PURDUE UNIVERSITY

PGS

EIGHTH G.A. LEONARDS LECTURE

GROUND SETTLEMENT FROM PILE DRIVING

May 1, 2010

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UNIVERSITY OF NOTRE DAME

MICHIGAN

MY CONNECTIONS TO JERRY

- Research Engineer, AF Weapons Lab 1963

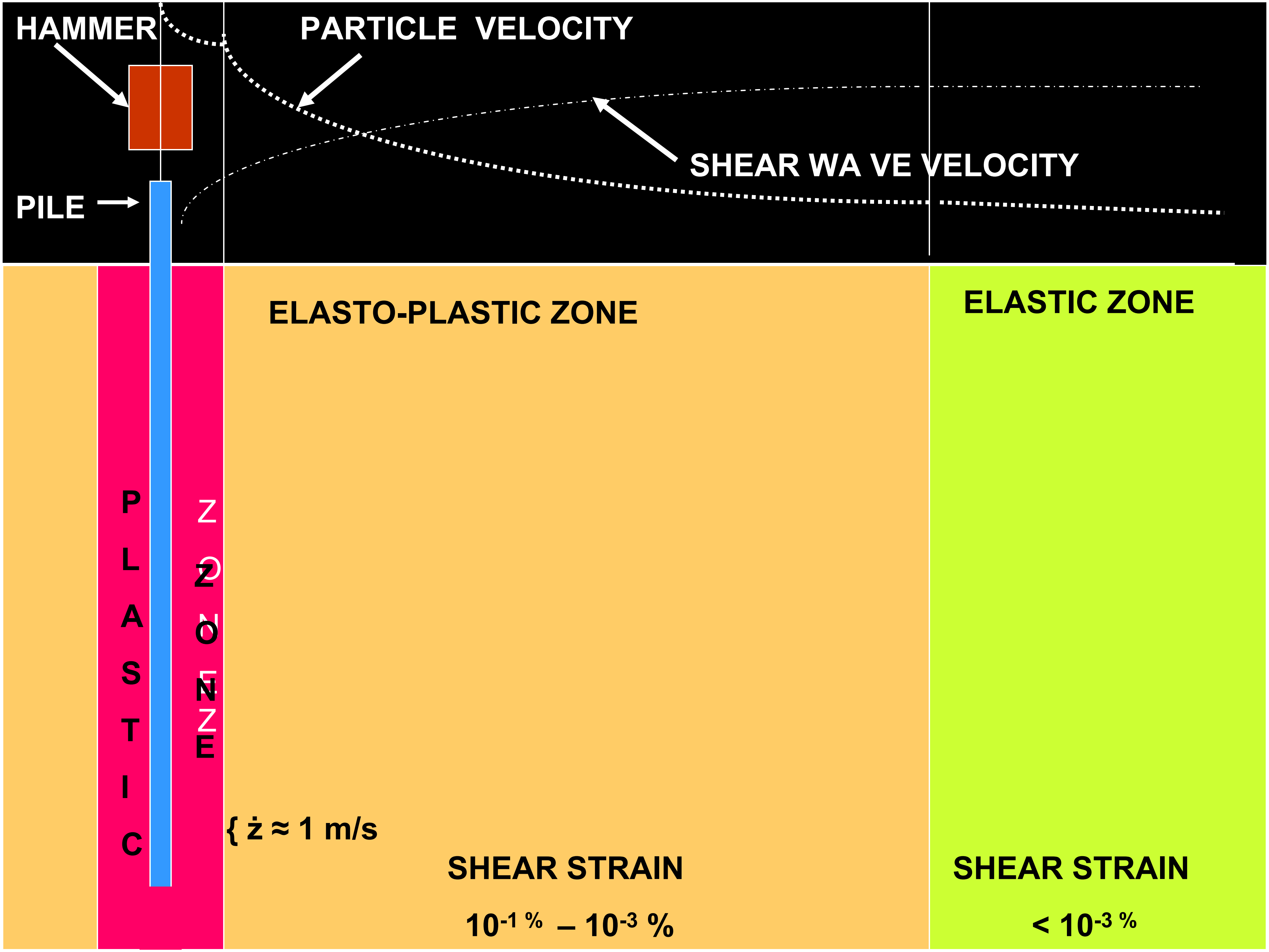
  My first job after M.S. as project monitor on Jerry's AFWL research.

- Invited to apply to Ph.D. program at Purdue.

- Tokyo ISSMFE Conference 1977, post conference tour with Jerry and Beryl, Jorg Osterberg and others.

GROUND SETTLEMENT FROM PILE DRIVING

- GENERAL CONCEPTS
- EXAMPLES FROM PRACTICE

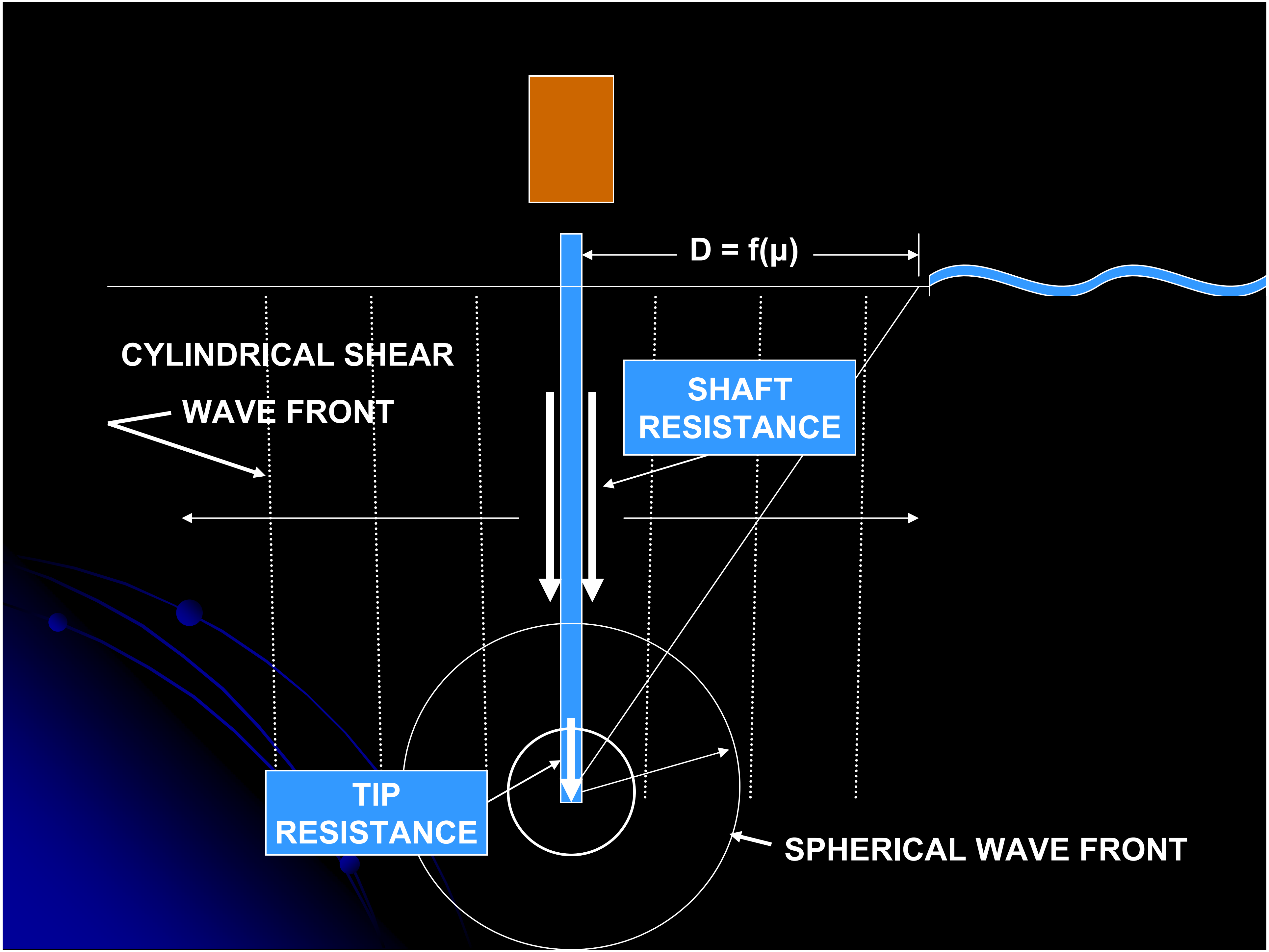

HAMMER
PARTICLE VELOCITY
SHEAR WA VE VELOCITY
PILE
ELASTO-PLASTIC ZONE
ELASTIC ZONE
PLASTIC
ZONE
{ ż ≈ 1 m/s
SHEAR STRAIN
10-1 % – 10-3 %
SHEAR STRAIN
< 10-3 %

