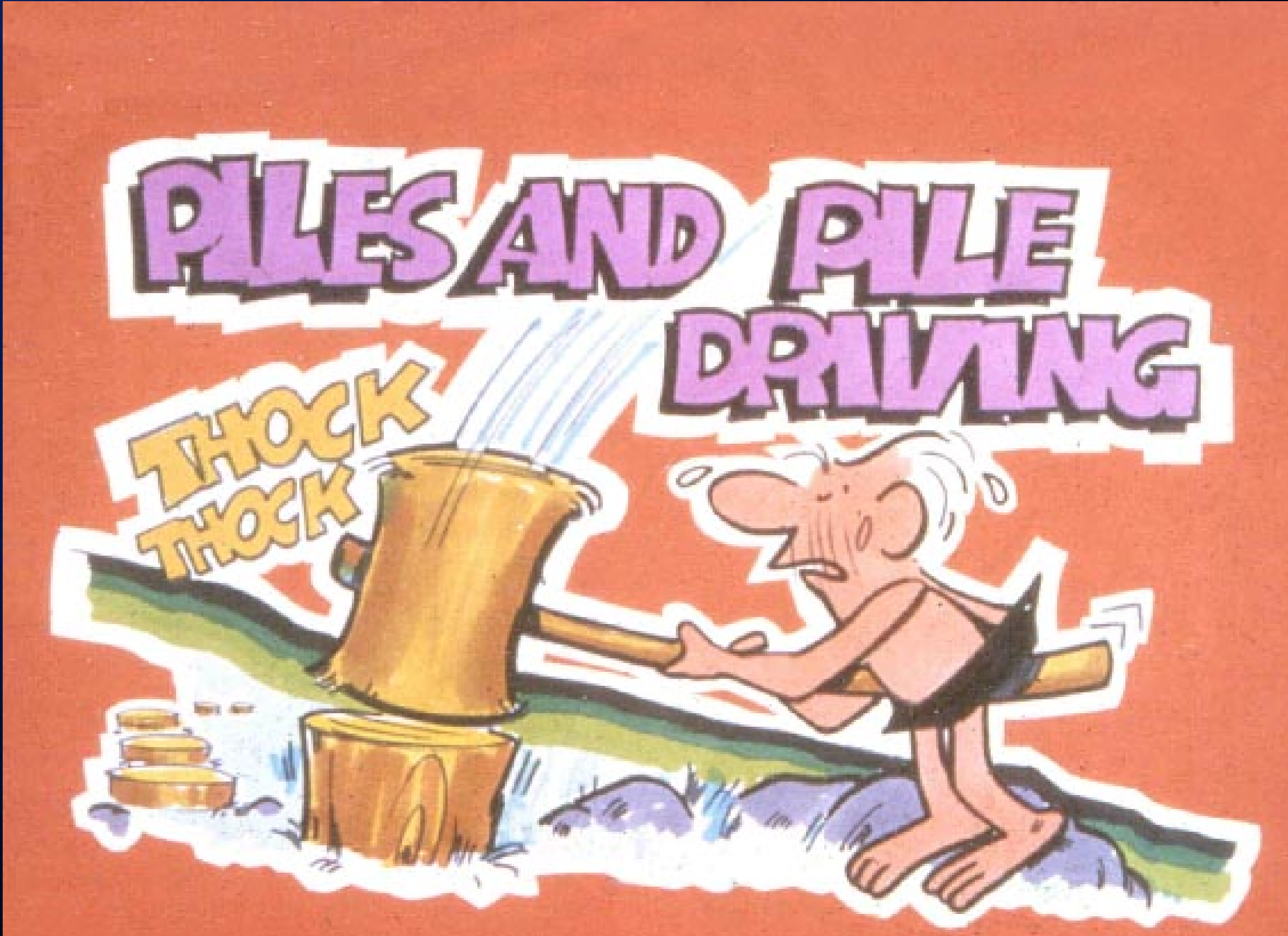
Deep Foundations

Lesson 9 - Topic 2
Construction Monitoring and Quality Assurance
(Section 9.9)

Learning Outcomes

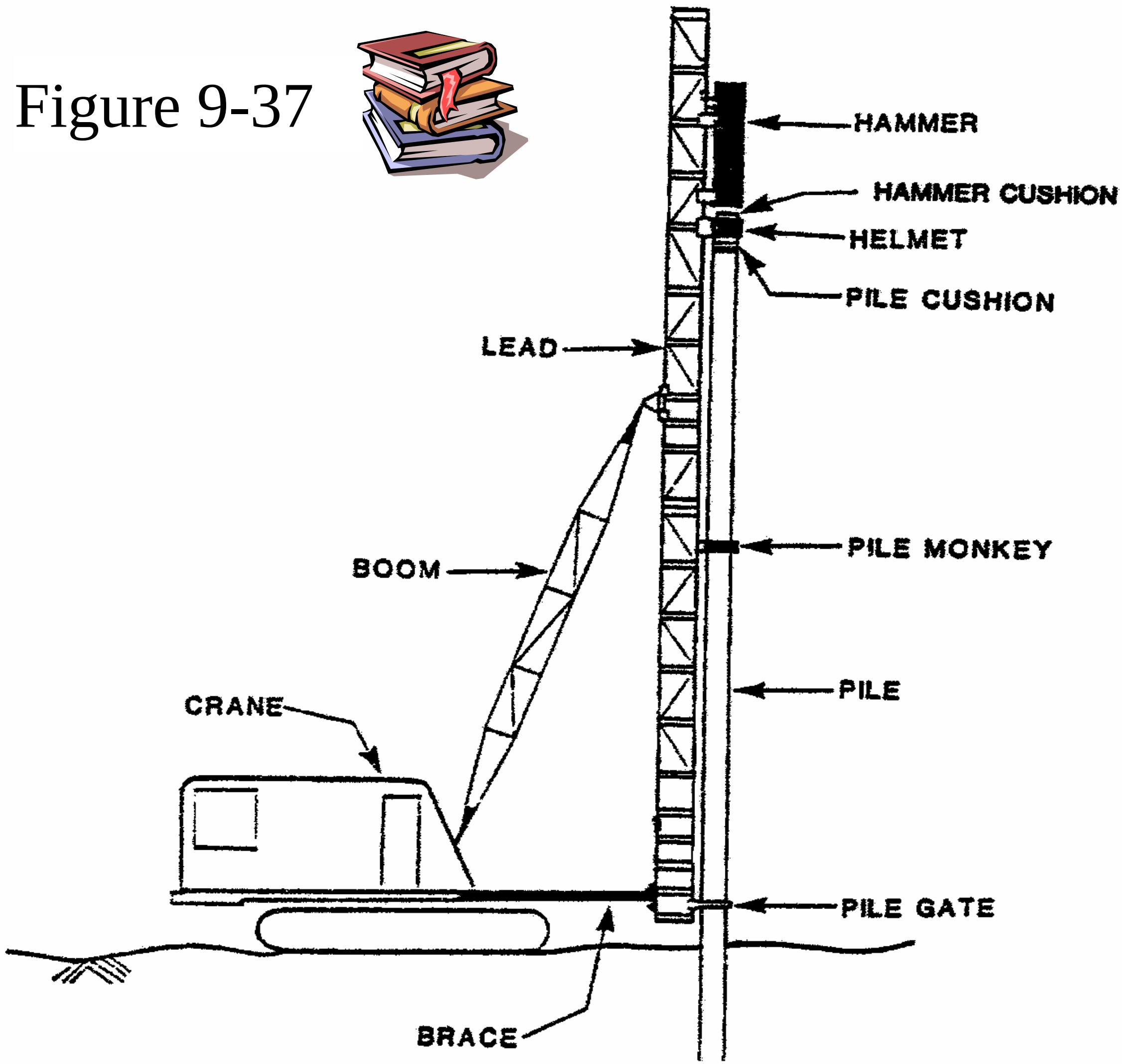
- At the end of this session, the participant will be able to:
  - Recall pile driving equipment
  - Review wave equation analysis
  - Assess pile driveability


PILES AND PILE DRIVING
THOCK
THOCK

Pile Driving Equipment and Operation

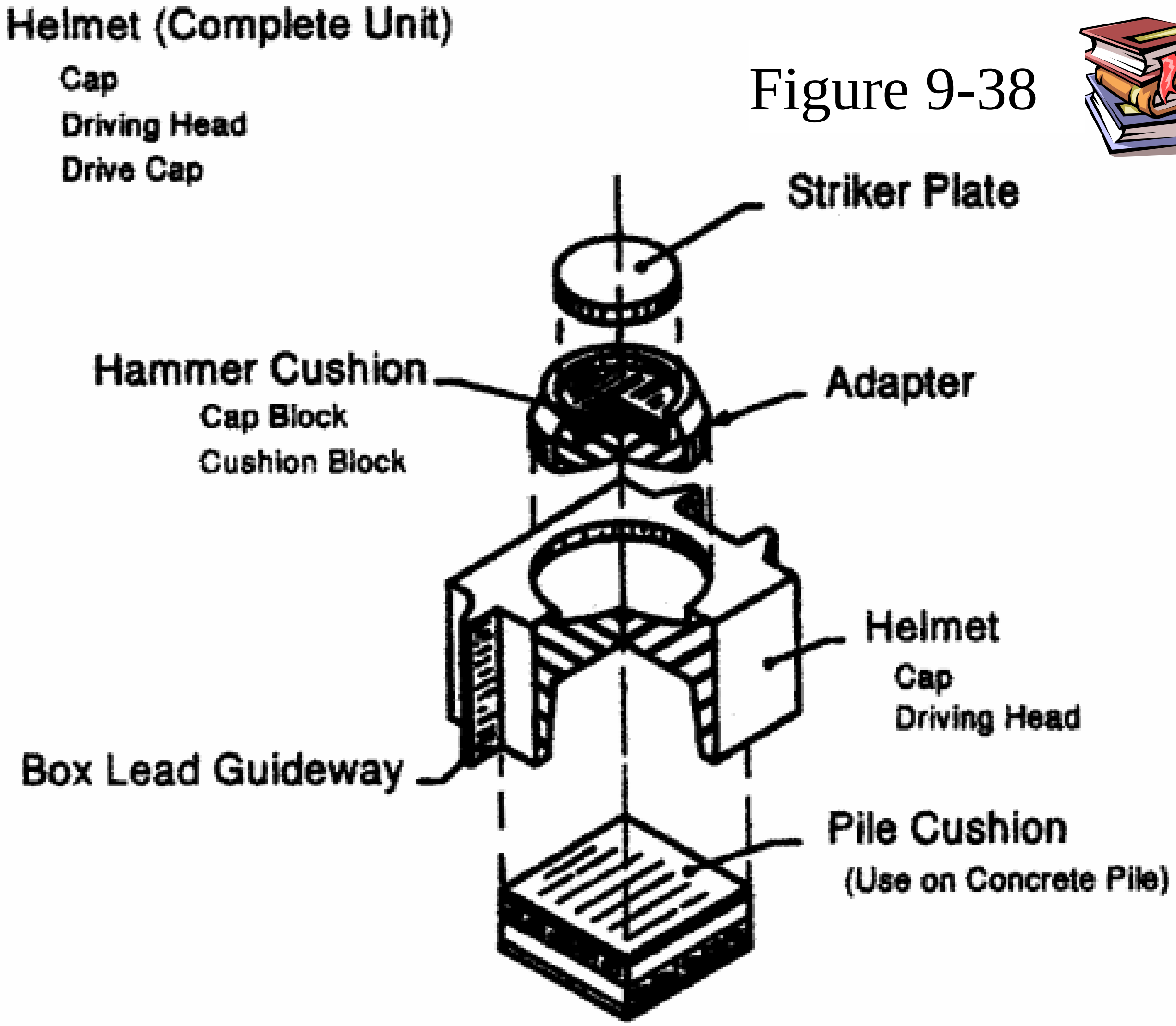
Both the pile and the driving equipment must be sized to permit pile installation to the designed geotechnical soil resistance without damage

