | 25 | 15 - 30 | 3.2<br>[4.0] | 2.8<br>[4.0] | 3.2<br>[4.8] | 3.6<br>[5.6] | 3.2(3)<br>[4.8] | 3.6(3)<br>[5.6] | 4.4(3)<br>[6.4] | 2.4<br>[3.2] | 2.8<br>[3.6] | 3.2<br>[4.0] | 4.0<br>[5.2] |
| Cohesive or glacial material(1) | > 35 | --- | (2) | 2.8<br>[4.0] | 3.2<br>[4.8] | 3.6<br>[5.6] | (2) | (2) | (2) | 2.0(4)<br>[3.2] | 2.4(4)<br>[4.0] | 2.8(4)<br>[4.4] | 3.6(4)<br>[5.6] |

Table notes:

(1) For double entries the upper value is for an embedded pile within 30 feet of the natural ground elevation, and the lower value [ ] is for pile depths more than 30 feet below the natural ground elevation.

(2) Do not consider use of this pile type for this soil condition, wood with N > 25, prestressed concrete with N > 35, or steel pipe with N > 40.

(3) Prestressed concrete piles have proven to be difficult to drive in these soils. Prestressed piles should not be driven in glacial clay with consistent N > 30 to 35.

(4) Steel pipe piles should not be driven in soils with consistent N > 40.

[BDM Table 6.2.7]

## Step 4 Nominal Pile Resistance

| Soil Stratum | Soil Description | | Stratum Thickness (ft) | Average SPT N Value (blows/ft) | Estimated Unit Nominal Resistance for Friction Pile (kips/ft) |
|---|---|---|---|---|---|
| 1 | Soft Silty Clay | | 6 | 4 | 0.8 |
| 2 | Silty Sand | | 9 | 6 | 1.2 |
| 3A | Firm Glacial Clay | within 30 feet of natural ground elevation | 8 | 11 | 2.8 |
| 3B | | more than 30 feet below natural ground elevation | 65 | 12 | 3.2 |

## Step 5. Resistance Factor

**Resistance Factors for DESIGN of Single Pile in Axial Compression (Contract Length)**

| Theoretical Analysis [c] | Construction Control (field verification) [a] | | | | | Resistance Factor [b] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Driving Criteria Basis | | PDA/CAPWAP | Retap Test 3-Days After EOD | Static Pile Load Test | Cohesive | | | Mixed | Non-Cohesive |
| | Iowa DOT ENR Formula | WEAP | | | | $\phi$ | $\phi_{EOD}$ | $\phi_{setup}$ | $\phi$ | $\phi$ |
| Iowa Blue Book | Yes | - | - | - | - | 0.60 | - | - | 0.60 | 0.50 |
| | | | - | - | - | 0.65 | - | - | 0.65 | 0.55 |
| | - | Yes [d] | Yes | - | - | 0.70 [e] | - | - | 0.70 | 0.60 |
| | | | | Yes | - | 0.80 | - | - | 0.70 | 0.60 |
| | | | - | - | Yes | 0.80 | - | - | 0.80 | 0.80 |

Notes:
(a) Determine the construction control that will be specified on the Plans to achieve the Target Nominal Driving Resistance.
(b) Resistance factors presented in Table E1 are for redundant pile groups (minimum of 4 piles).
(c) Use BDM Article 6.2.7 to estimate the theoretical nominal pile resistance, based on the Iowa Blue Book.
(d) Use the Iowa Blue Book soil input procedure to complete WEAP analyses.
(e) Setup effect has been included when WEAP is used to establish driving criteria and CAPWAP is used as a construction control.

## Step 5. Resistance Factor

**Resistance Factors for DESIGN of Single Pile in Axial Compression (Contract Length)**

| Resistance Factor [b] | | | | |
|---|---|---|---|---|
| Cohesive | | | Mixed | Non-Cohesive |
| $\phi$ | $\phi_{EOD}$ | $\phi_{setup}$ | $\phi$ | $\phi$ |
| 0.60 | - | - | 0.60 | 0.50 |
| 0.65 | - | - | 0.65 | 0.55 |

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## Step 5 Resistance Factor

Select resistance factor to estimate pile length

$\varphi =$ 0.65 for cohesive soil *

$\varphi =$ 0.65 for mixed soil *

$\varphi =$ 0.55 for non-cohesive soil *

* average over full depth of estimated pile penetration

$>$ 70% of pile embedment in cohesive soil $\therefore \varphi = 0.65$

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## Step 5 Resistance Factor

| Generalized Soil Category | Soil Classification Method | | | |
|---|---|---|---|---|
| | AASHTO | USDA Textural | BDM 6.2.7 Geotechnical Resistance Chart | |
| Cohesive | A-4, A-5, A-6 and A-7 | Clay<br>Silty clay<br>Silty clay loam<br>Silt<br>Clay loam<br>Silt loam<br>Loam<br>Sandy clay | Loess | Very soft silty clay |
| | | | | Soft silty clay |
| | | | | Stiff silty clay |
| | | | | Firm silty clay |
| | | | | Stiff silt |
| | | | | Stiff sandy clay |
| | | | Glacial Clay | Firm silty glacial clay |
| | | | | Firm clay (gumbotil) |
| | | | | Firm glacial clay |
| | | | | Firm sandy glacial clay |
| | | | | Firm-very firm glacial clay |
| | | | | Very firm glacial clay |
| | | | | Very firm sandy glacial clay |
| | | | | Cohesive or glacial material |
| Non-Cohesive | A-1, A-2 and A-3 | Sandy clay loam<br>Sandy loam<br>Loamy sand<br>Sand | Alluvium Or Loess | Stiff sandy silt |
| | | | | Silty sand |
| | | | | Clayey sand |
| | | | | Fine sand |
| | | | | Coarse sand |
| | | | | Gravely sand |
| | | | | Granular material (N>40) |

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## Step 6 Required Nominal Resistance

The required nominal pile resistance is:

$$R_n = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi} = \frac{128 + 0}{0.65} = 197 \text{ kips/pile}$$

where: $\sum \eta\gamma Q = \gamma Q = 128\text{kips}$ (Step3)

$\gamma_{DD} DD = 0$ (no downdrag)

$\varphi = 0.65$ (Step 5)

## Step 7 Estimate pile length

Estimate contract pile length, L

$D_0 = 0 \text{ ft}, R_{n-BB0} = 0$

$D_1 = 6 \text{ ft}, R_{n-BB1} = R_{n-BB0} + (0.8 \text{ klf})(6') = 4.8 \text{ kips}$

$D_2 = 6 + 9 = 15 \text{ ft}, R_{n-BB2} = R_{n-BB1} + (1.2 \text{ klf})(9')$
$= 4.8 + 10.8 = 15.6 \text{ kips}$

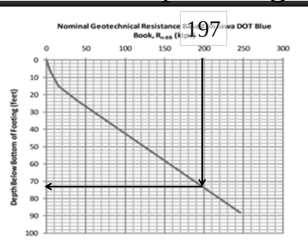
$D_3 = 15 + 8 = 23 \text{ ft}, R_{n-BB3} = R_{n-BB2} + (2.8 \text{ klf})(8')$
$= 15.6 + 22.4 = 38.0 \text{ kips}$