COMPONENTS OF PILE VIBRATION ANALYSIS

- **TRANSFER OF ENERGY FROM PILE TO SOIL**
- **DISIPATION OF ENERGY THROUGH SOIL**
- **THRESHOLD OF SETTLEMENT CAUSING VIBRATIONS**

GENERATION OF GROUND DISTURBANCE

TRANSFER OF DRIVING ENERGY INTO SURROUNDING GROUND


D = f(μ)
CYLINDRICAL SHEAR
WAVE FRONT
SHAFT
RESISTANCE
TIP
RESISTANCE
SPHERICAL WAVE FRONT

TIP RESISTANCE

GOBLE (1980) $R_T = J\ Z^P\ \dot{z}$

J = Damping or loss factor

Z^P = Pile impedance

$\dot{z}$ = particle velocity in pile

IWANOWSKI AND BODARE (1988)

J = ratio of pile and soil impedance and also related to "K" in Heckman & Hagerty (1978)

MASSARSCH AND FELLENIUS (2008)

$$R_T = Z_P\ v_o$$

$Z_P = A^P\ v_{ps}\ \rho_s$

v_o = Hammer impact velocity

SHAFT RESISTANCE

MASSARSCH AND FELLENIUS (2008)

$$R_S = z_s\, \dot{z}\, A^C$$

z_s = specific impendence of soil

$\dot{z}$ = particle velocity in pile

A^C = contact area between soil and pile

$$\dot{z} = t_f / v_s\, \rho \qquad \text{(often > 12 in/sec)}$$

t_f = shearing strength of soil

v_s = shear wave velocity

ρ = mass density of soil

$\{(\dot{z})_{max} \approx$ 1 m/s Observed in densification studies$\}$

DISSIPATION OF ENERGY WITH DISTANCE

GEOMETRICAL

AND

MATERIAL DAMPING

EQUATIONS DESCRIBING ENERGY DISIPATION

BORNITZ EQUATION

$$w = w_1 (r_1/r)^n \exp[-\alpha(r - r_1)]$$

w_1 = amplitude at known distance r_1
w = amplitude at any distance r
r_1 = distance from source to point of known amplitude
r = distance from source to any point
n = coefficient depending on type of wave
- n = 1 for body waves in half-space
- n = 2 for body waves along surface
- n = 0.5 for Rayleigh waves

α = coefficient of attenuation

PROPOSED CLASSIFICATION OF EARTH MATERIALS BY ATTENUATION COEFFICIENT

CLASS	ATTENUATION COEFFICIENT α (1/ft) 5 Hz	50Hz	DESCRIPTION OF MATERIAL
I	0.003 to 0.01	0.03 to 0.10	Weak or Soft Soils-lossy soils, dry or partially saturated peat and muck, mud, loose beach sand, and dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, toposoil. (shovel penetrates easily) **N < 5**
II	0.001 to 0.003	0.01 to 0.03	Competent Soils- most sands, sandy clays, silty clays, gravel, silts, weathered rock. (can dig with shovel) **5< N < 15**
III	0.0001 to 0.001	0.001 to 0.01	Hard Soils- dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock. (cannot dig with shovel, must use pick to break up) **15< N < 50**
IV	<0.0001	<0.001	Hard, Competent Rock- bedrock, freshly exposed hard rock. (difficult to break with hammer) **N > 50**

EQUATIONS DESCRIBING ENERGY DISSIPATION

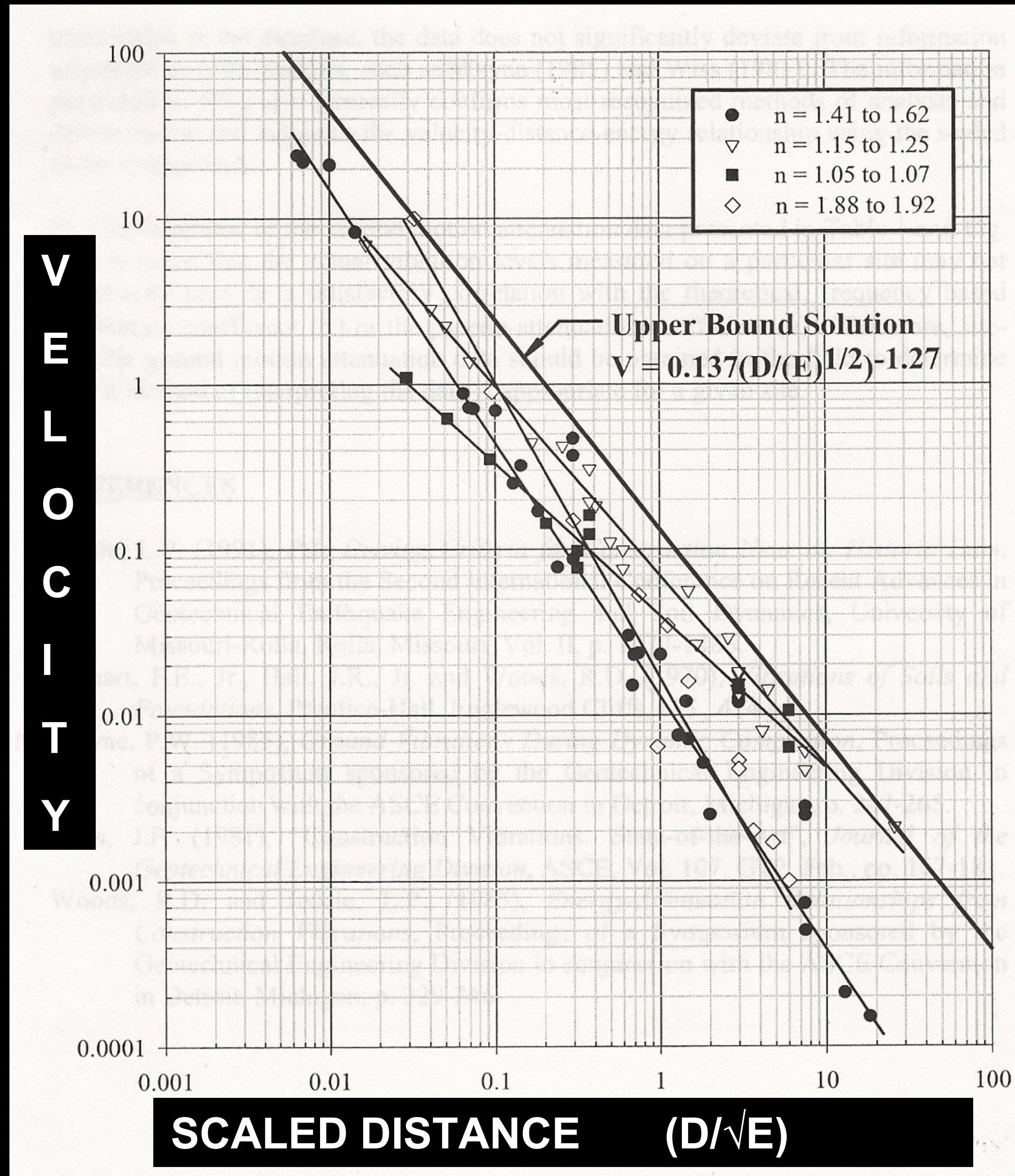
PSEUDO - ATTENUATION

$$\dot{z} = k\,[D/\sqrt{E}]^{-N}$$

$\dot{z}$ = peak particle velocity
k = intercept at 1 energy unit
D = distance from source
E = energy of source
N = slope of line on log-log plot of $\dot{z}$ vs scaled distance