Figure 9-37

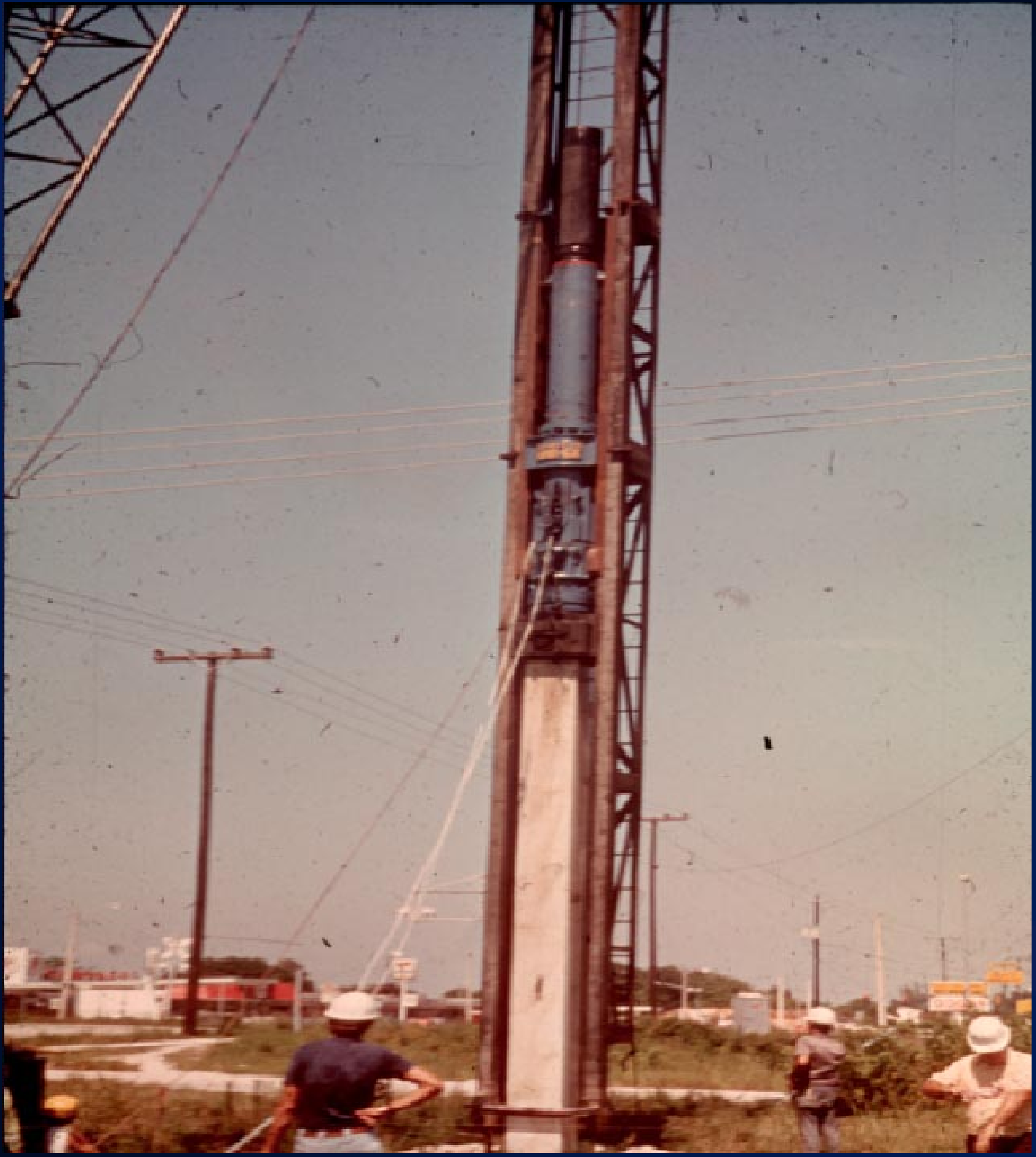


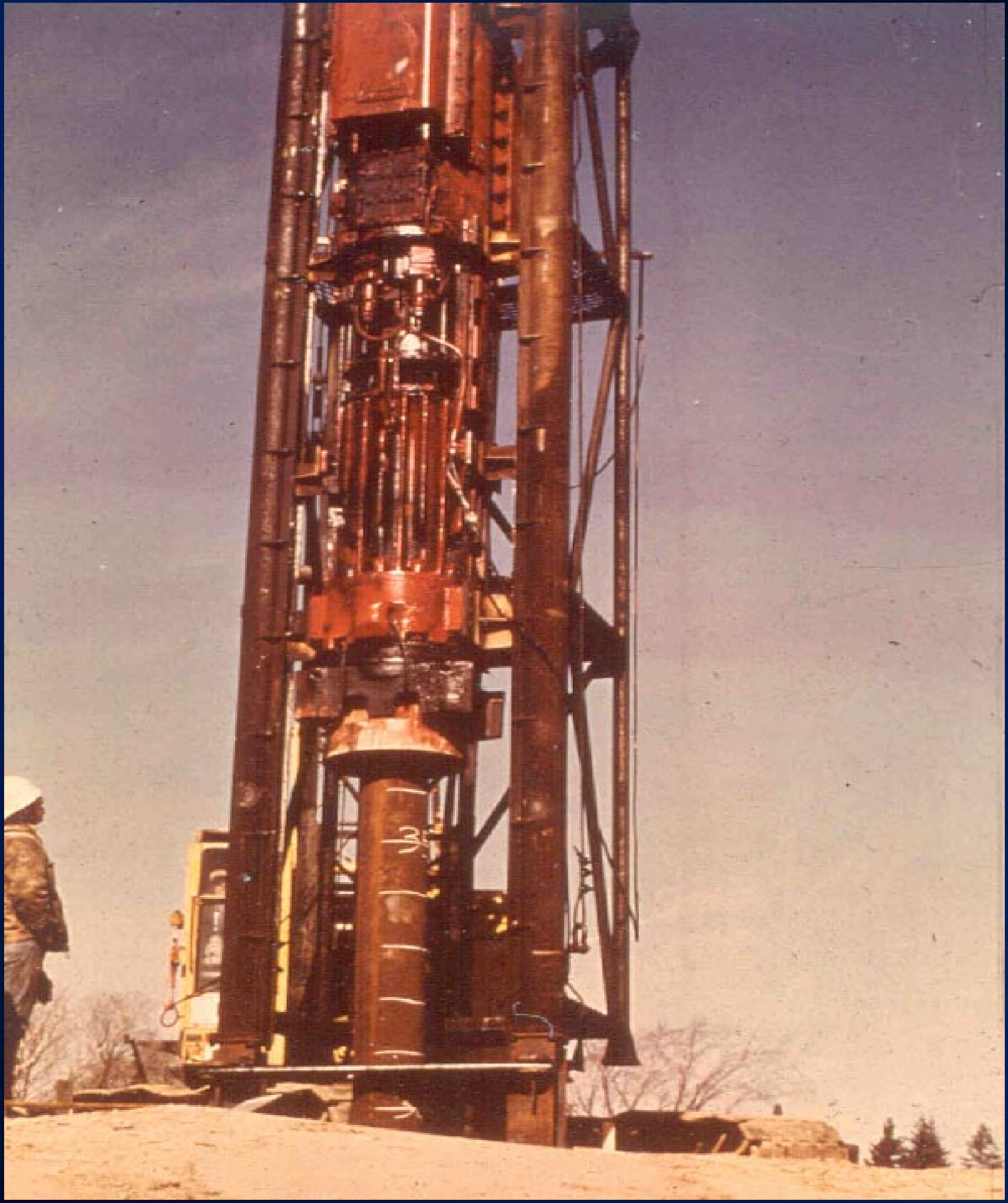
Pile Support System

Figure 9-38



Note: The helmet shown is for nomenclature only. Various sizes and types are available to drive H, pipe, concrete (shown) and timber piles. A system of inserts or adapters is utilized up inside of the helmet to change from size to size and shape to shape.





Driving System Analysis

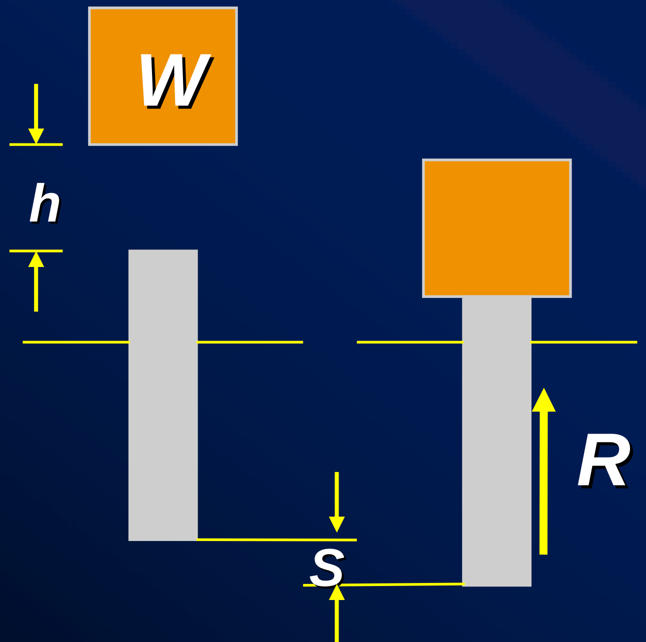
- ***Fundamental pile driving mechanism***
- ***EN approach***
- ***Wave equation approach***

