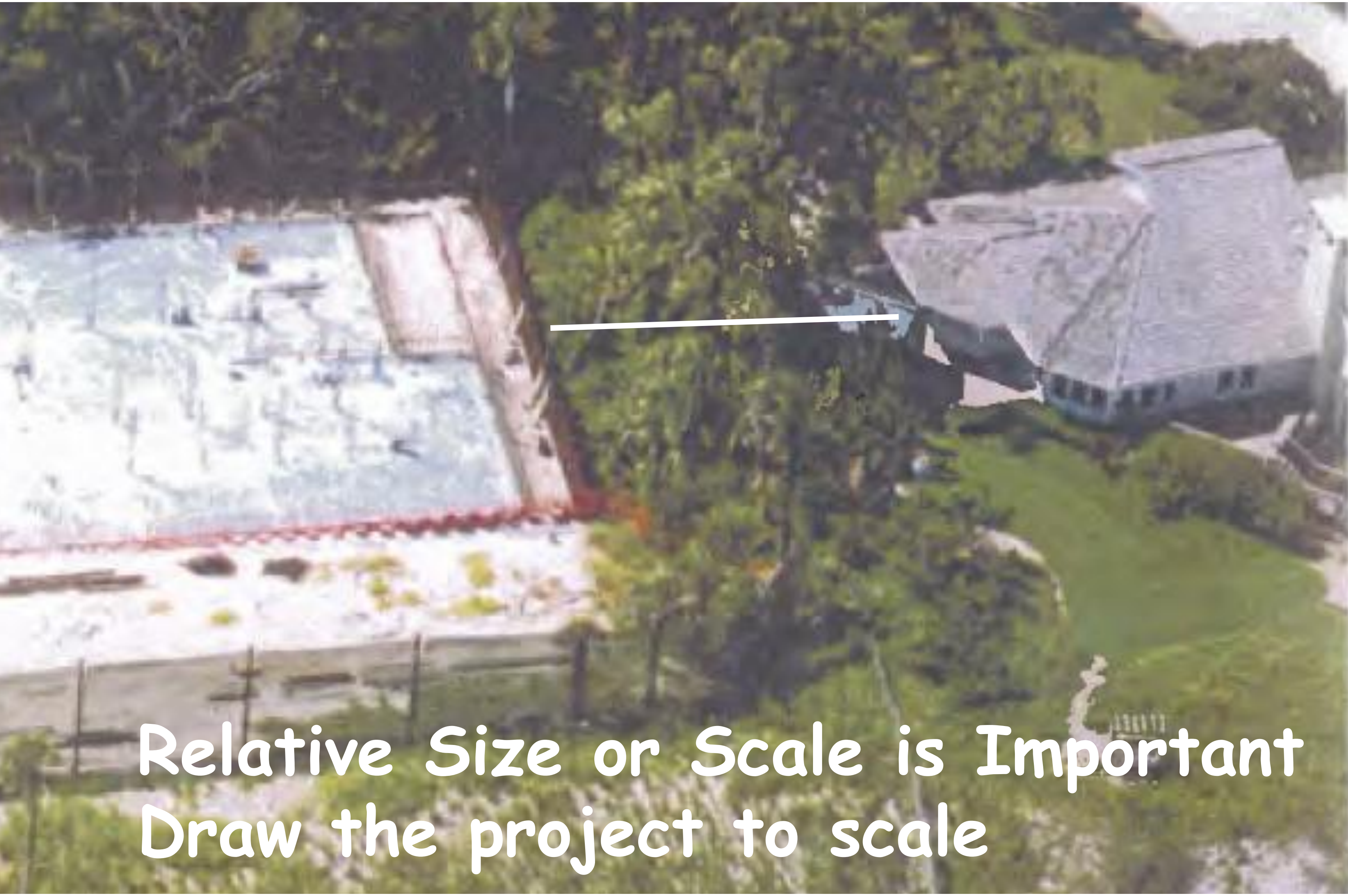
Alleged Vibratory Pile Driving Induced Settlement