PSEUDO ATTENUATION

PEAK PARTICLE VELOCITY



SCALED DISTANCE (D/√E)

VIBRATIONS CAUSING SETTLEMENT

SHEARING STRAIN

AND

VOLUMETRIC STRAIN

SHEARING STRAIN

$$\gamma = \dot{z} / v_s$$

(For harmonic motion only)

γ equivalent for non-harmonic vibrations, displacement gradient suggested by Brandenberg et al (2009)

$$\partial u_z / \partial y$$

$$\dot{z} = \sigma_Z v_p / E_p$$

(free end of pile)

THRESHOLD STRAIN

- SILVER & SEED (1971) $\gamma_t \approx 0.01\%$
- YOUD (1972) $\gamma_t = 0.01\ \%$ (limit of his tests)
- DOBRY (1983) $\gamma_t = 0.01\%$ (for liquefaction)
- HSU & VUCETIC (2004) $\gamma_t = <0.01\%$ (10 cycles)
- MASSARSCH (2008) $\gamma_t = 0.001\ \%$ (many cycles)
- BRANDENBERG ET AL (2009) $\gamma_t = <0.01\%$

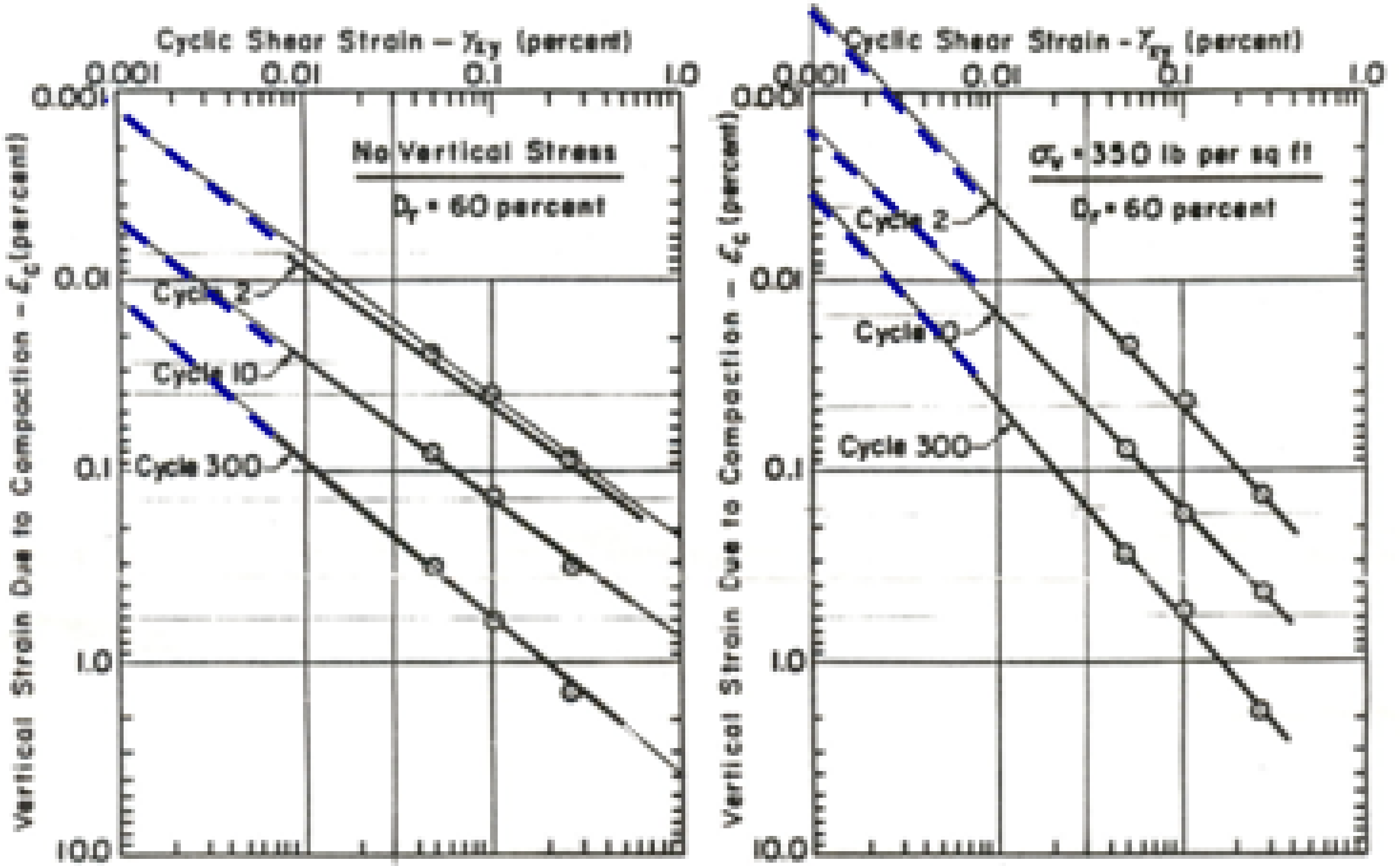


FIG. —VERTICAL SETTLEMENT—SHEAR STRAIN RELATIONSHIP FOR SILICA SAND (D_r = 60 %)