$D_4 = 23 + 65 = 88 \text{ ft}, R_{n-BB4} = R_{n-BB3} + (3.2 \text{ klf})(65')$
$= 38.0 + 208.0 = 246.0 \text{ kips}$

## Step 7 Estimate pile length

73' soil embedment
1' cutoff
+ 2' ftg. embedment
76'

L = 75 feet* 73




Check resistance factor:
% cohesive soil = [(72-9)/72] (100) = 88% > 70% OK

* H-pile length estimated to the nearest 5' increment [BDM 6.2.4.2]

## Step 8. Target Nominal Driving Resistance

**Resistance Factors for CONSTRUCTION CONTROL**

| Theoretical Analysis (c) | Construction Control (field verification) (a) | | | | | Resistance Factor (b) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Driving Criteria Basis | | PDA/CAPWAP | Retap Test 3-Days After EOD | Static Pile Load Test | Cohesive | | | Mixed | Non-Cohesive |
| | Iowa DOT ENR Formula | WEAP | | | | $\phi$ | $\phi_{EOD}$ | $\phi_{setup}$ | $\phi$ | $\phi$ |
| Iowa Blue Book | Yes | - | - | - | - | 0.55 (f) | - | - | 0.55 (f) | 0.50 (f) |
| | - | Yes (d) | - | - | - | - | 0.65 | 0.20 | 0.65 | 0.55 |
| | | | - | Yes | - | 0.70 | - | - | | |
| | | | Yes (e) | - | - | - | 0.75 | 0.40 | 0.70 | 0.70 |
| | | | | Yes | - | 0.80 | - | - | | |
| | | | - | - | Yes | 0.80 | - | - | 0.80 | 0.80 |

Notes:
(a) Refer to the Plans for the specified construction control that is required to achieve the Target Nominal Driving Resistance.
(b) Resistance factors presented are for redundant pile groups (minimum of 4 piles).
(c) Use BDM Article 6.2.7 to estimate the theoretical nominal pile resistance, based on the Iowa Blue Book.
(d) Use the Iowa Blue Book soil input procedure to complete WEAP analyses.
(e) Use signal matching to determine Nominal Driving Resistance.
(f) Reduce the resistance factor to 0.35 for redundant groups of driven timber pile, if the Iowa DOT ENR formula is used for construction control. This is based on Iowa historic timber pile test data. For timber pile driven with WEAP, the resistance factor may be taken as 0.40.

## Step 8. Target Nominal Driving Resistance

Resistance Factors for CONSTRUCTION CONTROL

| Resistance Factor (b) | | | | |
|---|---|---|---|---|
| Cohesive | | | Mixed | Non-Cohesive |
| $\phi$ | $\phi_{EOD}$ | $\phi_{setup}$ | $\phi$ | $\phi$ |
| 0.55 (f) | - | - | 0.55 (f) | 0.50 (f) |
| - | 0.65 | 0.20 | 0.65 | 0.55 |
| 0.70 | - | - | | |
| - | 0.75 | 0.40 | | |

## Step 8 Target nominal driving resistance

Estimate target nominal pile driving resistance, $R_{ndr-T}$

$\varphi_{EOD}$ = 0.65 for cohesive soil *

$\varphi_{SETUP}$ = 0.20 for cohesive soil *

$\varphi$ = 0.65 for mixed soil *

$\varphi$ = 0.55 for non-cohesive soil *

* average over full depth of estimated pile penetration

Determine $R_n$ at end of drive by scaling-back setup gain, and then adjust retaps to account for setup.

$\Sigma\eta\gamma Q + g_{DD}DD \le \varphi R_n$

where $\eta$ = 1.0 = load modifier [BDM 6.2.3.1]

## Step 8 Target nominal driving resistance

Let $R_n = R_T$ = nominal pile resistance at time T (days) after EOD.

$$R_{EOD} \ge \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi_{EOD} + \varphi_{SETUP}\left(F_{SETUP} - 1\right)}$$

where: $\sum \eta\gamma Q = \gamma Q$ = 128 kips, (Step 3)

$\gamma_{DD} DD = 0$ (no downdrag)

$F_{SETUP}$ = Setup Ratio = $R_T / R_{EOD}$

## Step 8 Target nominal driving resistance

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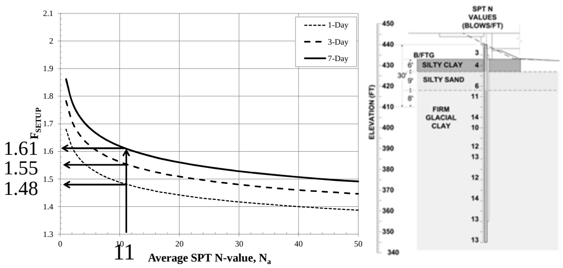
Calculate average SPT N-value for cohesive soil portion.

Avg. SPT N-value = [(6')(4) + (8')(11) + (72'- 23')(12)] / (72'- 9') = 11




## Step 8 Target nominal driving resistance

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Let $\varphi_{TAR}$ = Resistance factor for target nominal resistance ≤ 1.00

$$= \varphi_{EOD} + \varphi_{SETUP}\left(F_{SETUP} - 1\right)$$

and $R_{ndr-T} = R_{EOD}$

The target pile driving resistance at End Of Drive, EOD, is

$$R_{ndr-T} = R_{EOD}$$

$$\geq \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi_{TAR}}$$

$$= \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi_{EOD} + \varphi_{SETUP}\left(F_{SETUP} - 1\right)}$$

$$= \frac{128 + 0}{(0.65) + (0.2)(1.61 - 1)} = \frac{128}{0.77}$$

= 166 kips/pile = 83 tons/pile

## Step 8 Target nominal driving resistance

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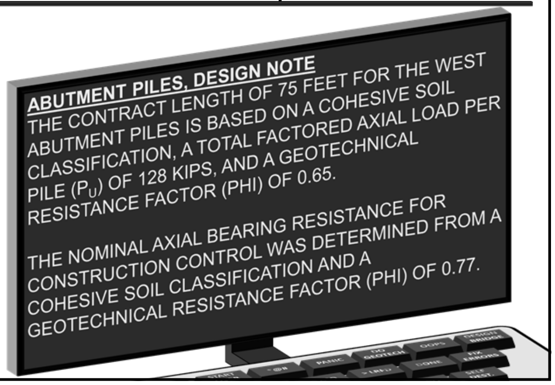
**Retap target nominal driving resistance:**

$R_{ndr\text{-}T\,(retap)}$ = minimum [$R_{EOD} \times F_{setup}$ or $R_n$ (IBB)]

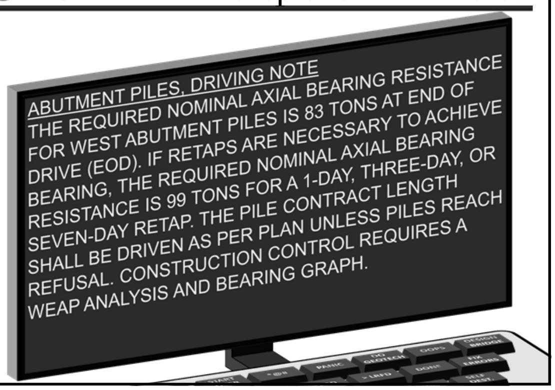
$R_{ndr\text{-}T\,(1\text{-}day)}$ = smaller of [166×1.48= 246 kips or 197 kips]=99 tons
$R_{ndr\text{-}T\,(3\text{-}day)}$ = smaller of [166×1.55=257 kips or 197 kips]=99 tons
$R_{ndr\text{-}T\,(7\text{-}day)}$ = smaller of [166×1.61=267 kips or 197 kips]=99 tons

Thus, target nominal driving resistance = 99 tons/pile after EOD

## Step 9 CADD Notes




## Step 9 CADD Notes




## Step 10 Check the design

- Independent check of the bridge design, when the final plans are complete.