The Fundamental Pile Driving Formula

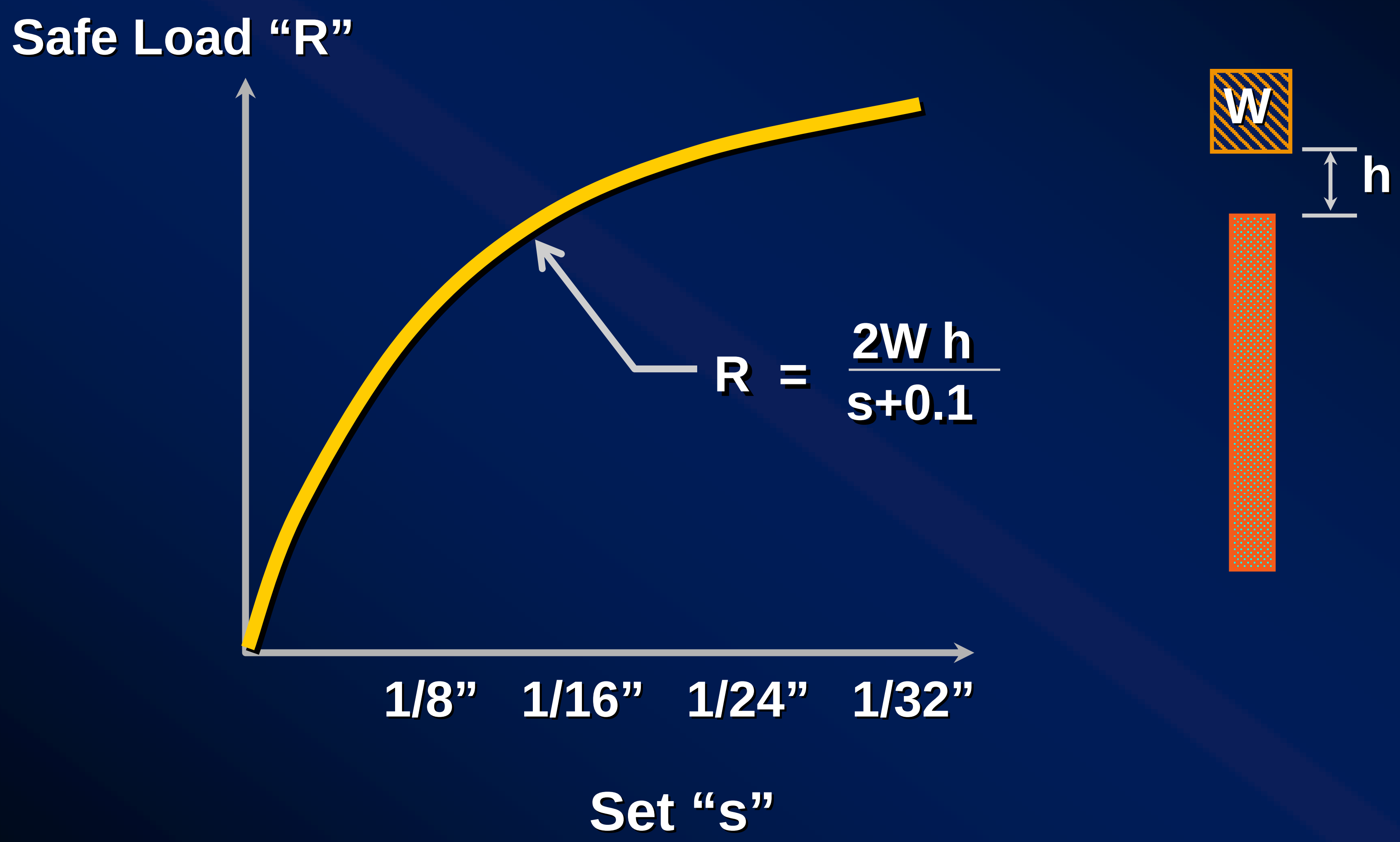
$$Hammer\ Energy = Work\ of\ Soil\ Resistance$$

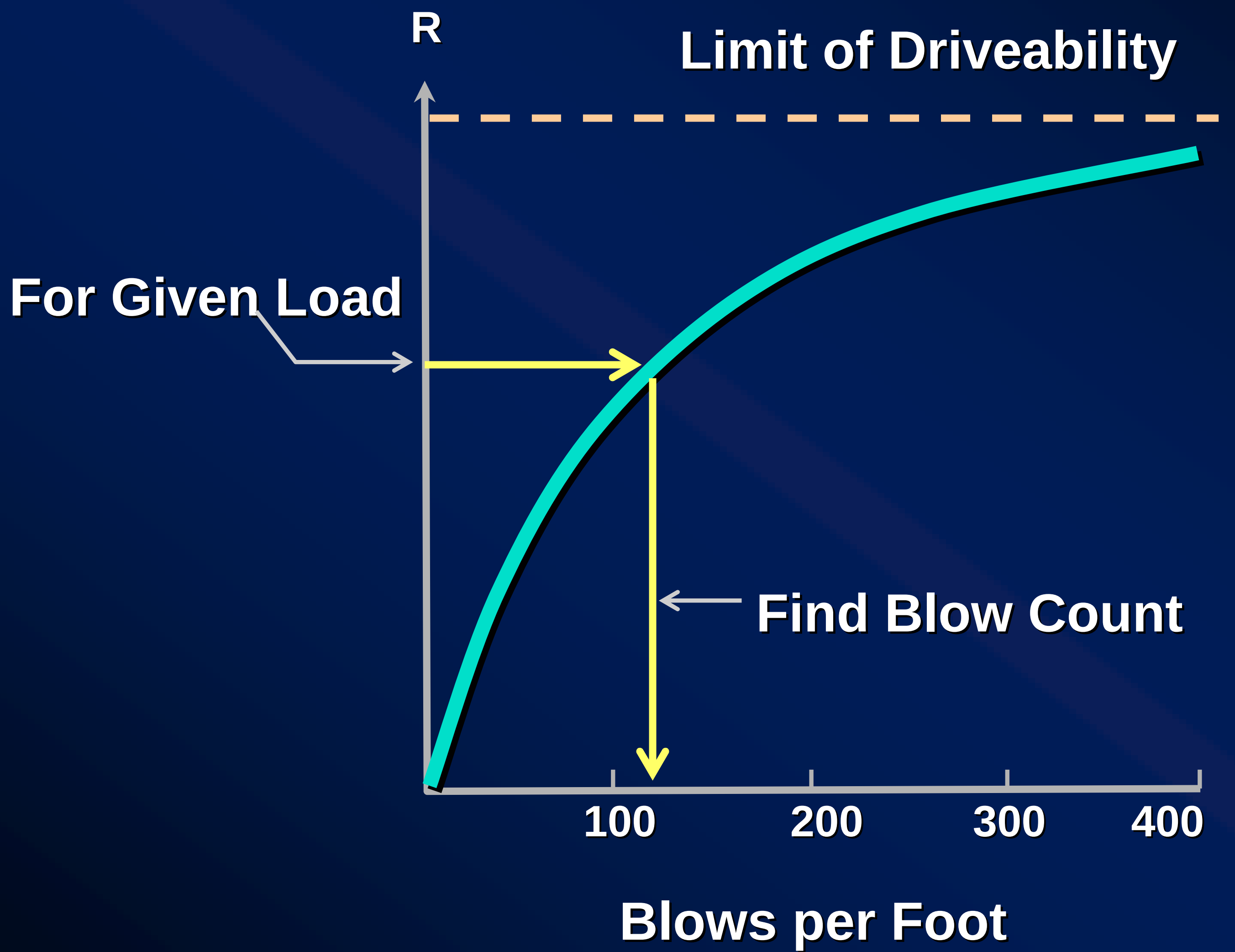
$$W\,h = R\,s$$

$$R = \frac{W\,h}{s}$$



The EN Bearing Graph



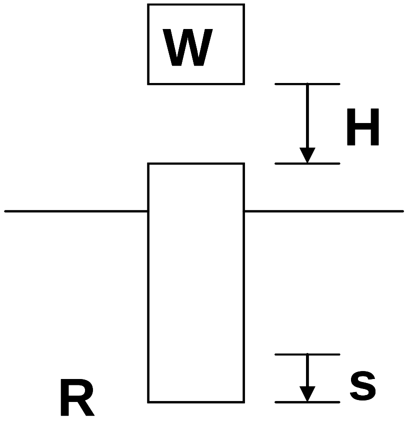

R
Limit of Driveability
For Given Load
Find Blow Count
100
200
300
400
Blows per Foot

Construction Considerations in Design

- ***Intelligent preparation of plan and specifications can only be done by one who understands the construction operation as well as structural design concepts***

EN Formula Factor of Safety

To find F.S. between P and R, revise ENR to be dimensionally correct and compare the resulting equation for P with R



$$R = \frac{WH}{s}$$

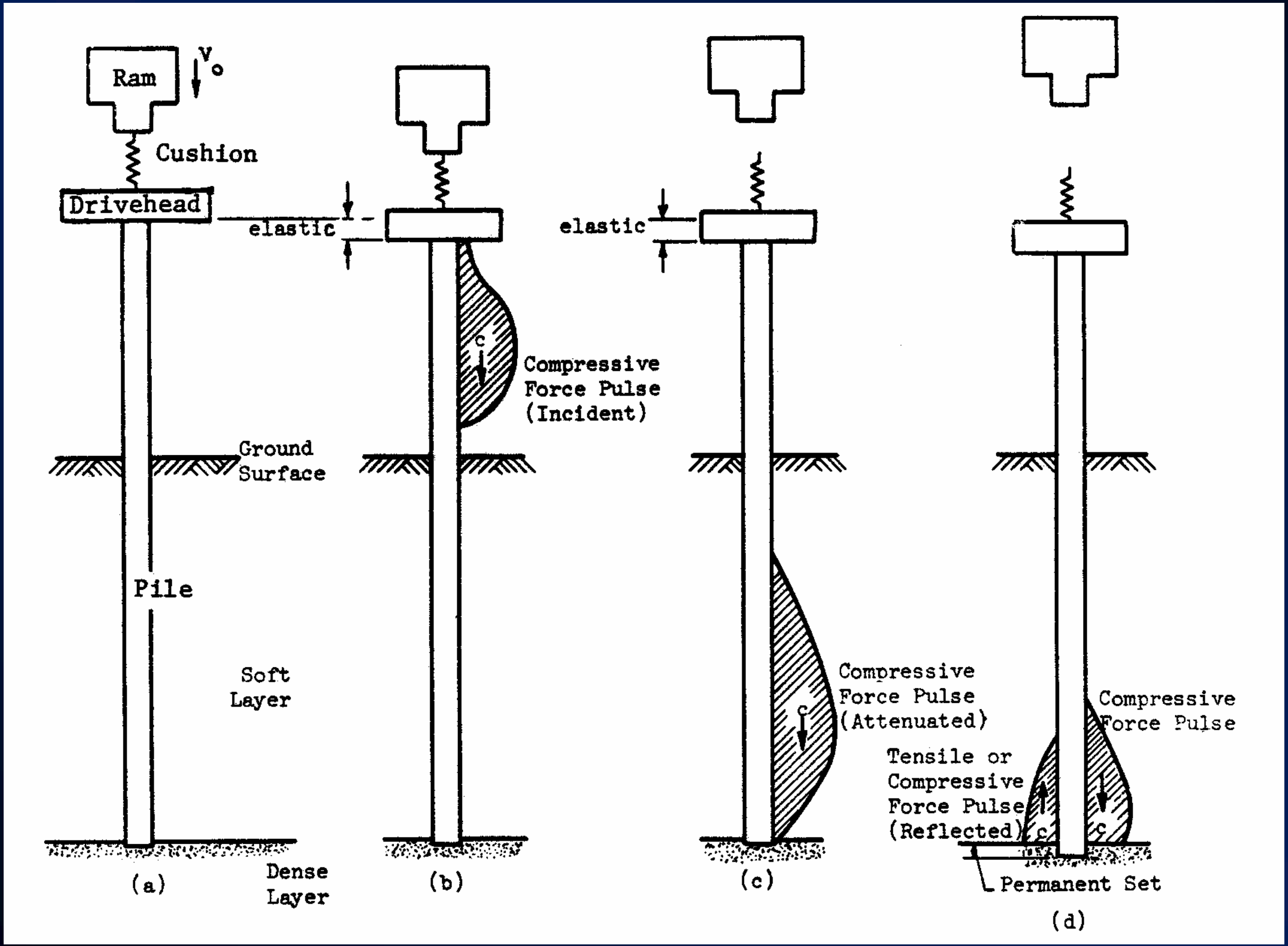
$$P = \frac{2\,W^{\#}H(ft)}{s(in) + 0.1}$$