VARIABLES AFFECTING γ_t

NO

- RELATIVE DENSITY
- VOID RATIO
- EFFECTIVE CONFINING PRESSURE

YES

- NUMBER OF CYCLES
- STRAIN LEVEL

EXAMPLE 1

BLACKWATER RIVER BRIDGE

I-10

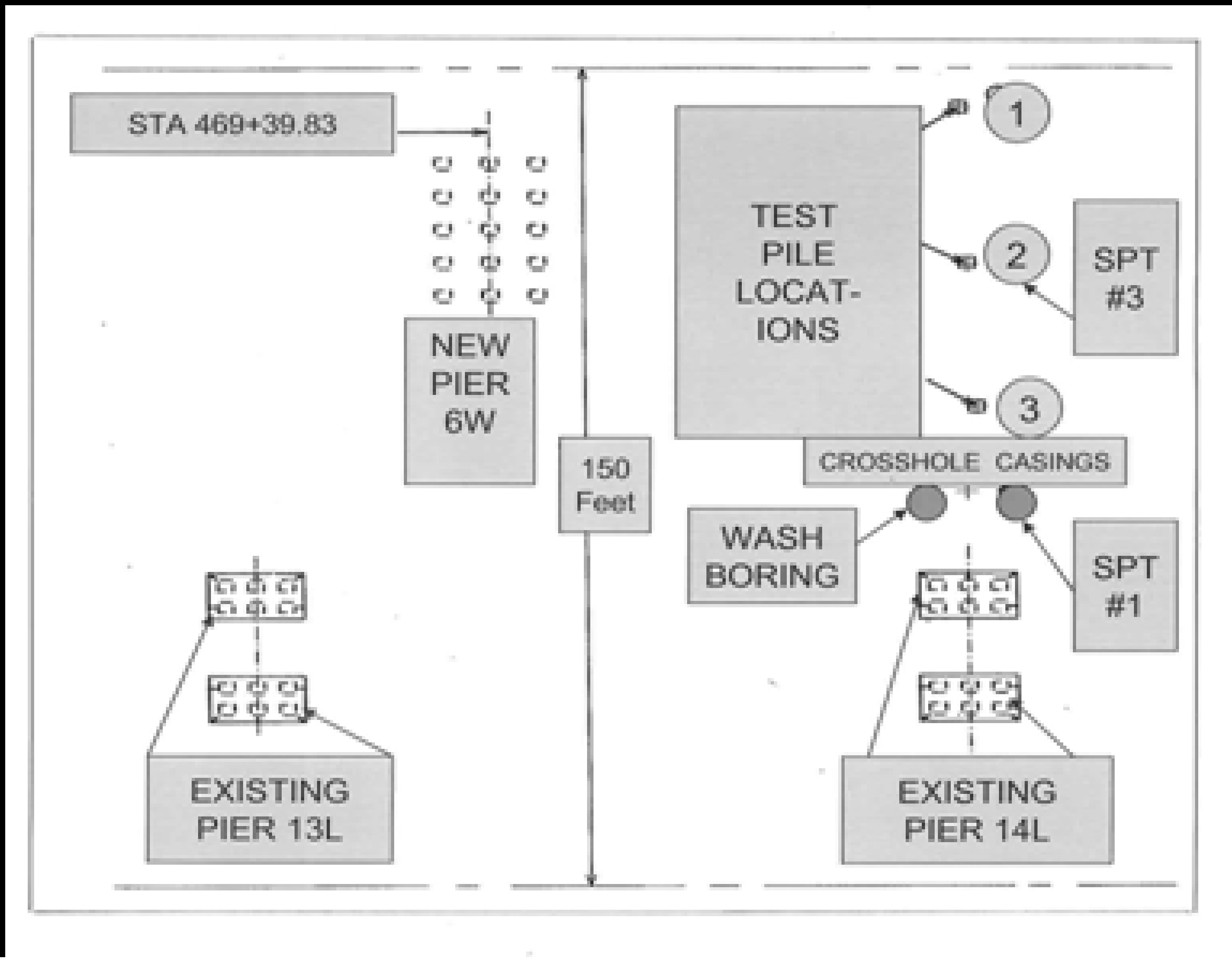
PENSACOLA, FLORIDA

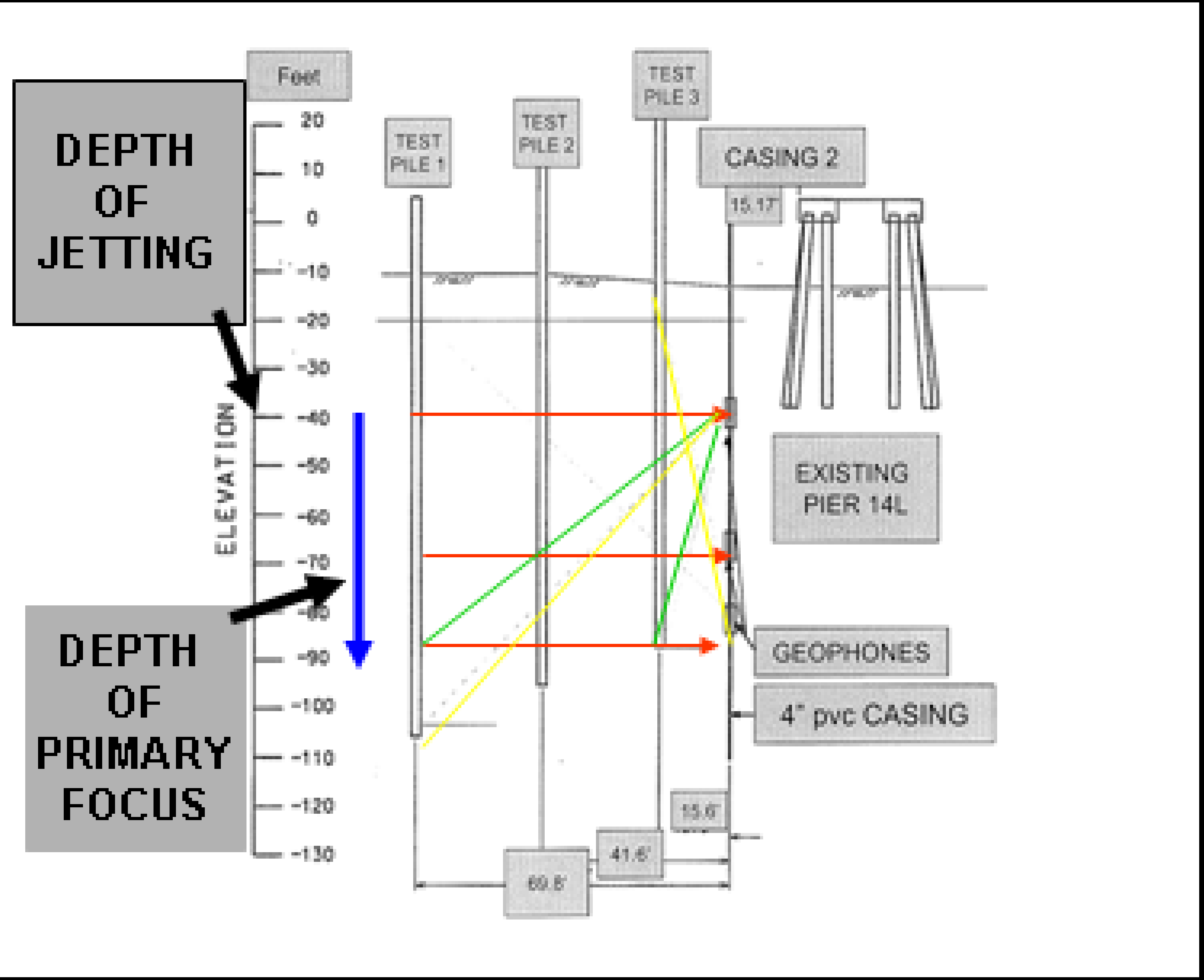
BLACKWATER RIVER BRIDGE looking SOUTH

BLACKWATER RIVER BRIDGE looking WEST

INITIAL LEVEL SURVEY

TEST PILE INSTALLATION

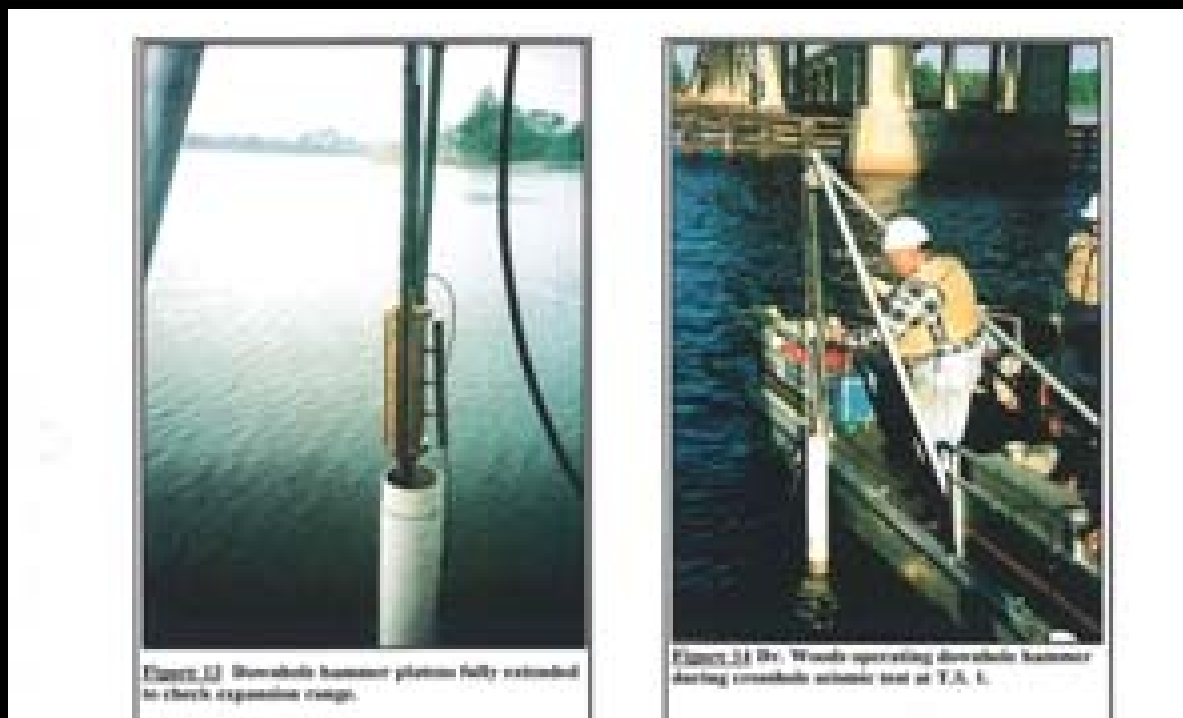




ELEVATION THROUGH TEST PILE SECTION

FIELD MEASUREMENTS

C R O S S H O L E



V_S VELOCITY

TYPICAL

CROSSHOLE

WAVE FORMS

(Repetitions
to show
reproducibility)