Charles H Dowding
Northwestern University

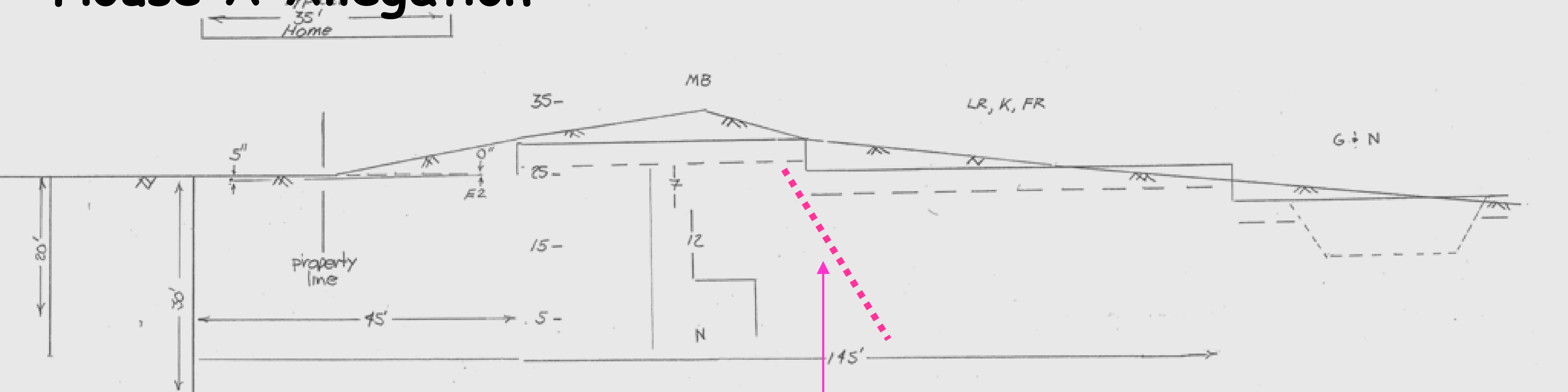
Smaller home
replaced
by the larger home

Home owners A
sue
Home owners B &
contractors


Allegation:
Demolition and vibratory pile driving cracked residential structure,


Relative Size or Scale is Important
Draw the project to scale

House A Allegation



- Upper 12 to 30 ft, N=7 loose sand, b) lower dense (N ~ 57) layer

- PPV attenuated vertically upward to lower intensities from the lower dense layer. Employed Atwell Farmer to estimate higher PPV in lower dense layer
- Drabkin polynomial model employed to estimate settlement

- Literature support of opinion
  - Lacy and Gould: Pile driving settlements with "PPV as low as 0.1 to 0.2ips"
  - Clough & Chameau: Minimal vibratory driving settlements until accel > 0.05g
  - Massarch: process of densification is initiated at a shear strain of 0.01%

Drabkin Multifactor Polynomial Model

$$\ln Y = 2.27 + 1.19x_1 - 0.71x_1^2 + 0.49x_2 - 0.68x_2^2 - 0.80x_3 + 1.09x_3^2 - 0.46x_4 + 0.06x_4^2 + 0.45x_5 - 0.38x_5^2 - 0.19x_6 - 0.10x_7$$

Where, "Y" is the calculated number of units of settlement, where one unit of settlement is equal to 0.0254 mm (0.001 in), and the polynomial factors are presented in the table below.