$$P = \frac{2WH}{s + 0.1}(1/12) = \frac{WH}{6s}$$

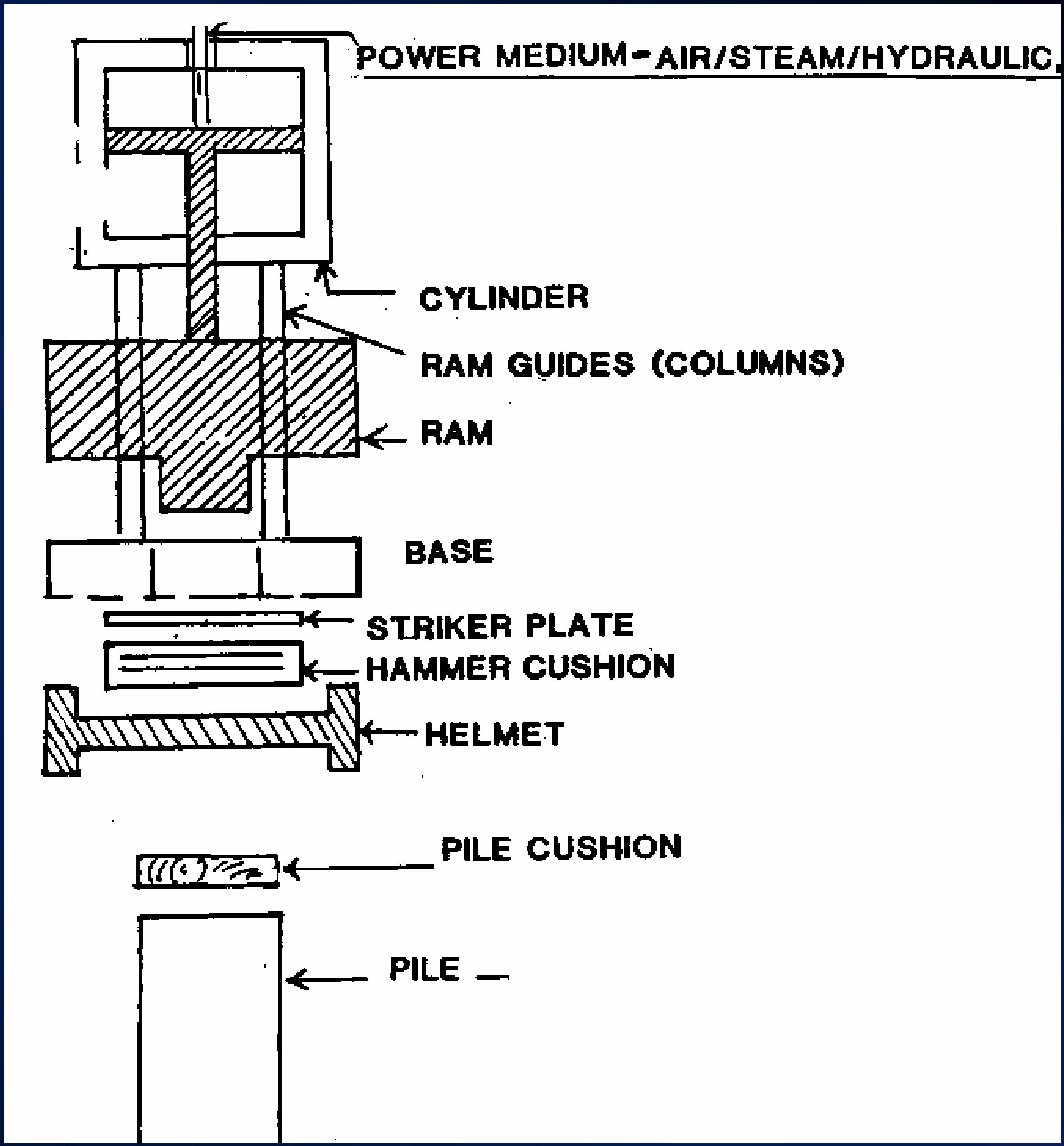
$$R = 6P$$

Safety Factor = 6

Dynamic Analysis of Pile Driving



Important Driving System Properties



Hammer

- Impact hammers and vibratory hammers
  - Numerous manufacturers
  - Variations in power source, configurations and rated energy
- Mechanical efficiency determines percentage rated energy transmitted to the pile
  - Typical values are 50% for air-steam, 70% for diesel and 90% for hydraulic
- Force wave shape characteristics are different for different hammer types
  - Affects pile stress and pile penetration

Pile and Appurtenances (Cushions, Helmets, etc.)

- ***Stiffness of appurtenances (e.g., hammer cushion) = AE/t***
  - *Major effect on blow count and stress transfer to the pile*
  - *Must not degrade during driving resulting in decreasing blow count and increasing pile stress*
- ***Cross-sectional area of pile is major factor in driveability***
  - *The hammer energy is absorbed in strain rather than performing work (i.e., penetrating pile) for long piles with small c/s area*