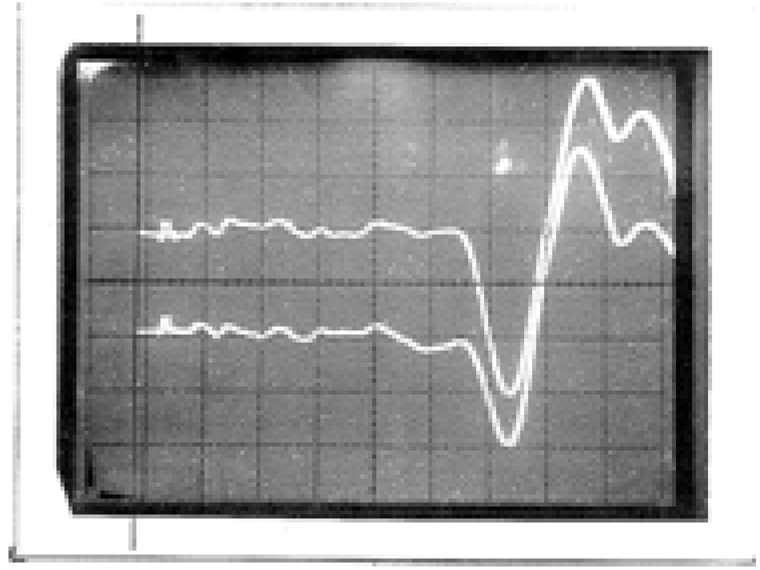


PHOTO NUMBER 1-14

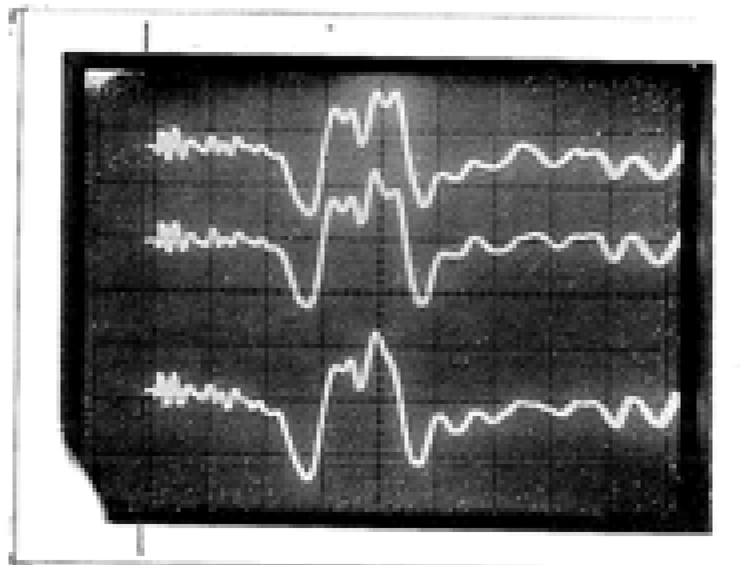
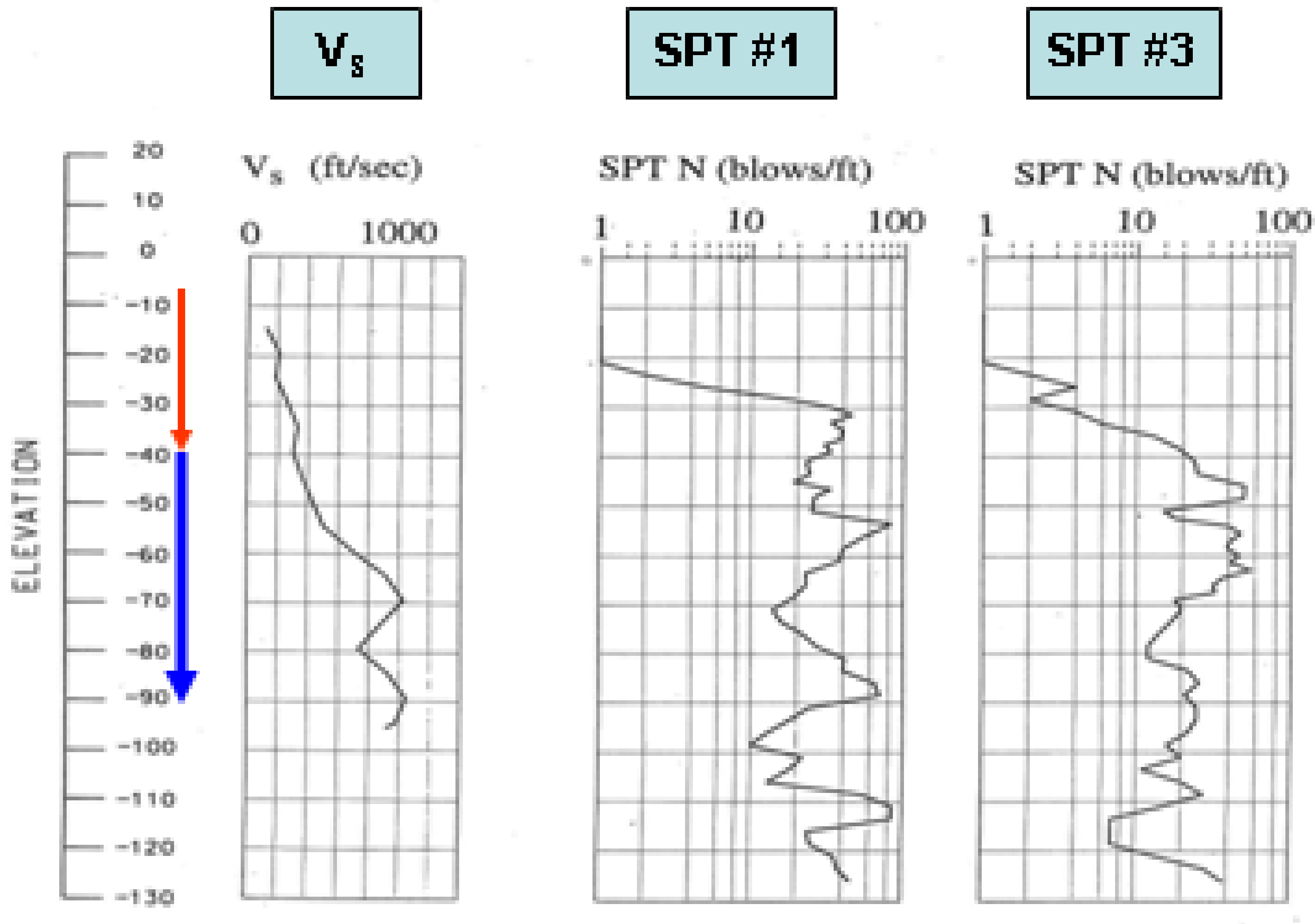


PHOTO NUMBER 1-16


CROSSHOLE
CASING
14

PRE-DESIGN SOIL DATA



EMPIRICAL EQUATIONS FOR V_s AND V_v

$$V_s = a + bN^n(\sigma_o)^m$$

where N is SPT Blow Count
σ_o is effective octahedral confining pressure
and a, b, n, & m are empirical constants

$$V_v = a\,(\text{dist.}/\sqrt{\text{energy}})^{-n}$$

where a & n are empirical constants
dist. is source to receiver distance
and energy is enthru per blow