**END DESIGN PHASE**

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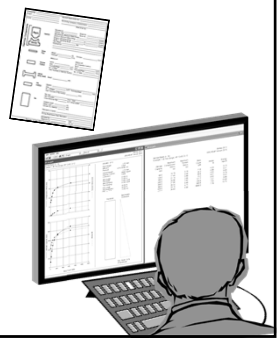
## Step 11 Bearing Graph

**BEGIN CONSTRUCTION PHASE**

- Contractor: provide hammer data sheets
- Office of Construction: perform WEAP analysis & prepare LRFD driving graph



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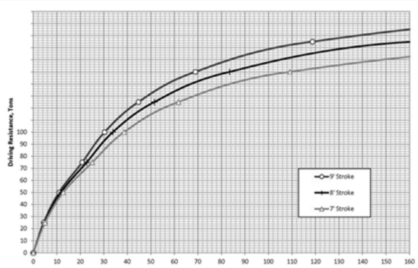
## Step 11 Bearing Graph

| Special Driving Conditions | Stroke (ft) | Monitor at 10 Blow Increments | Do NOT Exceed | Project No: | Design Example DGT11 | Graph No: | XX-XXXX-XX-XXX |
|---|---|---|---|---|---|---|---|
| | | | | Design No: | XXX | Hammer No: | XXXXXX |
| | 7 | ----- | ----- | County: | XXXXX | Cap No: | XXX |
| | 8 | ----- | ----- | Location: | West Abutment | Pile Type: | HP 10x57 |
| Blows per foot | 9 | ----- | ----- | Hammer: | Delmag D19-42 | Pile Length: | 75 feet |




LRFD Driving Graph

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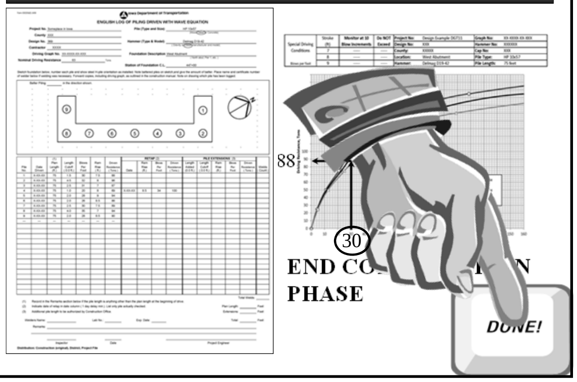
## Step 12 Construction observation

Observe construction, record driven resistance and resolve any construction issues

- Record hammer stroke and number of blows
- Use the LRFD driving graph to determine driven resistance at EOD
- If resistance at EOD is less than the target, retap pile 24 hours after EOD

## Step 12 Construction observation




## Track 1, Example 1

Wrap-up

- Blue Book unit nominal resistance
- Resistance factor = f (Limit State, soil category, & construction control)
- Contract pile length, L = 75 feet
- Construction Control: WEAP analysis
- Resistance factor at EOD = 0.77
- Target driving resistance = 83 tons at EOD
- Pile retap = 99 tons at any retap after EOD

## Questions? – Kam Ng

## Tracks 1 and 2 Comparison - Kam Ng

## Learning Outcomes

A. Recognize the different design and construction control procedures of Track 1 and Track 2.

B. Compare the different outcomes from Track 1 and Track 2

C. Recognize the advantages of using WEAP as a construction control method

## Steps

| | |
|---|---|
| **Design Step** | |
| 1 | Preliminary Design Engineer: Develop bridge situation plan (or TS&L, Type, Size, and Location) (1) |
| 2 | Soils Design Engineer: Develop soils package, including borings & foundation recommendations (1) |
| 3 | Final Design Engineer: Determine pile arrangement, pile loads, and other design requirements (1) |
| 4 | Estimate nominal geotechnical resistance per foot of pile embedment |
| 5 | Select resistance factor & estimate pile length, based on soil profile & construction control |
| 6 | Calculate required nominal pile resistance, $R_n$ |
| 7 | Estimate contract pile length, L |
| 8 | Estimate target nominal pile driving resistance, $R_{ndr-T}$ |
| 9 | Prepare CADD note for bridge plans |
| 10 | Check design (2) |
| **Construction Step** | |
| 11 | Prepare bearing graph |
| 12 | Observe construction, record driven resistance, and resolve any construction issues |

Notes: (1) These steps determine the basic information for geotechnical pile design and will vary depending on bridge project and office practice.

(2) Checking will vary depending on bridge project and office practice.

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## Example 1

**Integral Abutment**
**H-Pile & Cohesive Soil with Setup**
**Construction Controls:**
**WEAP versus Modified Iowa ENR**

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## Step 1 - Situation Plan

- 120 ft, single-span, prestressed concrete beam superstructure
- Zero skew
- Integral abutments
- Pile foundations, no prebored holes (because the bridge length is less than 130 ft) (BDM 6.5.1.1.1)
- Bottom of abutment footing elevation 433 ft

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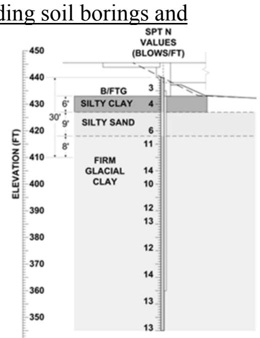
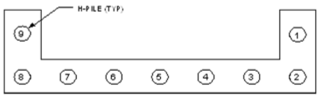
## Step 2. Soils Package

Develop soils package, including soil borings and foundation recommendations

Soils Design Engineer
- 6’ soft silty clay
- 9’ silty sand
- firm glacial clay



## Step 3 Pile Arrangement




Final Design Engineer

- HP10x57 friction pile
- 128 kips/pile (STR I limit state controls)
- No uplift, downdrag or scour
- Construction Control: Track 1 = WEAP, Track 2 = Modified Iowa ENR
- No planned retap
- No need for lateral load or special analysis

## Step 4 Nominal Pile Resistance

| Soil Stratum | Soil Description | | Stratum Thickness (ft) | Average SPT N Value (blows/ft) | Estimated Unit Nominal Resistance for Friction Pile (kips/ft) |
|---|---|---|---|---|---|
| 1 | Soft Silty Clay | | 6 | 4 | 0.8 |
| 2 | Silty Sand | | 9 | 6 | 1.2 |
| 3A | Firm Glacial Clay | within 30 feet of natural ground elevation | 8 | 11 | 2.8 |
| 3B | Firm Glacial Clay | more than 30 feet below natural ground elevation | 65 | 12 | 3.2 |