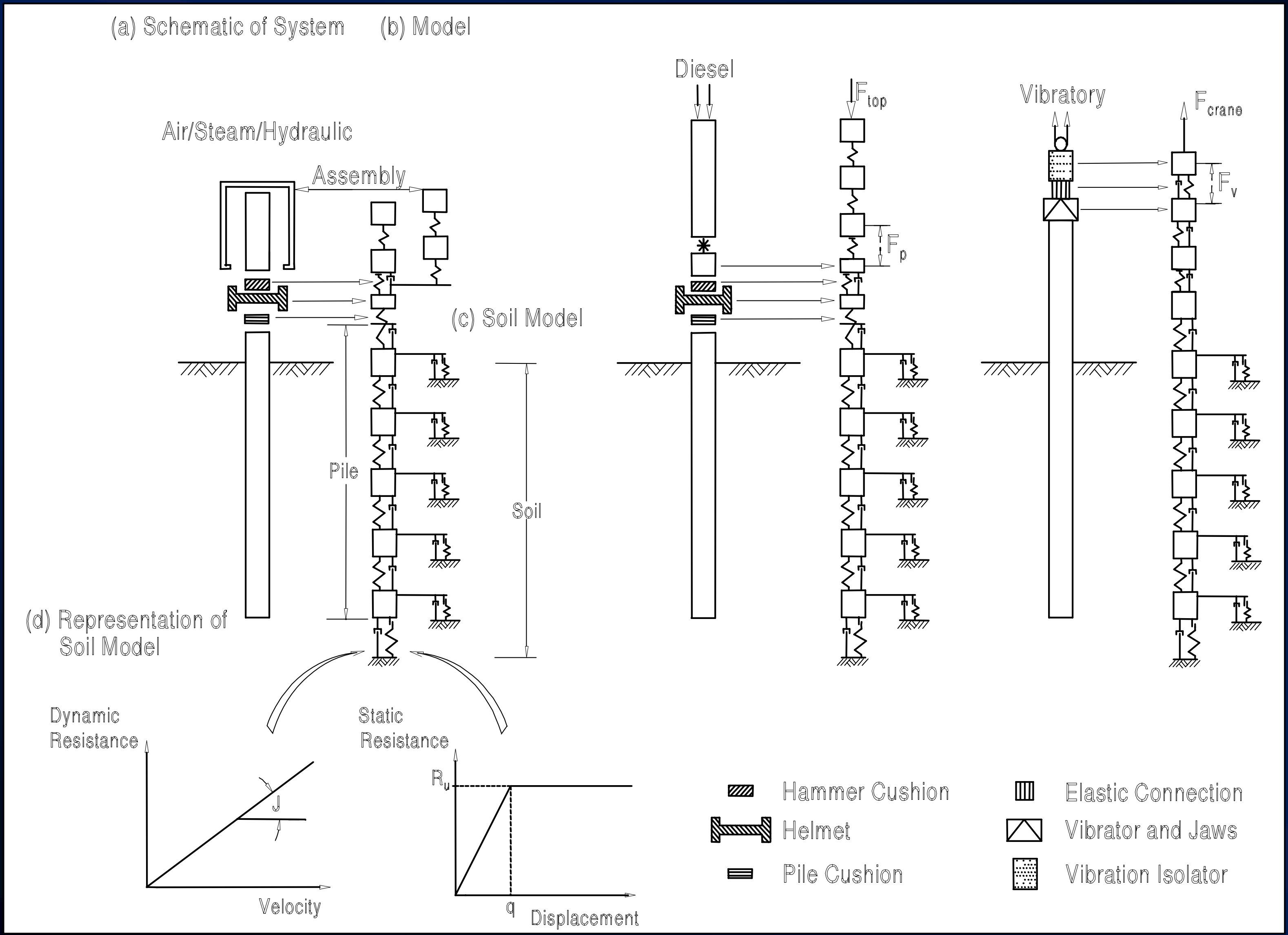
Soil

- Setup
- Relaxation

- Important soil properties
  - Quake
  - Damping

- Total soil resistance to be overcome during driving to estimated length

Wave Equation Methodology



Analysis Procedure

1. Soil model and ultimate capacity assumed.

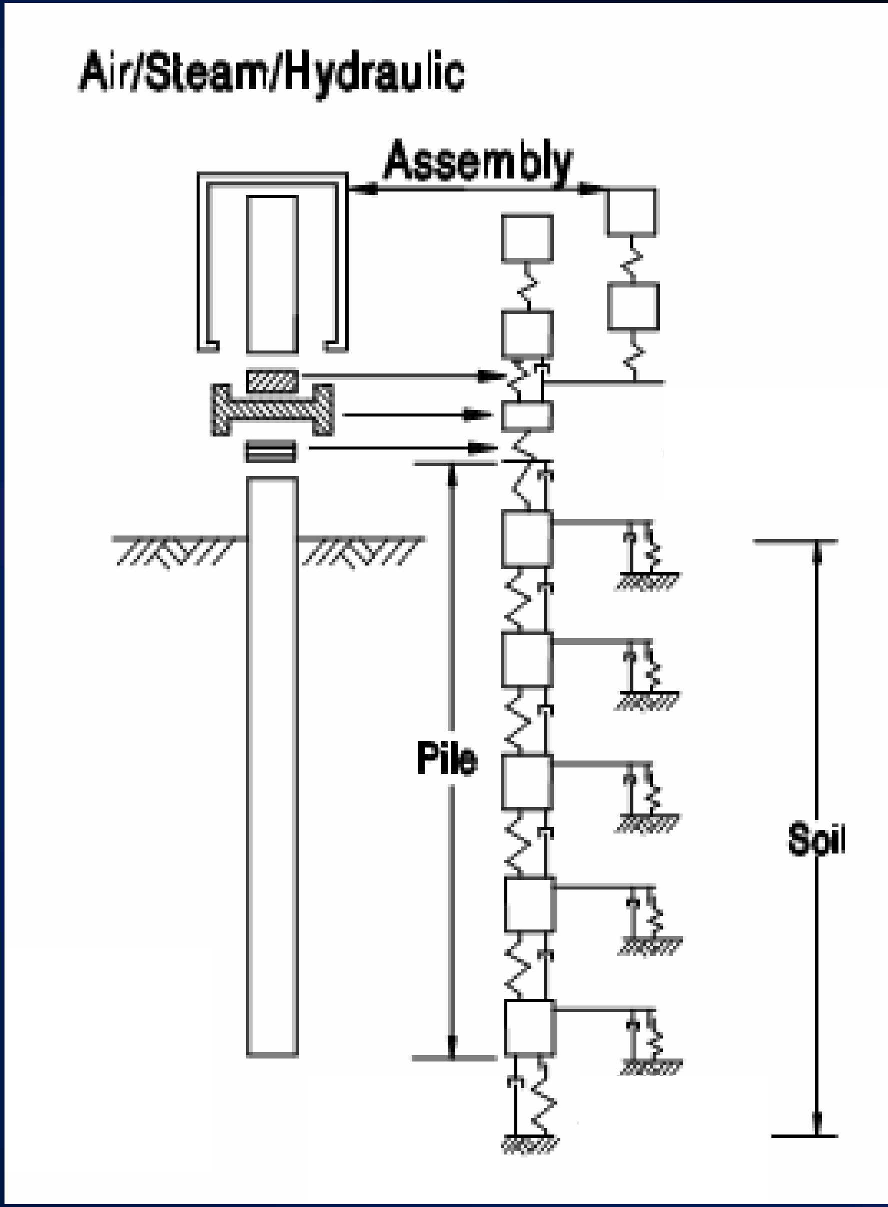
2. Analysis set in motion by selecting hammer efficiency.

3. Impact velocity of hammer mass elements calculated from efficiency.

4. For each time step, the acceleration, velocity, force, and displacement for each element and the pile toe are calculated based on force equilibrium (F = ma).

5. Process continues until pile toe rebounds.

6. Final set calculated for capacity.



Wave Equation Applications

- ***Develop driving criterion***
  Blow count for a required ultimate capacity
  blow count for capacity as a function of energy/stroke

- ***Check driveability***
  Blow count vs. Penetration depth
  Driving stresses vs penetration depth

- ***Determine optimal driving equipment***
  Driving time

- ***Refined matching analysis***
  Adjust input parameters to fit dynamic measurements

IMPORTANT NOTES

- ***The wave equation analysis CANNOT determine pile length***
- ***Does the method determine capacity?***

Input to Wave Equation Analysis

- ***Hammer***
  - *Model*
  - *Stroke and Stroke Control*
  - *Any Modifications*

- ***Driving System***
  - *Helmet Weight (including Striker Plate & Cushions)*
  - *Hammer Cushion Material (E, A, t, e_r)*
  - *Pile Cushion Material (E, A, t, e_r)*

Input to Wave Equation Analysis

- ***Pile***
  - *Length,*
  - *Cross Sectional Area*
  - *Taper or Other Non-uniformities*
  - *Specific Weight*
  - *Splice Details*
  - *Design Load*
  - *Ultimate Capacity*
  - *Pile Toe Protection*

Input to Wave Equation Analysis

- ***Soil***
  - *Boring Locations with Elevations*
  - *Soil Descriptions*
  - *N-values or Other Strength Parameters vs Depth*
  - *Elevation of Excavation*
  - *Elevation of Pile Cut-off*
  - *Elevation of Water Table*
  - *Scour Depth or Other Later Excavations*

Pile Driving and Equipment Data Form

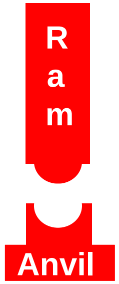
Contract No.: ____________________ Structure Name and/or No.: ____________________

Project: ____________________ ____________________

____________________ Pile Driving Contractor or Subcontractor: ____________________

County: ____________________ ____________________

(Piles driven by)



Hammer

Manufacturer: ____________ Model No.: ____________

Hammer Type: ____________ Serial No.: ____________

Manufacturers Maximum Rated Energy: ____________ (ft-lbs)

Stroke at Maximum Rated Energy: ____________ (ft)

Range in Operating Energy: ____________ to ____________ (ft-lbs)

Range in Operating Stroke: ____________ to ____________ (ft)

Ram Weight: ____________ (kips)

Modifications: ____________________

____

____

Striker Plate

Weight: ____________ (kips) Diameter: ____________ (in)

Thickness: ____________ (in)

Hammer Cushion

Material #1

Name: ____________

Area: ____________ (in^2)

Thickness/Plate: ____________ (in)

No. of Plates: ____________

Material #2 (for Composite Cushion)

Name: ____________

Area: ____________ (in^2)

Thickness/Plate: ____________ (in)

No. of Plates: ____________

Total Thickness of Hammer Cushion: ____________

Helmet (Drive Head)

Weight: ____________ (kips)

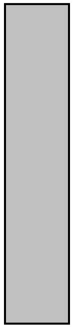
Pile Cushion

Material: ____________________

Area: ____________ (in^2) Thickness/Sheet: ____________ (in)

No. of Sheets: ____________

Total Thickness of Pile Cushion: ____________ (in)



Pile

Pile Type: ____________________

Wall Thickness: ____________ (in) Taper: ____________

Cross Sectional Area: ____________ (in^2) Weight/Ft: ____________

Ordered Length: ____________ (ft)

Design Load: ____________ (kips)

Ultimate Pile Capacity: ____________ (kips)

Description of Splice: ____________________

____

Driving Shoe/Closure Plate Description: ____________________

____

Submitted By: ____________ Date: ____________

Telephone No.: ____________ Fax No.: ____________

Output from Wave Equation Analysis

- ***For a given hammer, driving system, pile and soil model combination, the WEA output includes the following:***
  - *Predicted blow count*
  - *Pile stresses*
  - *Delivered hammer energy*

Example Output from Wave Equation Analysis

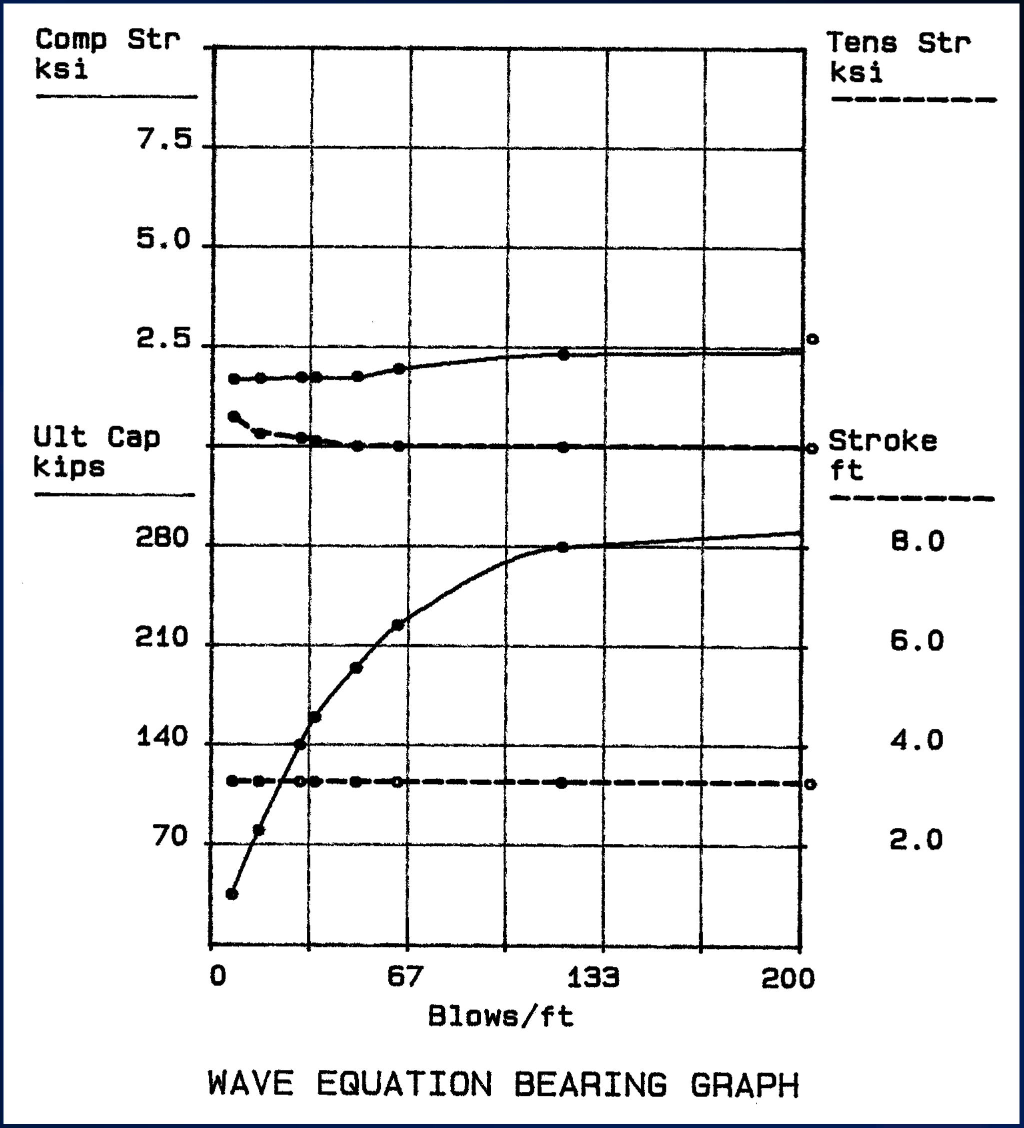
- *Output is usually plotted for interpretation*