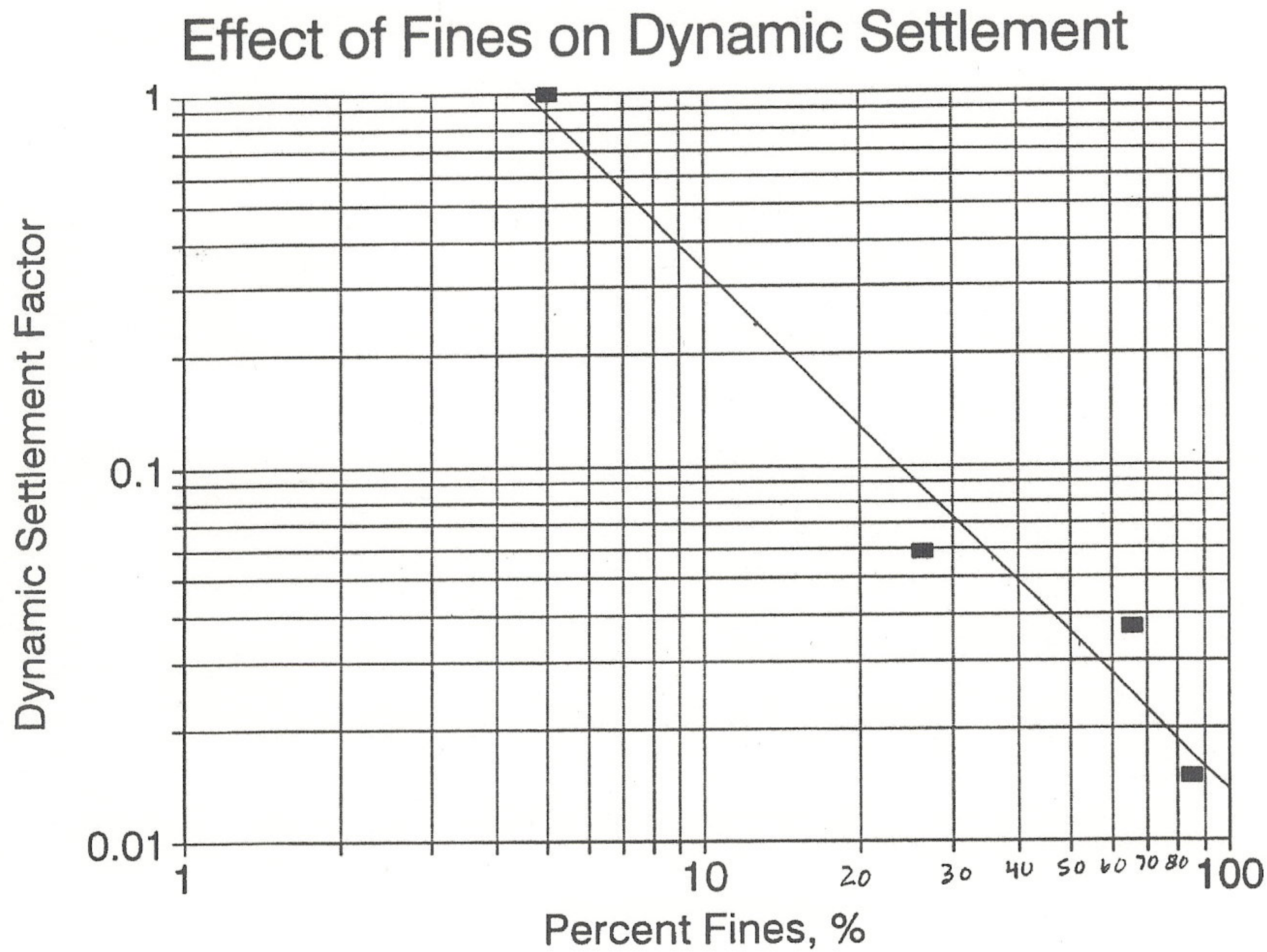
MEASURED & PREDICTED SETTLEMENT

- PREDICTED

  $(\Delta H)_{max} = 1.47$ ft

- MEASURED

  $\Delta H < 0.01$ ft

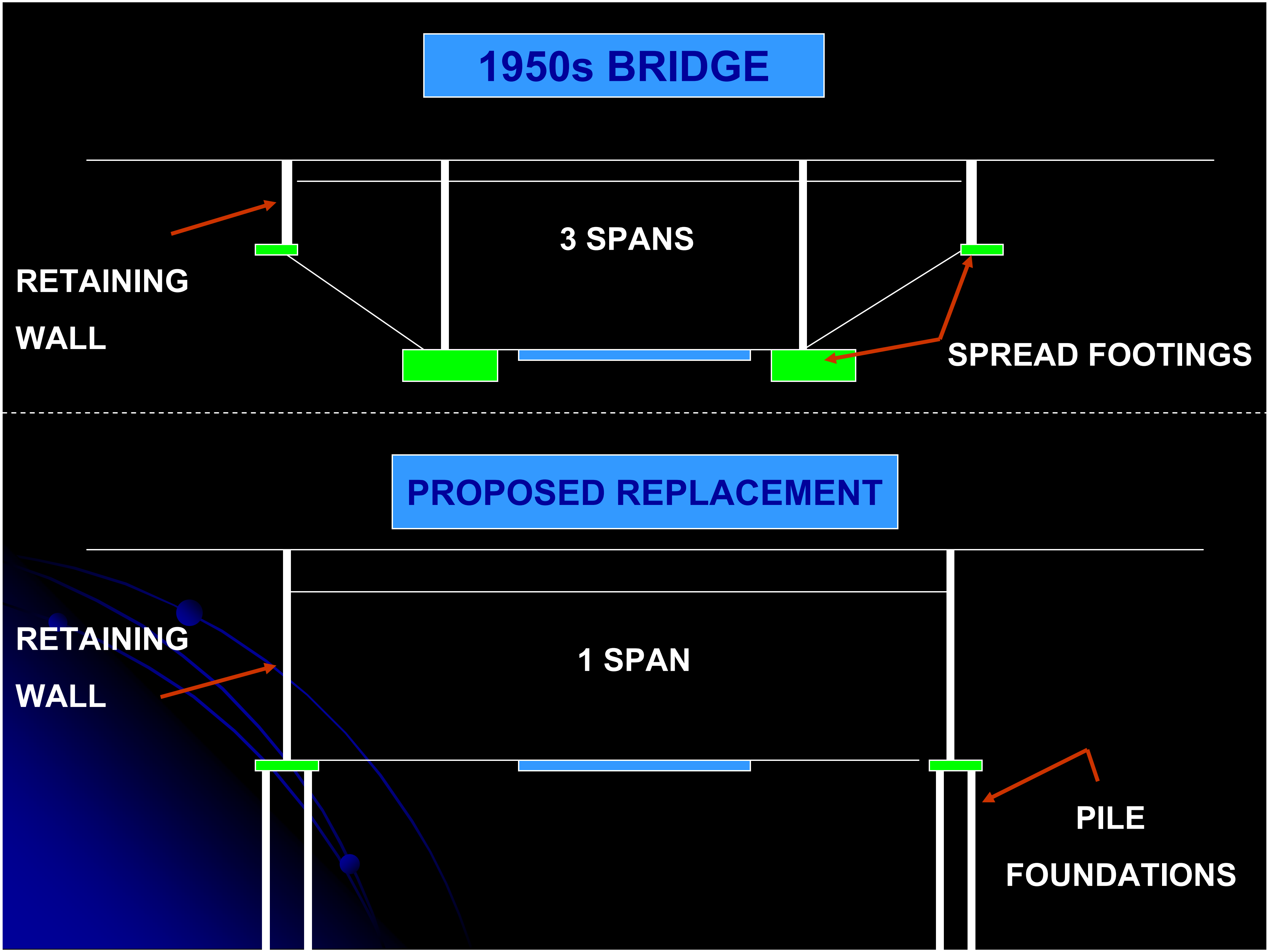


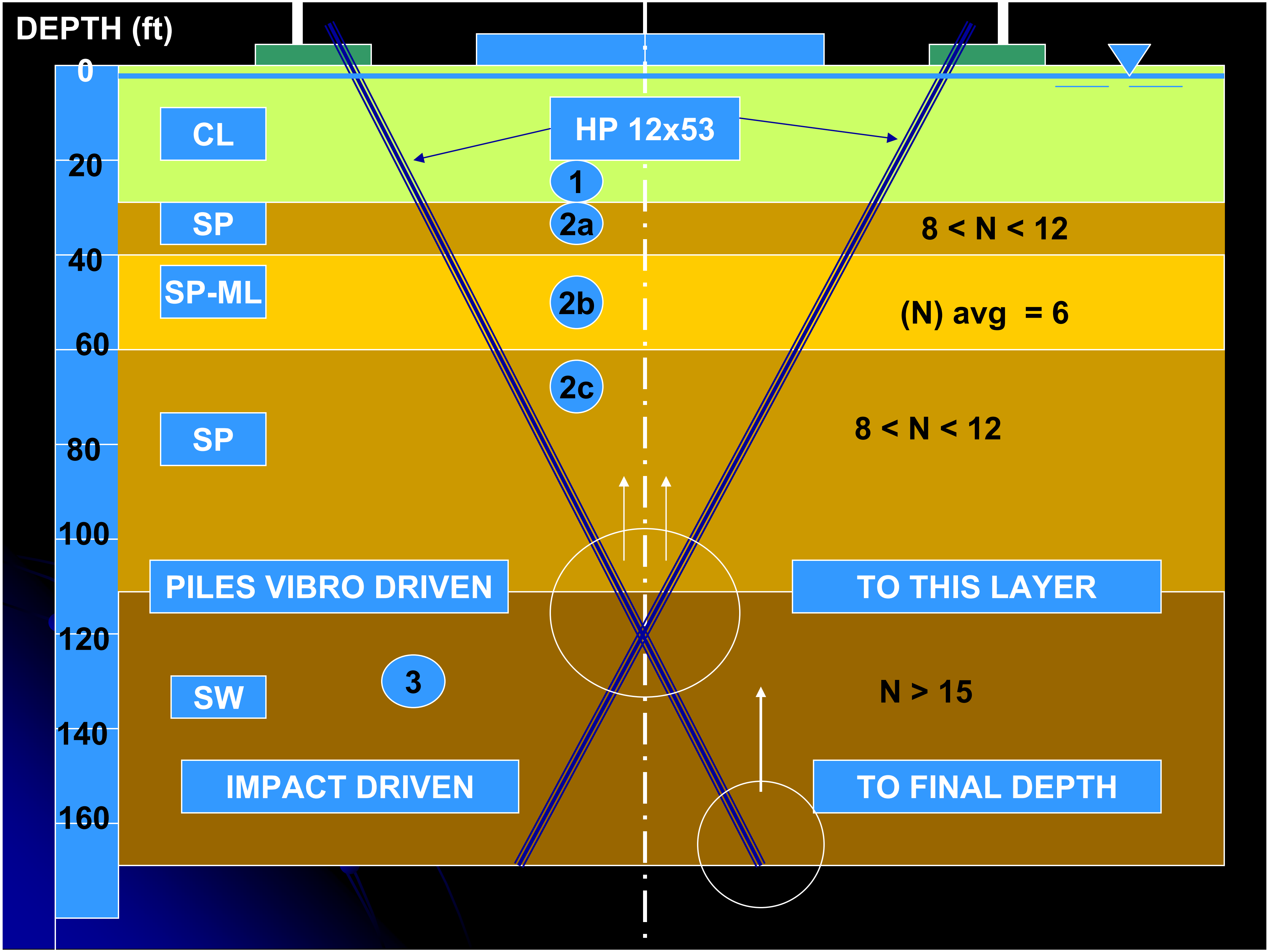
BORDEN & SHAO (1995)

EXAMPLE 2

INFRASTRUCTURE REHABILITATION

INTERSTATE BRIDGE REPLACEMENT


1950s BRIDGE
3 SPANS
RETAINING
WALL
SPREAD FOOTINGS
PROPOSED REPLACEMENT
1 SPAN
RETAINING
WALL
PILE
FOUNDATIONS


DEPTH (ft)
0
20
40
60
80
100
120
140
160
CL
SP
SP-ML
SP
SW
HP 12x53
1
2a
2b
2c
3
8 < N < 12
(N) avg = 6
8 < N < 12
N > 15
PILES VIBRO DRIVEN
TO THIS LAYER
IMPACT DRIVEN
TO FINAL DEPTH

DYNAMIC PILE ANALYSIS

GRLWEAP(TM) Version 2005

DELMAG 19-42 : 40 kip-ft

Comp. Stress ksi	Tension Stress ksi	Stroke ft	ENTHRU kips-ft
0.000	0.000	10.60	0.0