## Step 5 Resistance Factor

Select resistance factor (φ) to estimate pile length

- Track 1: WEAP
  - 0.65 for cohesive
  - 0.65 for mixed
  - 0.55 for non-cohesive

- Track 2: ENR
  - 0.60 for cohesive
  - 0.60 for mixed
  - 0.50 for non-cohesive

Track 1 has higher resistance factors

## Step 6 Required Nominal Resistance

The required nominal pile resistance in cohesive soil is:

- Track 1: WEAP
  - $R_n = \frac{\sum \gamma Q}{\varphi}$
  
    $R_n = \frac{128}{0.65}$
    
    $R_n = 197$ kips/pile
- Track 2: ENR
  - $R_n = \frac{\sum \gamma Q}{\varphi}$
  
    $R_n = \frac{128}{0.60}$
    
    $R_n = 213$ kips/pile

Track 1 requires smaller $R_n$ by 16 kips/pile

## Step 7 Estimate pile length

Estimate contract pile length, L

- Track 1: WEAP
  - Required 73 ft
  - 1 ft cutoff
  - 2 ft ftg embedment
  - 75 ft contract length
- Track 2: ENR
  - Required 78 ft
  - 1 ft cutoff
  - 2 ft ftg embedment
  - 80 ft contract length

Track 1 requires smaller contract length by 5 ft/pile

## Step 8 Target nominal driving resistance

Estimate target nominal pile driving resistance at EOD, $R_{ndr-T}$ (EOD)

- Track 1: WEAP
  - $\varphi_{EOD} = 0.65$
  - $\varphi_{setup} = 0.20$
  - $N_a = 11$
  - $F_{setup} = 1.61$
  - $R_{ndr-T} = \frac{\sum \gamma Q}{\varphi_{EOD} + \varphi_{setup}(F_{setup} - 1)}$
  - $R_{ndr-T} = \frac{128}{0.65 + 0.20(1.61 - 1)} = \frac{128}{0.77}$
  - $R_{ndr-T}(\text{EOD}) = 166$ kips/pile
- Track 2: ENR
  - $\varphi = 0.55$
  - $R_{ndr-T} = \frac{\sum \gamma Q}{\varphi}$
  - $R_{ndr-T} = \frac{128}{0.55}$
  - $R_{ndr-T}(\text{EOD}) =$ 233 kips/pile

Track 1 requires smaller $R_{ndr-T}$ (EOD) by 67 kips/pile

## Step 8 Target nominal driving resistance

Estimate target nominal pile driving resistance at retap, $R_{ndr-T}$

| • Track 1: WEAP | • Track 2: ENR |
|---|---|
| – $R_{ndr-T}$ (1 day) ≥ min[197 or 1.47×166 = 244] = 197 kips/pile<br>– $R_{ndr-T}$ (3 day) ≥ min[197 or 1.55×166 = 257] = 197 kips/pile<br>– $R_{ndr-T}$ (7 day) ≥ min[197 or 1.61×166 = 267] = 197kips/pile | – $R_{ndr-T}$ (1 day or later) ≥ 233 kips/pile |

Track 1 requires a lower $R_{ndr-T}$ at retaps

## Step 9 CADD Notes

Design Notes

| Track 1: WEAP | Track 2: ENR |
|---|---|
| THE CONTRACT LENGTH OF **75 FEET** FOR THE WEST ABUTMENT PILES IS BASED ON A COHESIVE SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE ($P_U$) OF 128 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF **0.65.**<br>THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF **0.77.** | THE CONTRACT LENGTH OF **80 FEET** FOR THE WEST ABUTMENT PILES IS BASED ON A COHESIVE SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE ($P_U$) OF 128 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF **0.60.**<br>THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF **0.55.** |

## Step 9 CADD Notes

Driving Notes

| Track 1: WEAP | Track 2: ENR |
|---|---|
| THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR WEST ABUTMENT PILES IS **166 KIPS** AT END OF DRIVE (EOD). IF RETAPS ARE NECESSARY TO ACHIEVE BEARING, THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE IS **197 KIPS**. THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. **CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS AND BEARING GRAPH.** | THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR WEST ABUTMENT PILES IS **233 KIPS** AT END OF DRIVE (EOD). IF RETAPS ARE NECESSARY TO ACHIEVE BEARING, THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE IS **233 KIPS**. THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. **CONSTRUCTION CONTROL REQUIRES A MODIFIED IOWA DOT FORMULA.** |

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## Step 10 Check the design

- Independent check of the bridge design, when the final plans are complete.

**END DESIGN PHASE**

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## Step 11 Construction Control

**BEGIN CONSTRUCTION PHASE**

| Track 1: WEAP | Track 2: ENR |
|---|---|
| • Perform WEAP analysis<br>• Prepare bearing graph<br>• Observe construction<br>• Record hammer blow counts<br>• Determine driving resistance from bearing graph | • Check minimum energy requirement<br>• Observe construction<br>• Record hammer blow counts<br>• Determine driving resistance from modified Iowa ENR formula |

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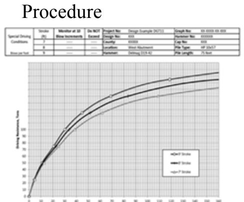
## Step 11 Hammer Data

| Track 1: WEAP | Track 2: ENR |
|---|---|
| Contractor provides Delmag D19-42 hammer | |
| • Iowa Blue Book Soil Input Procedure<br> | • Based on Iowa DOT SS: $29 \text{ ft-kips} \le E \le 40 \text{ ft-kips}$<br>• Delmag D19-42 with settings 2 (E = 31.7 ft-kips) and setting 3 (E = 37.9 ft-kips) are accepted |

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## Step 12 Observe Construction

| Track 1: WEAP | Track 2: ENR |
|---|---|
| At the EOD, hammer stroke = 7.5 ft and driving resistance = 30 blows/ft are recorded. | |
| • Based on the bearing graph, $R_{ndr}$ = 88 tons = 176 kips, which is larger than $R_{ndr\text{-}T}$ = 166 kips. **Hence, the pile performance is accepted.** | • Using the modified ENR formula: $R_{ndr} = \frac{12E}{s+0.1} \times \frac{W}{W+M}$ <br> W = 2.007 tons × 0.80 = 1.606 tons <br> M = 2.28+0.375+0.6 = 3.26 tons <br> E = WH = 12.045 ft-tons <br> s = 12 in/30 blows = 0.4 in/blow <br> $R_{ndr} = \frac{12 \times 12.045}{0.4+0.1} \times \frac{1.606}{1.606+3.26} \times 2$ <br> $R_{ndr} = 191$ kips $\leq R_{ndr-T} = 233$ kips. <br> **Hence, the pile performance is not accepted.** |