WAVE EQUATION SUMMARY

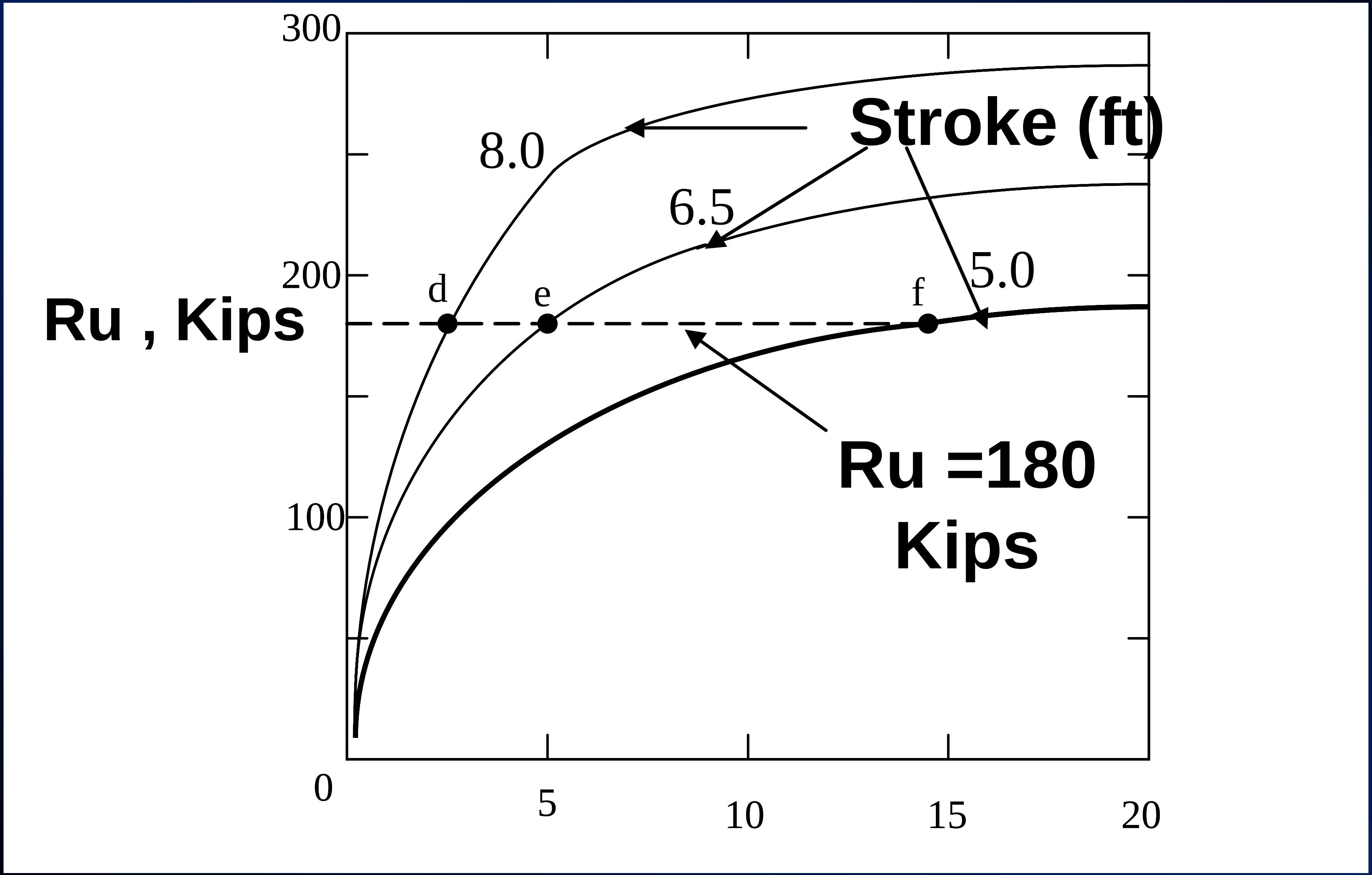
R_{ult} Kips	Blow Count BPF	Stroke Ft.	Tensile Stress Ksi	Compressive Stress Ksi	Transfer Energy Ft-Kip
35.0	7	3.27	-0.73	1.68	13.6
80.0	16	3.27	-0.32	1.71	13.6
140.0	30	3.27	-0.20	1.73	13.0
160.0	35	3.27	-0.14	1.73	13.0
195.0	49	3.27	-0.00	1.75	12.8
225.0	63	3.27	0.0	1.96	12.7
280.0	119	3.27	0.0	2.34	12.6
350.0	841	3.27	0.0	2.75	12.5

Interpretation of WEA Output

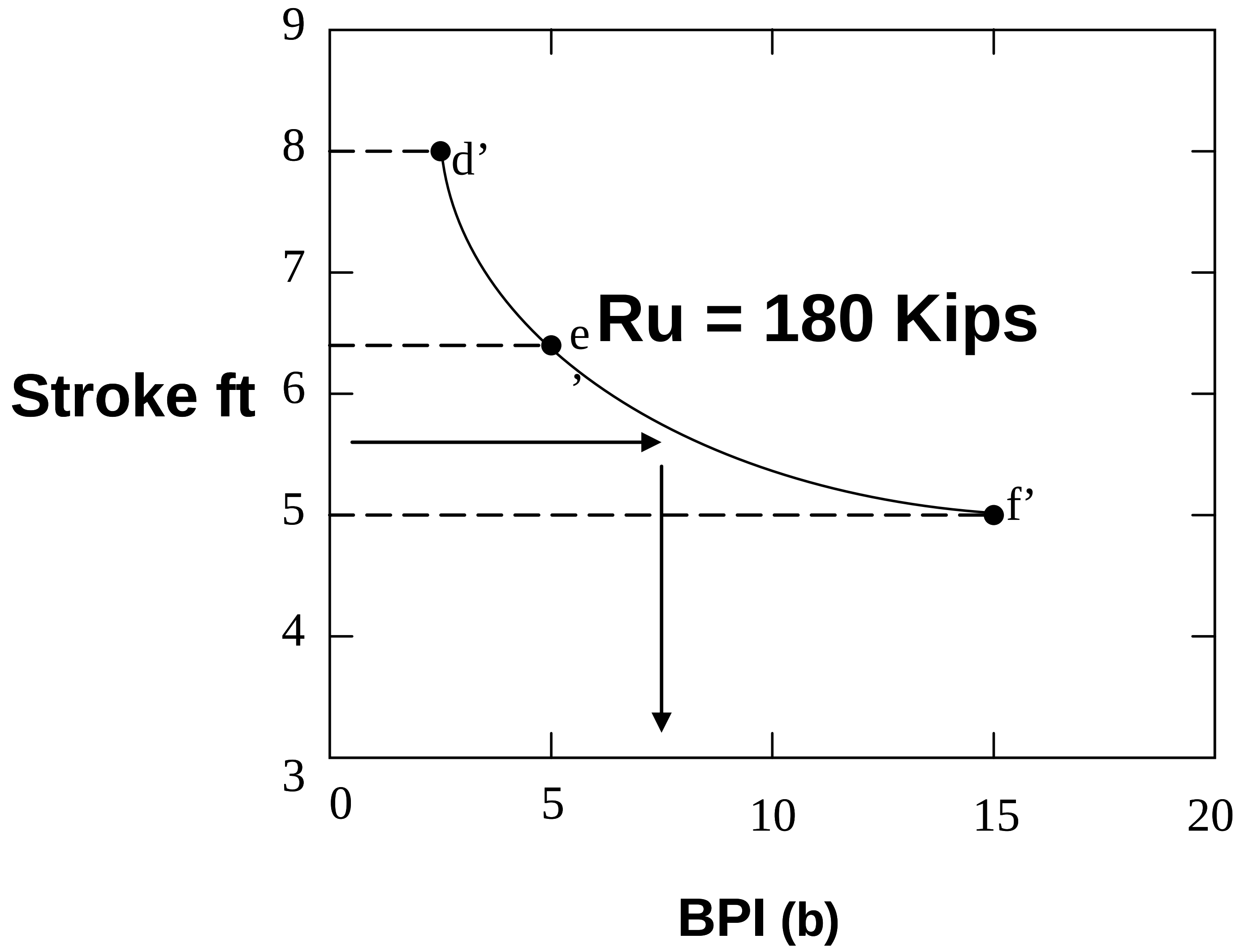
- Output is usually plotted for interpretation
- Following plots are usually created
  - Blow count vs resistance
  - Blow count vs stress
- Bearing Graph
- Constant stroke for air-steam hammer



Diesel Hammer at Constant Stroke



Variable Stroke – Diesel Hammer



Driving Stresses

- In almost all cases, the highest stress levels in a pile occur during pile driving
- High driving stresses are necessary to achieve pile penetration
- WEA can predict driving stresses
- Compare predicted stresses to safe stress levels
- Table 9-10 

General Criteria for Pile Driveability

- Acceptable driving stresses
  - Table 9-10
- Hammer blows between 30 to 144 bpf for friction piles and higher blows of short duration for end bearing piles

Example 9-4

Example: Determine If The 14" Square Concrete Pile Can Be Driven To A Driving Capacity Of 225 Kips By Using The Wave Equation Output Summary. Assume The Concrete Compressive Strength Is 4000 psi And The Pile Prestress Force Is 700 psi.