0.000	0.000	10.60	0.0
15.879	-4.929	4.46	23.0
21.333	-3.802	5.24	20.8
21.303	-3.663	5.20	20.6
23.891	-3.170	5.68	19.6
25.728	-3.619	6.13	19.1
25.768	-3.532	6.14	19.1
28.075	-3.782	6.94	19.5
29.923	-3.068	7.71	20.6
30.011	-3.046	7.75	20.7
30.211	-3.238	7.84	20.7
30.310	-2.580	7.92	20.7

DRIVING 5 PILES WITH D 19-42 HAMMER, 300 BLOWS EACH

40 K-FT

shearing strain 5 Hz (in/in)	shearing strain 50 HZ (in/in)	1-D vert vol. chg 5Hz (in/in)	1-D vert vol. chg 50Hz (in/in)	Vertical Settle 5 Hz (in)	Vertical Settle 50 Hz (in)
0.000849	0.00043078	0.005	0.003	4.56	2.736
0	0			0	0
0.000739	0.000340489	0.0045	0.0025	4.104	2.28
0	0			0	0
0.00087	0.000447908	0.0045	0.0025	4.104	2.28
0	0			0	0
0.000864	0.000442854	0.0045	0.0025	4.104	2.28
0	0			0	0
0.000442	0.000127222	0.003	0.0009	2.736	0.8208
			sum	19.608	10.3968