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## Step 12 Observe Construction

| Track 1: WEAP | Track 2: ENR |
|---|---|
| At the 1-day retap, hammer stroke = 8.5 ft and driving resistance = 40 blows/ft are recorded. | |
| • Based on the bearing graph, $R_{ndr}$ = 114 tons = 228 kips, which is higher than $R_{ndr\text{-}T}$ = 197 kips. **Again, the pile performance is accepted.** | • Using the modified ENR formula: $R_{ndr} = \frac{12E}{s+0.1} \times \frac{W}{W+M}$ <br> W = 2.007 tons × 0.80 = 1.606 tons <br> M = 2.28+0.375+0.6 = 3.26 tons <br> E = WH = 13.65 ft-tons <br> s = 12 in/40 blows = 0.30 in/blow <br> $R_{ndr} = \frac{12 \times 13.65}{0.30+0.1} \times \frac{1.606}{1.606+3.26} \times 2$ <br> $R_{ndr} = 270$ kips $\geq R_{ndr-T} = 233$ kips. <br> **Hence, the pile performance is now accepted.** |

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## Example 1

Summary of comparison

| Track 1: WEAP | Track 2: ENR |
|---|---|
| • 9 HP 10×57 steel piles <br> • Total contract length = **675 ft** <br> • $R_n$/pile = **197 kips** <br> • $R_{ndr\text{-}T}$ (EOD) = **166 kips** <br> • $R_{ndr\text{-}T}$ (Retap) = **197 kips** <br> • Pile performance is **likely** to be **accepted** at EOD <br> • **Lower chances** of pile retaps | • 9 HP 10×57 steel piles <br> • Total contract length = **720 ft** <br> • $R_n$/pile = **213 kips** <br> • $R_{ndr\text{-}T}$ (EOD) = **233 kips** <br> • $R_{ndr\text{-}T}$ (Retap) = **233 kips** <br> • Relatively, pile performance is **less likely** to be **accepted** at EOD <br> • **Higher chances** of pile retaps |

## Learning Outcomes

A. Recognize the different design and construction control procedures of Track 1 and Track 2.
B. Compare the different outcomes from Track 1 and Track 2
C. Recognize the advantages of using WEAP as a construction control method

## Questions? – Kam Ng

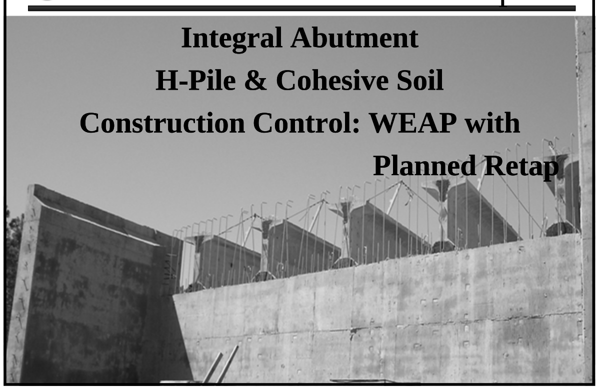
## Track 3 Example – Kam Ng

## Learning Outcomes

A. Follow the geotechnical design and construction steps to implement Iowa LRFD Pile Design.
B. Select a resistance factor to estimate the contract pile length, L.
C. Estimate the target nominal pile driving resistance, $R_{ndr\text{-}T}$.
D. Describe what is required for planned retaps.

## Track 3 Example 2

**Integral Abutment**
**H-Pile & Cohesive Soil**
**Construction Control: WEAP with Planned Retap**



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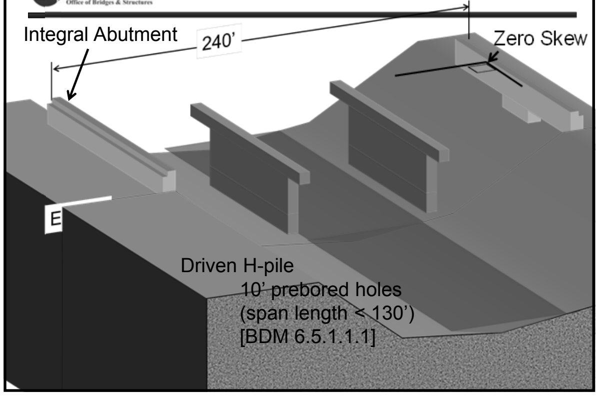
## Step 1. Situation Plan

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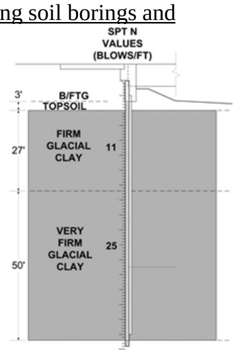
## Step 2. Soils Package

Develop soils package, including soil borings and foundation recommendations

Soils Design Engineer

- 3' topsoil
- 27' firm glacial clay
- 50' very firm glacial clay

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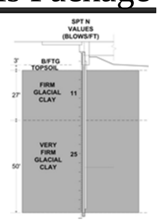
## Step 2. Soils Package

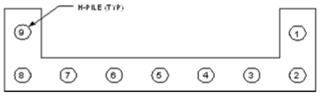


Soils Design Engineer

Develop foundation recommendations

- Friction pile: tip out in very firm glacial clay
- Normal driving resistance
- Structural Resistance Level-1, SRL-1 (driving analysis not required by Office of Construction during design) [BDM 6.2.6.1]
- No special site considerations for stability, settlement, or lateral movement

## Step 3 Pile Arrangement





Final Design Engineer

- HP10x57 friction pile
- 128.6 kips/pile (STR I limit state controls)
- No uplift, downdrag or scour
- Construction Control: WEAP analysis with 3-day planned retap
- No need for lateral load or special analysis

## Step 4 Nominal Pile Resistance

| Soil Stratum | Soil Description | Stratum Thickness (ft) | Average SPT N Value (blows/ft) | Estimated Nominal Resistance for Friction Pile (kips/ft) | Cumulative Nominal Friction Resistance at Bottom of Layer (kips) | Estimated Nominal Resistance for End Bearing (ksi) |
|---|---|---|---|---|---|---|
| 1 | Topsoil | 3 (prebore) | --- | --- | --- | --- |
| 2A | Firm glacial clay | 7 (prebore) | | | | |
| 2B | Firm glacial clay | 20 (below prebore) | 11 | 2.8 | 56 | --- |
| 2 | Very firm glacial clay | 50 | 25 | 4.0 | 256 | 2.0 |

## Step 5. Resistance Factor

**Resistance Factors for DESIGN of Single Pile in Axial Compression (Contract Length)**

| Theoretical Analysis [c] | Construction Control (field verification) [a]: Driving Criteria Basis: Iowa DOT ENR Formula | Driving Criteria Basis: WEAP | PDA/CAPWAP | Retap Test 3-Days After EOD | Static Pile Load Test | Resistance Factor [b]: Cohesive: $\phi$ | Cohesive: $\phi_{EOD}$ | Cohesive: $\phi_{setup}$ | Mixed: $\phi$ | Non-Cohesive: $\phi$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Iowa Blue Book | Yes | - | - | - | - | 0.60 | - | - | 0.60 | 0.50 |
| | | | - | - | - | 0.65 | - | - | 0.65 | 0.55 |
| | - | Yes [d] | Yes | - | - | 0.70 [e] | - | - | 0.70 | 0.60 |
| | | | | Yes | - | 0.80 | - | - | 0.70 | 0.60 |
| | | | - | - | Yes | 0.80 | - | - | 0.80 | 0.80 |

Notes:
(a) Determine the construction control that will be specified on the Plans to achieve the Target Nominal Driving Resistance.
(b) Resistance factors presented in Table E1 are for redundant pile groups (minimum of 4 piles).
(c) Use BDM Article 6.2.7 to estimate the theoretical nominal pile resistance, based on the Iowa Blue Book.
(d) Use the Iowa Blue Book soil input procedure to complete WEAP analyses.
(e) Setup effect has been included when WEAP is used to establish driving criteria and CAPWAP is used as a construction control.