WAVE EQUATION OUTPUT SUMMARY

R_{ult} Kips	Blow Count BPF	Stroke Ft.	Tensile Stress Ksi	Compressive Stress Ksi
35.0	7	3.27	-0.73	1.68
80.0	16	3.27	-0.32	1.71
140.0	30	3.27	-0.20	1.73
160.0	35	3.27	-0.14	1.73
195.0	49	3.27	-0.00	1.75
225.0	63	3.27	0.0	1.96
280.0	119	3.27	0.0	2.34
350.0	841	3.27	0.0	2.75

Solution

- Acceptable driveability depends on achieving the hammer blows between 30 and 144 bpf as the driving resistance and allowable compressive and tensile stresses are not exceeded
- At R_{ult} = 225 kips, blow count = 63 bpf
  - Between 30 and 144 bpf
  - Okay

Solution

- ***Based on Table 9-10***
- ***Allowable compressive stress***

$$0.85\, f'_c - f_{pe} = 3400 - 700 = 2700 \text{ psi}$$

- ***Maximum compressive stress from WEA = 1.96 ksi = 1,960 psi < 2,700 psi***
  - *Okay*

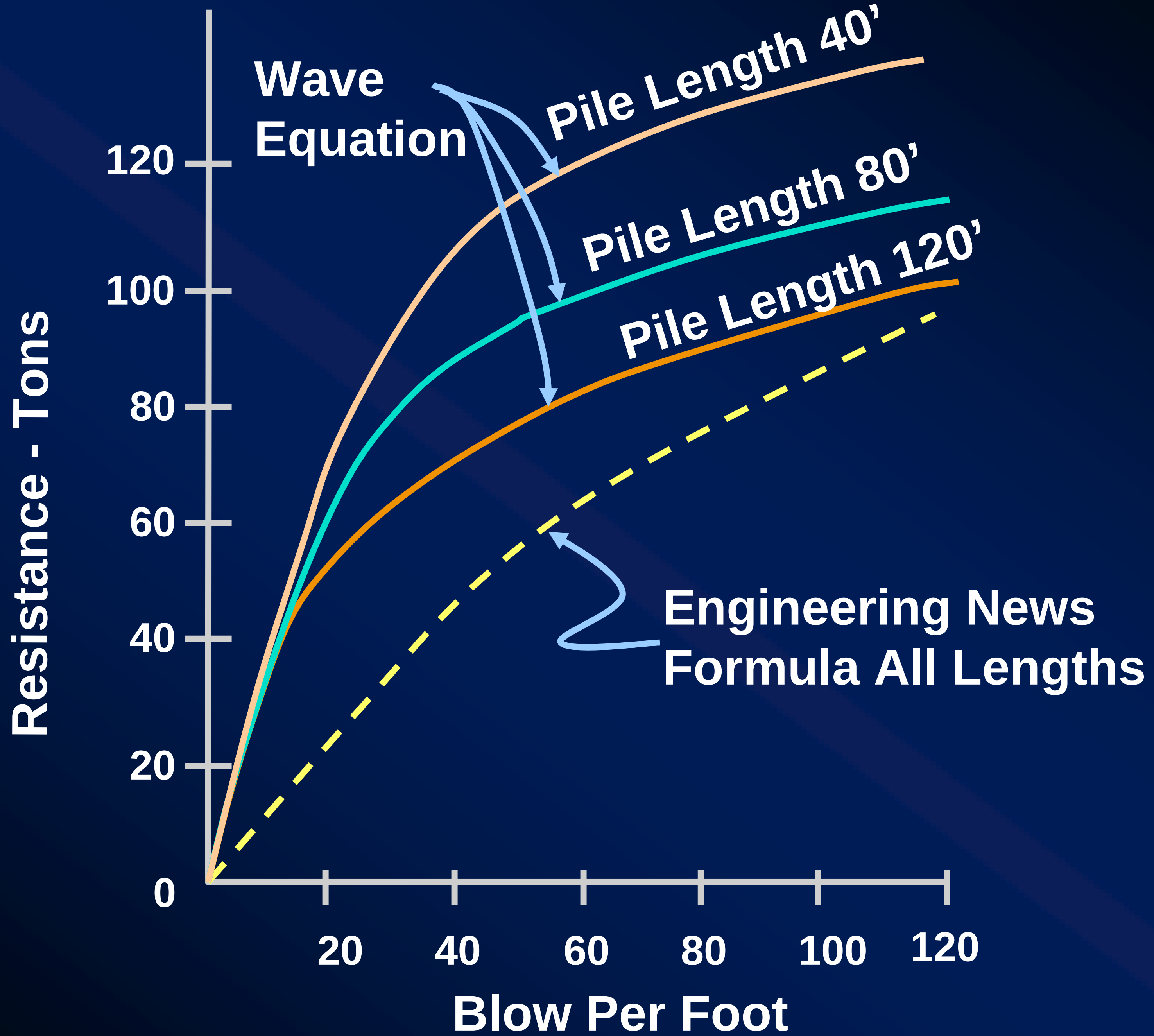
Solution

- *Based on Table 9-10*
- *Allowable tensile stress*

$$3\,(f'_c)^{1/2} + f_{pe} = 190 + 760 = 890 \text{ psi}$$

- *Maximum tensile stress from WEA = 0.730 ksi = 730 psi < 890 psi*
  - *Okay*

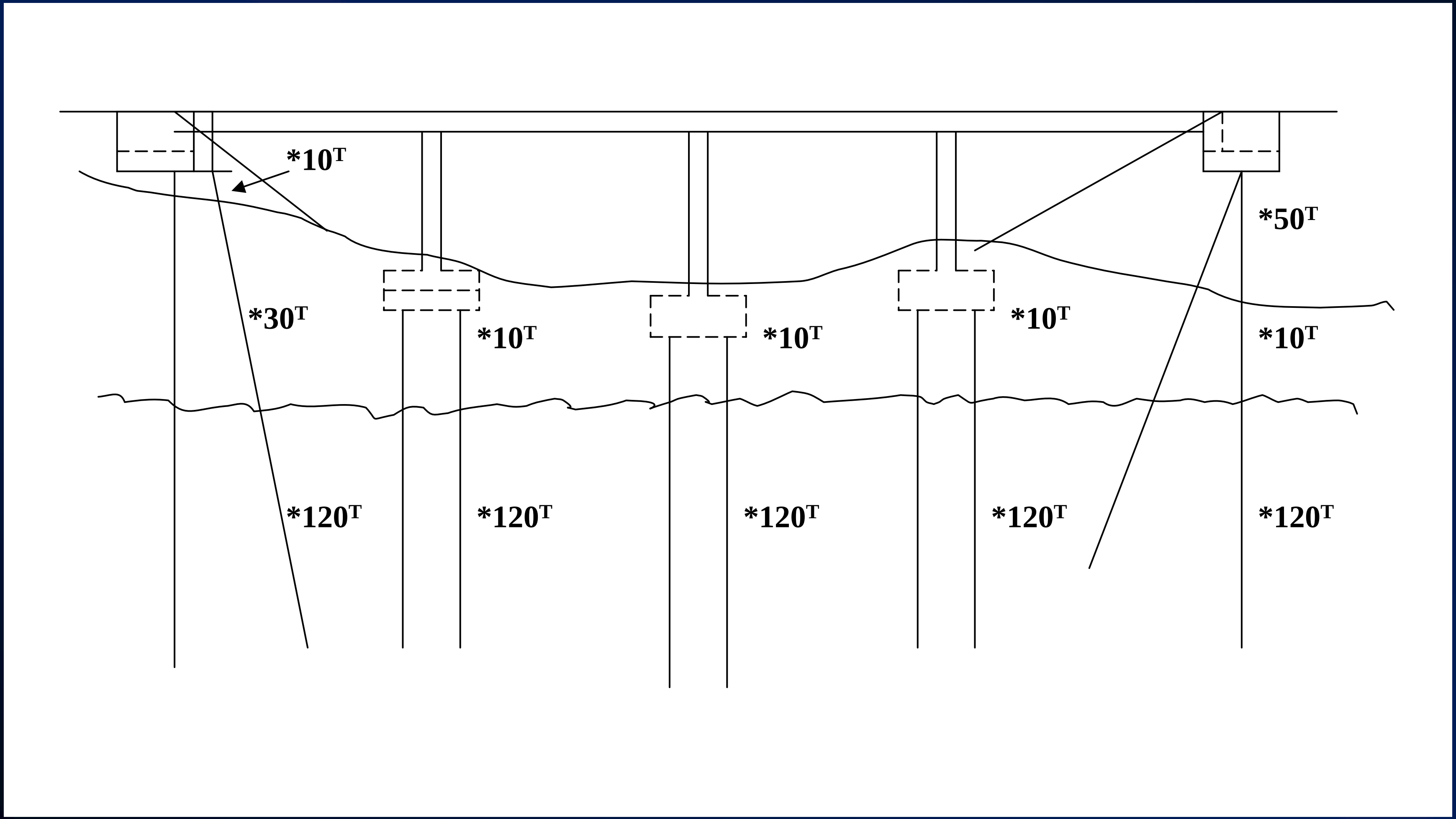
- ***Analyzed driving system is approved***


Wave
Equation
Pile Length 40’
Pile Length 80’
Pile Length 120’
Engineering News
Formula All Lengths
Resistance - Tons
0
20
40
60
80
100
120
20
40
60
80
100
120
Blow Per Foot

Student Exercise 8

- ***The soil profile shows the calculated driving resistance in each soil layer at each footing for the proposed 12” diameter steel pipe piles (fy=36 ksi). Using maximum driving resistance at any footing, find the anticipated maxiumum driving stress and blow count from wave equation summaries shown for 3 pile sizes. Compare these values to the recommended friction piles values for blow count and driving stress to determine minimum acceptable pile wall thickness for the pipe piles at this site***

Student Exercise 8
Soil Profile



Student Exercise 8 - Summaries

GRLWEAP S & F STUDENT EXERCISE 0.250″ WALL THICKNESS

R_{ult} Kips	Bl Ct bpf	Stroke (eq. Ft)	Min str. ksi	Max str. ksi	Enthru kip-ft
260.0	35.3	3.25	-0.85	36.34	14.8
360.0	111.8	3.25	-0.98	42.07	13.8

GRLWEAP S & F STUDENT EXERCISE 0.312″ WALL THICKNESS

R_{ult} Kips	Bl Ct bpf	Stroke (eq. Ft)	Min str. ksi	Max str. ksi	Enthru kip-ft
260.0	31.8	3.25	-0.68	28.58	15.1
360.0	72.9	3.25	-0.70	35.98	14.2

GRLWEAP S & F STUDENT EXERCISE 0.375″ WALL THICKNESS

R_{ult} Kips	Bl Ct bpf	Stroke (eq. Ft)	Min str. ksi	Max str. ksi	Enthru kip-ft
260.0	30.2	3.25	-0.45	24.67	15.2
360.0	58.8	3.25	-0.95	30.47	14.5