DYNAMIC PILE ANALYSIS

PILECO D30-32 : 70 FT-KIPS

01-Apr-2009
GRLWEAP (TM) Version 2005

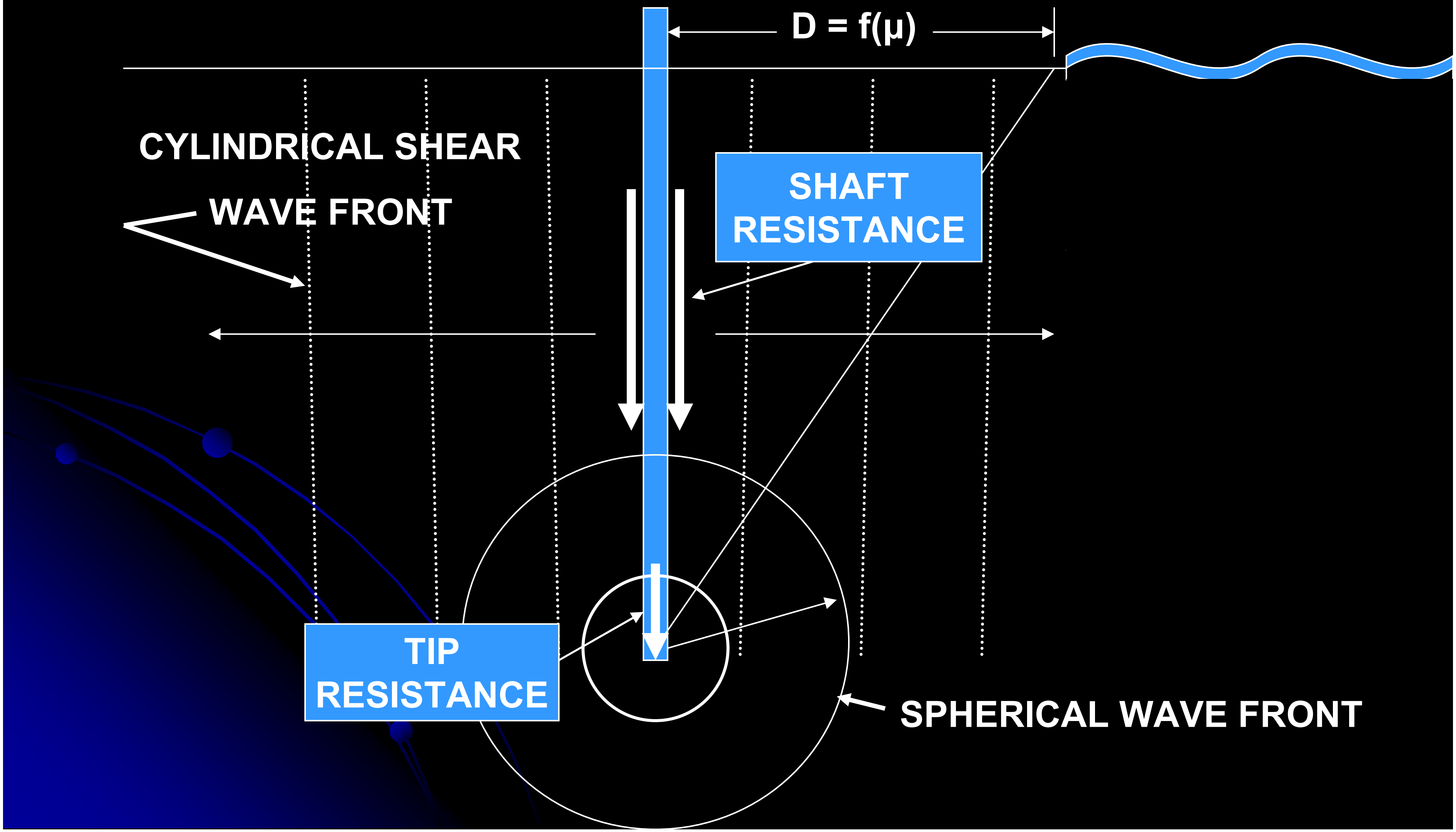
Ultimate Capacity kips	Maximum Compression Stress ksi	Maximum Tension Stress ksi	Blow Count blows/in	Stroke ft	Energy kips-ft
400.0	27.12	2.56	6.4	7.00	17.97
400.0	28.86	2.71	4.9	7.62	20.77
400.0	30.44	2.77	4.2	8.24	22.57
400.0	31.96	2.82	3.7	8.87	24.36
400.0	33.39	2.90	3.3	9.49	26.11
400.0	34.77	3.42	3.0	10.11	27.88
400.0	36.11	4.35	2.7	10.73	29.58
400.0	37.41	4.70	2.5	11.36	31.28
400.0	38.67	4.86	2.4	11.98	32.99
400.0	39.89	4.86	2.2	12.60	34.66

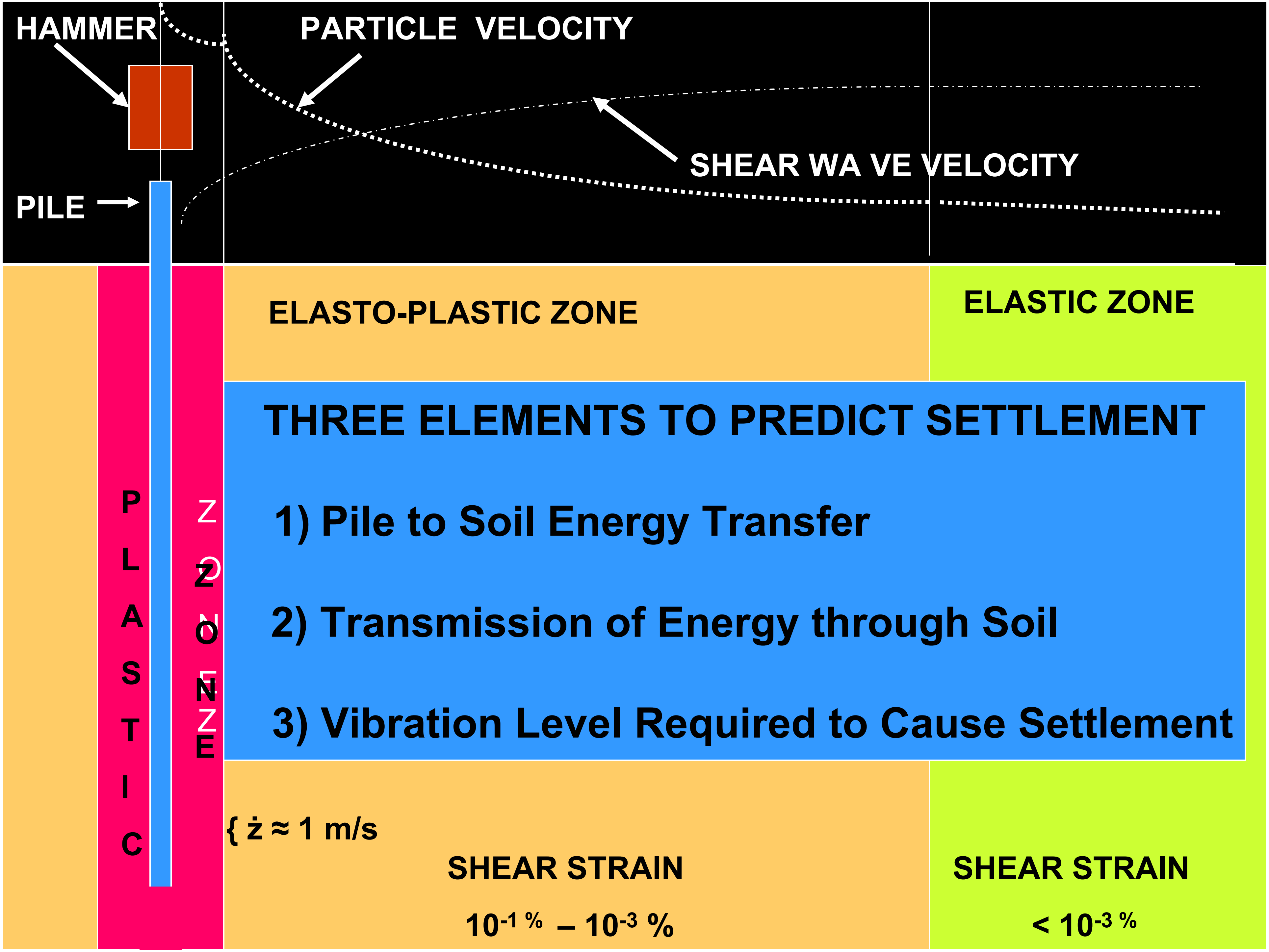
DRIVING 3 PILES WITH D30-32 HAMMER, 300 BLOWS EACH

70 K-FT

shearing strain 5 Hz (in/in)	shearing strain 50 HZ (in/in)	1-D vert vol. chg 5Hz (in/in)	1-D vert vol. chg 50Hz (in/in)	Vertical Settle 5 Hz (in)	Vertical Settle 50 Hz (in)
0.000338	8.50834E-05	0.0018	0.0004	1.641	0.3648
0	**0.000085**				0
0.000199	2.28521E-05	0.001	0.0001	0.91	0.0912
0	**0.000023**				0
0.000339	8.5278E-05	0.0018	0.0004	1.641	0.3648
	0.000085			4.195	0.8208

SUMMARY


D = f(μ)
CYLINDRICAL SHEAR
WAVE FRONT
SHAFT RESISTANCE
TIP RESISTANCE
SPHERICAL WAVE FRONT



HAMMER
PARTICLE VELOCITY
PILE
SHEAR WA VE VELOCITY
ELASTO-PLASTIC ZONE
ELASTIC ZONE
THREE ELEMENTS TO PREDICT SETTLEMENT
1) Pile to Soil Energy Transfer
2) Transmission of Energy through Soil
3) Vibration Level Required to Cause Settlement
P L A S T I C
Z O N E
{ ż ≈ 1 m/s
SHEAR STRAIN
10-1 % – 10-3 %
SHEAR STRAIN
< 10-3 %

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- Rainer Messarsch

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FINALLY

CONGRATULATIONS TO VINCE AND ROXANNE ON A BRILLIANT CAREER

THANK YOU !

DICK