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## Step 5. Resistance Factor

**Resistance Factors for DESIGN of Single Pile in Axial Compression (Contract Length)**

| Resistance Factor (b) | | | | |
|---|---|---|---|---|
| Cohesive | | | Mixed | Non-Cohesive |
| $\phi$ | $\phi_{EOD}$ | $\phi_{setup}$ | $\phi$ | $\phi$ |
| 0.60 | - | - | 0.60 | 0.50 |
| 0.65 | - | - | 0.65 | 0.55 |
| [illegible] | | | [illegible] | [illegible] |

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## Step 6 Required Nominal Resistance

The required nominal pile resistance is:

$$R_n = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi} = \frac{128.6 + 0}{0.65} = 197.8 \text{ kips/pile}$$

where: $\sum \eta\gamma Q = \gamma Q = 128.6$ kips (Step3)

$\gamma_{DD} DD = 0$ (no downdrag)

$\varphi = 0.65$ (Step 5)

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## Step 7 Estimate pile length

Estimate contract pile length, L

$D_0 = 0$ ft, $R_{n-BB0} = 0$

$D_1 = 10$ ft, $R_{n-BB1} = R_{n-BB0} + 0 = 0$ kips

$D_2 = 10 + 20 = 30$ ft, $R_{n-BB2} = R_{n-BB1} + (2.8 \text{ klf})(20')$

$= 0 + 56.0 = 56.0$ kips

$D_3 = 30 + X$ ft, $R_{n-BB3} = R_{n-BB2} + (2.0 \text{ ksi})(16.8 in^2)$

$= 56.0 + 33.6 = 89.6$ kips

$D_4 = 30 + X$ ft, X $= (197.8 - 89.6)/(4.0 \text{ klf}) = 27.1$ ft

$D_4 = 30 + 27.1$ ft $= 57.1$ ft

L = 57.1 + 2 + 1 = 60.1 feet   Use L = 60' *

* H-pile length estimated to the nearest 5' increment [BDM 6.2.4.2]

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## Step 8. Target Nominal Driving Resistance

**Resistance Factors for CONSTRUCTION CONTROL**

| Theoretical Analysis [c] | Construction Control (field verification) [a] | | | | | Resistance Factor [b] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Driving Criteria Basis | | PDA/CAPWAP | Retap Test 3-Days After EOD | Static Pile Load Test | Cohesive | | | Mixed | Non-Cohesive |
| | Iowa DOT ENR Formula | WEAP | | | | $\phi$ | $\phi_{EOD}$ | $\phi_{setup}$ | $\phi$ | $\phi$ |
| Iowa Blue Book | Yes | - | - | - | - | 0.55 [f] | - | - | 0.55 [f] | 0.50 [f] |
| | - | Yes [d] | - | - | - | - | 0.65 | 0.20 | 0.65 | 0.55 |
| | | | - | Yes | - | 0.70 | - | - | | |
| | | | Yes [e] | - | - | - | 0.75 | 0.40 | 0.70 | 0.70 |
| | | | | Yes | - | 0.80 | - | - | | |
| | | | - | - | Yes | 0.80 | - | - | 0.80 | 0.80 |

Notes:
(a) Refer to the Plans for the specified construction control that is required to achieve the Target Nominal Driving Resistance.
(b) Resistance factors presented are for redundant pile groups (minimum of 4 piles).
(c) Use BDM Article 6.2.7 to estimate the theoretical nominal pile resistance, based on the Iowa Blue Book.
(d) Use the Iowa Blue Book soil input procedure to complete WEAP analyses.
(e) Use signal matching to determine Nominal Driving Resistance.
(f) Reduce the resistance factor to 0.35 for redundant groups of driven timber pile, if the Iowa DOT ENR formula is used for construction control. This is based on Iowa historic timber pile test data. For timber pile driven with WEAP, the resistance factor may be taken as 0.40.

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## Step 8. Target Nominal Driving Resistance

| Resistance Factor [b] | | | | |
|---|---|---|---|---|
| Cohesive | | | Mixed | Non-Cohesive |
| $\phi$ | $\phi_{EOD}$ | $\phi_{setup}$ | $\phi$ | $\phi$ |
| 0.55 [f] | - | - | 0.55 [f] | 0.50 [f] |
| - | 0.65 | 0.20 | 0.65 | 0.55 |
| 0.70 | - | - | | |
| - | 0.75 | 0.40 | 0.70 | 0.70 |

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## Step 8 Target nominal driving resistance

$\varphi$ = 0.70 for cohesive soil, with retap test 3 days after EOD

Determine the nominal geotechnical bearing resistance per pile at 3-day retap.

$$R_n = \frac{128.6}{0.70} = 183.7 \text{ kips}$$

The average SPT N-value over the estimated pile embedment length is needed to use the setup factor chart.

$$N_a = \frac{(20)(11)+(27)(25)}{(20+27)} = 19$$

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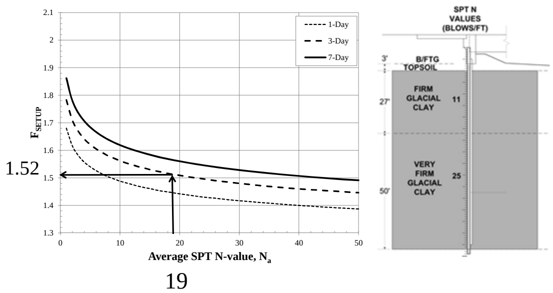
## Step 8 Target nominal driving resistance

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## Step 8 Target nominal driving resistance

$R_{EOD} = \frac{183.7}{1.57}$ = 117 kips = 59 tons

Determine the nominal resistance at 3 days. From the setup chart,

$F_{setup} = \frac{R_t}{R_{EOD}} = 1.52$

The target nominal geotechnical resistance at the 3-day retap is

$R_{3\text{-day}} = F_{setup} \times R_{EOD}$

$R_{3\text{-day}}$ = 1.52×117 = 177.8 kips = 89 tons/pile

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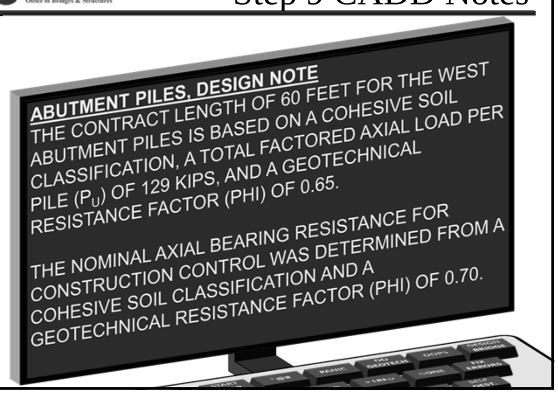
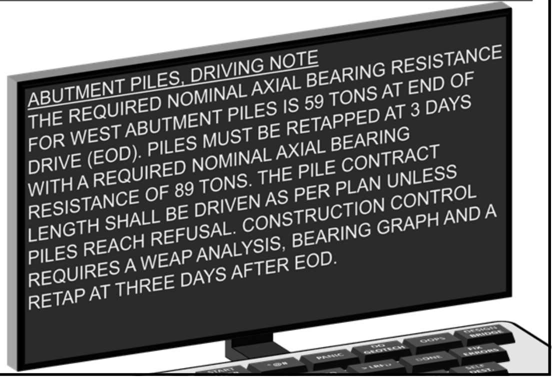
## Step 9 CADD Notes