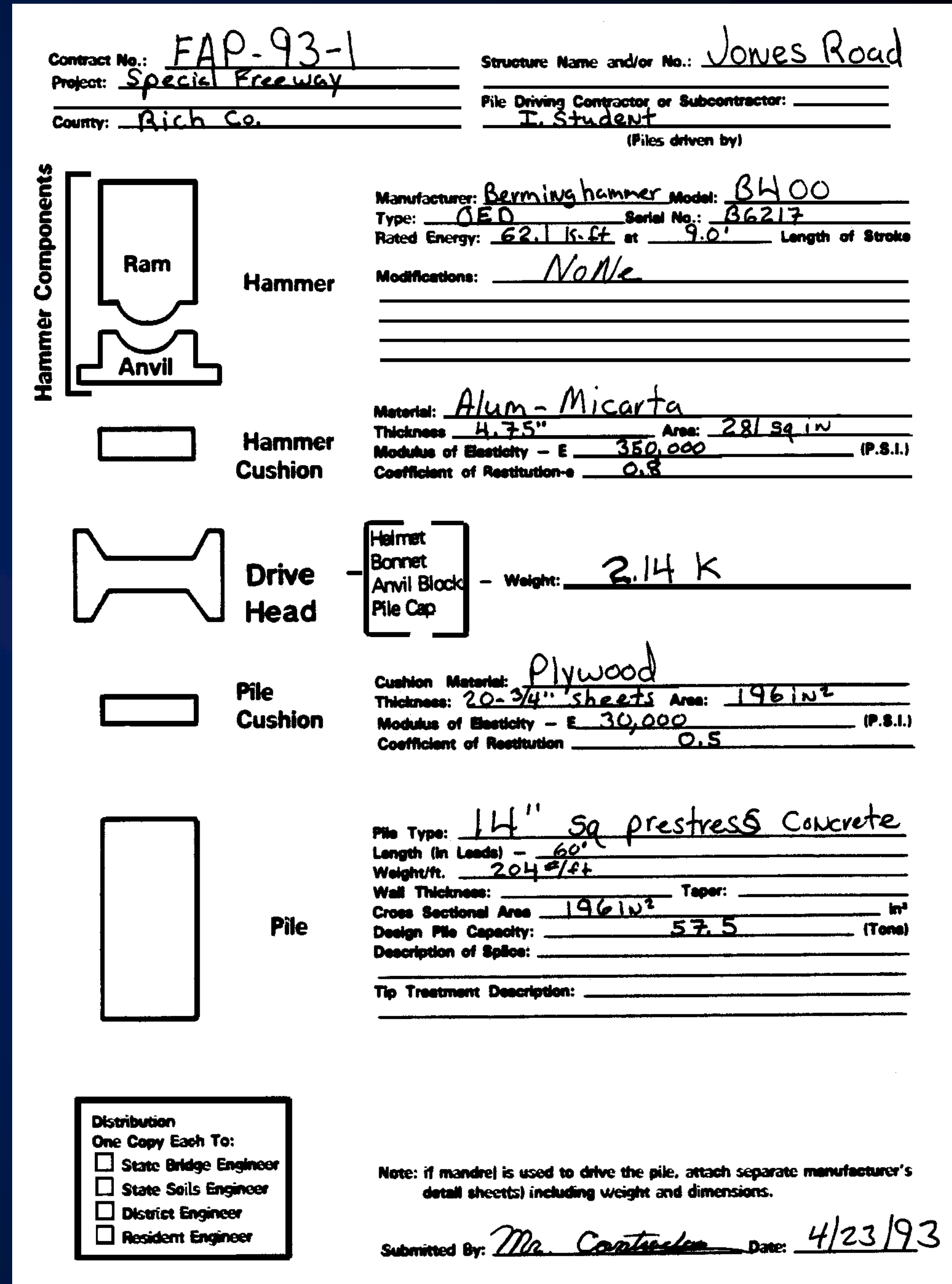
Student Exercise 8 - Solution

	Value	OK	N.G.
Pile 1: 0.250″ wall thickness (9.77 in^2)			
Maximum Stress	42	☐	☒
Blow Count	112	☒	☐
Pile 2: 0.312″ wall thickness (12.19 in^2)			
Maximum Stress	36	☐	☒
Blow Count	73	☒	☐
Pile 3: 0.375″ wall thickness (14.60 in^2)			
Maximum Stress	30.4	☒	☐
Blow Count	59	☒	☐

Select Pile 3, 0.375″ Wall Thickness, Which meets both the Blow Count and Stress Criteria.

Student Exercise 9 -Hammer Approval

- Pile Design capacity = 115k
- Pile Driving resistance = 300k
- Should you accept the hammer?



Contract No.: FAP-93-1
Project: Special Freeway
County: Rich Co.

Structure Name and/or No.: Jones Road
Pile Driving Contractor or Subcontractor: I. Student
(Piles driven by)

Hammer Components

Hammer (Ram, Anvil)
Manufacturer: Berminghammer Model: B400
Type: OED Serial No.: 36217
Rated Energy: 62.1 k-ft at 9.0' Length of Stroke
Modifications: NoNe

Hammer Cushion
Material: Alum - Micarta
Thickness: 4.75" Area: 281 sq in
Modulus of Elasticity - E 350,000 (P.S.I.)
Coefficient of Restitution-e 0.8

Drive Head
Helmet / Bonnet / Anvil Block / Pile Cap - Weight: 2.14 K

Pile Cushion
Cushion Material: Plywood
Thickness: 20-3/4" sheets Area: 196 in²
Modulus of Elasticity - E 30,000 (P.S.I.)
Coefficient of Restitution 0.5

Pile
Pile Type: 14" Sq prestress Concrete
Length (in Leads) - 60'
Weight/ft. 204 #/ft
Wall Thickness: Taper:
Cross Sectional Area 196 in² in²
Design Pile Capacity: 57.5 (Tons)
Description of Splice:
Tip Treatment Description:

Distribution
One Copy Each To:
☐ State Bridge Engineer
☐ State Soils Engineer
☐ District Engineer
☐ Resident Engineer

Note: if mandrel is used to drive the pile, attach separate manufacturer's detail sheet(s) including weight and dimensions.

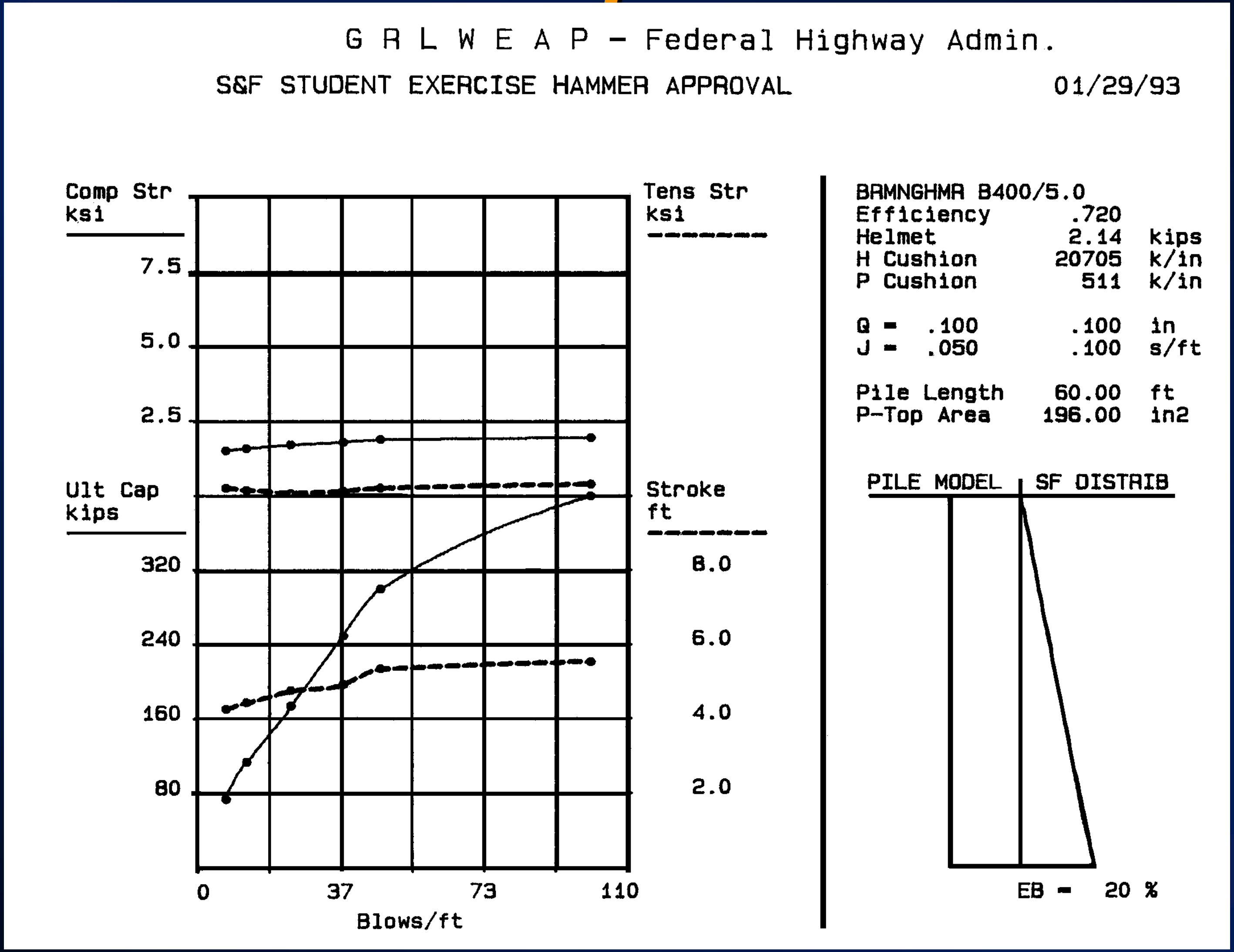
Submitted By: Mr. Contractor Date: 4/23/93

Student Exercise 9 WEA Output

Federal Highway 01/28/93 GRLWEAP S&F STUDENT EXERCISE HAMMER APPROVAL

Rut kips	Bl Ct bpf	Stroke (ft) down	up	min Str ksi	i,t	max Str ksi	i,t	ENTHRU kip-ft	Bl Rt b/min
75.0	7.2	4.3	4.3	-.30(	7, 19)	1.54(	2, 12)	13.2	56.7
115.0	12.5	4.5	4.5	-.20(	9, 21)	1.62(	2, 12)	11.7	55.3
175.0	24.0	4.8	4.7	-.11(	10, 21)	1.73(	2, 12)	10.1	53.8
250.0	37.3	5.0	5.1	-.19(	9, 30)	1.82(	2, 12)	8.8	52.4
300.0	47.0	5.4	5.3	-.28(	8, 29)	1.90(	2, 12)	8.8	50.9
400.0	102.2	5.6	5.7	-.41(	5, 28)	1.96(	2, 12)	8.1	49.5

Student Exercise 9
Plots of WEA Output



Student Exercise 9 Solution Summary

Acceptable Driving Stresses:

Maximum Compressive Stress = (0.85 × 5,000 psi) – 700 psi = **3,550 psi**

Maximum Tensile Stress = (3 × √5,000 psi) + 700 psi = **912 psi**

Acceptable Blow Count Range: **30-144** blows/foot

Wave Equation Results: <u>300 Kips Driving Resistance</u>

Max (compressive) stress = 1.9 ksi = 1,900 psi < 3,550 psi okay

Min (tensile) stress = -0.28 ksi = -280 psi < -912 psi okay

Blow Count = 47 bpf between 30 & 144 bpf okay

<u>HAMMER APPROVED</u> ✓

Learning Outcomes

- ***At the end of this session, the participant will be able to:***
  - *Recall pile driving equipment*
  - *Review wave equation analysis*
  - *Assess pile driveability*

Any Questions?