## Step 9 CADD Notes




## Step 10 Check the design

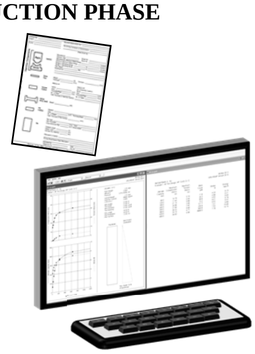
- Independent check of the bridge design, when the final plans are complete.

**END DESIGN PHASE**

## Step 11 Bearing Graph

**BEGIN CONSTRUCTION PHASE**

- Contractor: provide hammer data sheets
- Office of Construction: perform WEAP analysis & prepare LRFD driving graph



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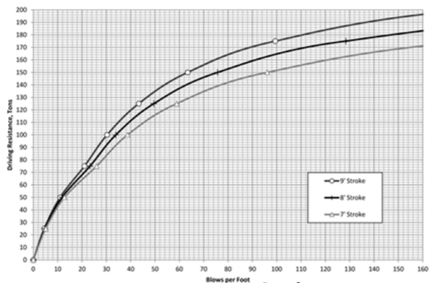
## Step 11 Bearing Graph

| Special Driving Conditions | Stroke (ft) | Monitor at 10 Blow Increments | Do NOT Exceed | Project No: | Design Example DGT32 | Graph No: | XX-XXXX-XX-XXX |
|---|---|---|---|---|---|---|---|
| | | | | Design No: | XXX | Hammer No: | XXXXXX |
| | 7 | ----- | ----- | County: | XXXXX | Cap No: | XXX |
| | 8 | ----- | ----- | Location: | West Abutment | Pile Type: | HP 10x57 |
| Blows per foot | 9 | ----- | ----- | Hammer: | Delmag D19-42 | Pile Length: | 60 |




LRFD Driving Graph

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## Step 12 Construction observation

Observe construction, record driven resistance and resolve any construction issues

- Record hammer stroke and number of blows
- Use the LRFD driving graph to determine driven resistance at EOD
- If resistance at EOD is less than the target resistance, retap pile at 3 days after EOD to verify its performance

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## Track 3, Example 2

Wrap-up

- Blue Book unit nominal resistance
- Resistance factor = f (Limit State, soil category, & construction control)
- Contract pile length, L = 60 feet
- Construction Control: WEAP analysis with 3-day planned retap
- Resistance factor at 7-days after EOD = 0.70
- Target nominal driving resistance = 59 tons at EOD
- Pile setup factor = 1.52 at 3-days after EOD
- Pile retap = 89 tons at 3-days

## Learning Outcomes

A. Follow the geotechnical design and construction steps to implement Iowa LRFD Pile Design.
B. Select a resistance factor to estimate the contract pile length, L.
C. Estimate the target nominal pile driving resistance, $R_{ndr-T}$.
D. Describe how planned retaps are accounted for.

## Questions? – Kam Ng

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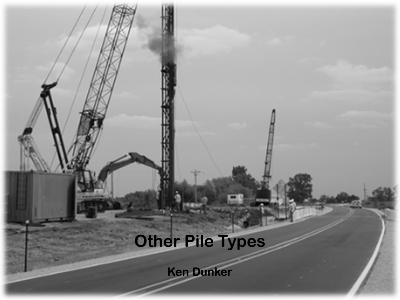


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## Typical Pile Types and Use

| | Steel H | Timber | Prestressed Concrete | Steel Pipe Concrete Fill |
|---|---|---|---|---|
| Integral Abutment | * | * | Do not use. | Do not use. |
| Stub Abutment | * | | | |
| Frame Pier | | | | |
| T-pier | * | | | |
| Pile Bent | * | * Temp. | * | * |

*These cases are detailed on standard plans. Usually simplified structural design information is available in BDM.

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## Design: All Pile Types

Basic LRFD relationship:
$\Sigma\eta\gamma Q \leq \varphi R_n$

- Structural (notation $Q = P$ and $R_n = P_n$)
- Geotechnical
- Driving Target

## Loads: All Pile Types

| | |
|---|---|
| $\gamma P$ | AASHTO except downdrag |
| $\gamma_{DD}$ | 1.0 |
| DD | BDM Table for friction |

Strength Limit State

## Structural: Steel H

| | |
|---|---|
| $P_n$ | SRL-1, SRL-2, & SRL-3, BDM |
| $P_{n\ integral}$ | ≤ SLR-2, BDM |
| $V_n$ | 18 kips plus battered pile component, BDM |
| φ | AASHTO |

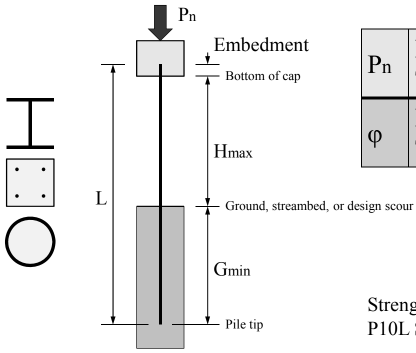
Strength Limit State

## Structural: Timber

| | |
|---|---|
| $P_n$ | 64 kips for 20-30-foot, 80 kips for 35-55-foot, BDM |
| $P_{n\ integral}$ | 64 kips, BDM |
| $V_n$ | 7 kips plus battered pile component, BDM |
| φ | AASHTO |

Strength Limit State

## Structural: Pile Bents, Three Types




| | |
|---|---|
| $P_n$ | BDM Table |
| φ | BDM Table |

Strength Limit State
P10L Standard

## Geotechnical: All Pile Types

Resistance factor varies with soil classification and construction control.

| | |
|---|---|
| $\varphi_{bearing}$ | BDM Table |
| $\varphi_{uplift}$ | BDM Table |
| $R_{n\ end}$ | BDM Table |
| $R_{n\ friction}$ | BDM Table |

Strength Limit State

## Driving Target: Three Pile Types

Resistance factor varies with soil classification and construction control.

| | |
|---|---|
| $\varphi_{TAR}$ | BDM Table |

Strength Limit State

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## Driving Target: Timber Piles

Resistance factor varies with construction control only.

| | |
|---|---|
| $\varphi$ TAR | 0.35, formula control<br>0.40, WEAP control<br>BDM Table Note |

Strength Limit State

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## Summary -1

| Factor | Steel H-pile | Timber pile | Prestressed concrete pile | Concrete-filled pipe pile |
|---|---|---|---|---|
| Structural load factors, $\Upsilon$ | AASHTO 3.4.1 | AASHTO 3.4.1 | AASHTO 3.4.1 | AASHTO 3.4.1 |
| Structural load factor for downdrag, $\Upsilon_{DD}$ | BDM 6.2.4.3<br>$\Upsilon_{DD}$ = 1.0 | BDM 6.2.4.3<br>$\Upsilon_{DD}$ = 1.0 | BDM 6.2.4.3<br>$\Upsilon_{DD}$ = 1.0 | BDM 6.2.4.3<br>$\Upsilon_{DD}$ = 1.0 |
| Downdrag load, DD | BDM Table 6.2.7-2 | BDM Table 6.2.7-2 | BDM Table 6.2.7-2 | BDM Table 6.2.7-2 |
| | | | | |
| Structural resistance factors, $\varphi$ | AASHTO 6.5.4.2 | AASHTO 8.5.2.2 | AASHTO 5.5.4.2.1 | AASHTO 6.5.4.2 |
| Structural bearing resistance factor for pile bent, $\varphi$ | BDM Table 6.6.4.2.1.1,<br>$\varphi$ = [illegible]70 | | BDM Table 6.6.4.2.1.2,<br>$\varphi$ = 0.75 | BDM Table 6.6.4.2.1.3,<br>$\varphi$ = 0.80 |
| Structural bearing resistance, [illegible] | BDM 6.2.6.[illegible]<br>SRL-1, SRL-2, SRL-3 | BDM 6.2.6.3<br>[illegible]0 kips, 100 kips | AASHTO Section 5 | AASHTO 6.9.5, 6.12.2.3 |
| Structural bearing resistance for integral abutment, $R_n$ | BDM Tables 6.5.1.1.1-1 and 6.5.1.1.1-2 | BDM 6.2.6.3<br>6[illegible] kips | | |
| Structural bearing resistance for pile bent, $R_n$ | BDM Table 6.6.4.2.1.1 or P10L | | BDM Table 6.6.4.2.1.2 or P10L | BDM Table 6.6.4.2.1.3 or P10L |
| Structural lateral resistance | BDM 6.2.6.1<br>18 kips | BDM 6.2.6.3<br>7 kips | | |
| | | | | |
| Geotechnical bearing resistance factor, $\varphi$ | BDM Table 6.2.9-1 | BDM Table 6.2.9-1 | BDM Table 6.2.9-1 | BDM Table 6.2.9-1 |
| Geotechnical uplift resistance factor, $\varphi$ | BDM Table 6.2.9-2 | BDM Table 6.2.9-2 | BDM Table 6.2.9-2 | BDM Table 6.2.9-2 |
| Geotechnical end resistance, $R_n$ | BDM Table 6.2.7-1 | BDM Table 6.2.7-1 | BDM Table 6.2.7-1 | BDM Table 6.2.7-1 |
| Geotechnical friction resistance, $R_n$ | BDM Table 6.2.7-2 | BDM Table 6.2.7-2 | BDM Table 6.2.7-2 | BDM Table 6.2.7-2 |
| | | | | |
| Driving resistance factor, $\varphi_{TAR}$ | BDM Table 6.2.9-3<br>Fig 6.2.10 | BDM Table 6.2.9-3<br>0.35 or 0.40 | BDM Table 6.2.9-3<br>Fig 6.2.10 | BDM Table 6.2.9-3<br>Fig 6.2.10 |

See Sheet in Notes

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## Summary - 2

- Use Bridge Design Manual (BDM) values for typical bridges.
- If no BDM value is available, or for non-typical bridges, use AASHTO LRFD Specifications.

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## Summary Table at the Strength Limit State for Pile Types ~ K. Dunker ~ 15 October 2012

| Factor | Steel H-pile | Timber pile | Prestressed concrete pile | Concrete-filled pipe pile |
|---|---|---|---|---|
| Structural load factors, $\Upsilon$ | AASHTO 3.4.1 | AASHTO 3.4.1 | AASHTO 3.4.1 | AASHTO 3.4.1 |
| Structural load factor for downdrag, $\Upsilon_{DD}$ | BDM 6.2.4.3<br>$\Upsilon_{DD}$ = 1.0 | BDM 6.2.4.3<br>$\Upsilon_{DD}$ = 1.0 | BDM 6.2.4.3<br>$\Upsilon_{DD}$ = 1.0 | BDM 6.2.4.3<br>$\Upsilon_{DD}$ = 1.0 |
| Downdrag load, DD | BDM Table 6.2.7-2 | BDM Table 6.2.7-2 | BDM Table 6.2.7-2 | BDM Table 6.2.7-2 |
| | | | | |
| Structural resistance factors, φ | AASHTO 6.5.4.2 | AASHTO 8.5.2.2 | AASHTO 5.5.4.2.1 | AASHTO 6.5.4.2 |
| Structural bearing resistance factor for pile bent, φ | BDM Table 6.6.4.2.1.1,<br>φ = 0.70 | | BDM Table 6.6.4.2.1.2,<br>φ = 0.75 | BDM Table 6.6.4.2.1.3,<br>φ = 0.80 |
| Structural bearing resistance, $R_n$ | BDM 6.2.6.1<br>SRL-1, SRL-2, SRL-3 | BDM 6.2.6.3<br>80 kips, 100 kips | AASHTO Section 5 | AASHTO 6.9.5, 6.12.2.3 |
| Structural bearing resistance for integral abutment, $R_n$ | BDM Tables 6.5.1.1.1-1 and 6.5.1.1.1-2 | BDM 6.2.6.3<br>64 kips | | |
| Structural bearing resistance for pile bent, $R_n$ | BDM Table 6.6.4.2.1.1 or P10L | | BDM Table 6.6.4.2.1.2 or P10L | BDM Table 6.6.4.2.1.3 or P10L |
| Structural lateral resistance | BDM 6.2.6.1<br>18 kips | BDM 6.2.6.3<br>7 kips | | |
| | | | | |
| Geotechnical bearing resistance factor, φ | BDM Table 6.2.9-1 | BDM Table 6.2.9-1 | BDM Table 6.2.9-1 | BDM Table 6.2.9-1 |
| Geotechnical uplift resistance factor, φ | BDM Table 6.2.9-2 | BDM Table 6.2.9-2 | BDM Table 6.2.9-2 | BDM Table 6.2.9-2 |
| Geotechnical end resistance, $R_n$ | BDM Table 6.2.7-1 | BDM Table 6.2.7-1 | BDM Table 6.2.7-1 | BDM Table 6.2.7-1 |
| Geotechnical friction resistance, $R_n$ | BDM Table 6.2.7-2 and 6.2.7 discussion | BDM Table 6.2.7-2 and 6.2.7 discussion | BDM Table 6.2.7-2 and 6.2.7 discussion | BDM Table 6.2.7-2 and 6.2.7 discussion |
| | | | | |
| Driving resistance factor, $\varphi_{TAR}$ | BDM Table 6.2.9-3<br>Fig 6.2.10 | BDM Table 6.2.9-3<br>0.35 or 0.40 | BDM Table 6.2.9-3<br>Fig 6.2.10 | BDM Table 6.2.9-3<br>Fig 6.2.10 |