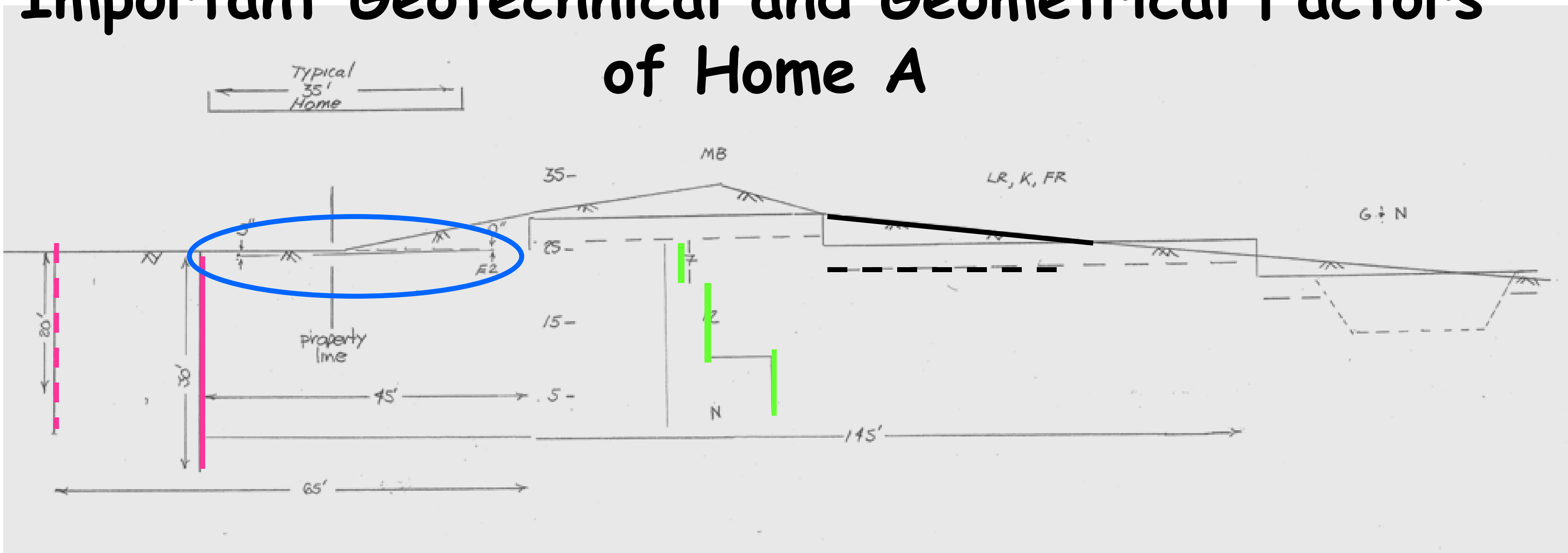
Factor ID	Factor Description	Tested Ranges	Coding of Factors
x_1	Peak Particle Velocity (PPV)	0.1 – 0.7 in/sec	$x_1 = -1 + (PPV - 0.1)/0.3$
x_2	Devatoric Stress (s)	2 – 15 psi	$x_2 = -1 + (s - 2)/6.5$
x_3	Confining Pressure (p)	10 – 30 psi	$x_3 = -1 + (p - 10)/10$
x_4	Sand Mixture	Coarse, Medium, Fine	Range is from –1 for coarse sand to +1 for fine sand
x_5	Number Vibration Cycles (N)	60 – 500,000 Cycles	$x_5 = -1 + (N - 600)/269{,}970$
x_6	Moisture Content	Dry, Saturated	Range is from –1 for dry sand to +2 for saturated sand
x_7	Initial Relative Density	Loose, Medium Dense	Range is from –1 for initially loose sand to +2 for initially medium dense sand

ASCE Jour Geotechnical Engineering Nov 1996
Drabkin, Lacy & Kim (from House A's report)

House A Calculates Large Settlements

Case #	Author	PPV (ips)	N	# of layers	layer Δ	Sett (in)	Other Assumptions	Comments or remarks
1	House A	0.24(top)-0.68 (bottom)	500000	23	1	0.76	1. ground water table at 12ft 2.Surcharge = 7.78 psi 3. Atwell-Farmer anttenuation from the bottom 4.K0 = 0.47	miscalculated s, p' Confirmed with Dowding's recalculation
2	House A2	0.24(top)-0.68 (bottom)	500000	23	1	1.36	Same as case 1	corrected s and p' Dowding's recalculation S = 1.41

Important Geotechnical and Geometrical Factors of Home A



Elevation view looking west showing

distance of

- 25 foot deep wind screen post to master bedroom (MB) 65 feet - - - - -
- 30 foot deep sheet piles to MB 41-45 feet ———

depth of footings - - - relative to

- original ground surface ———
- sand layers 7, 12 and dense ———

example settlement from single row sheet pile driving (Clough case history)

0 " (0 inches) at south edge of MB ⬭

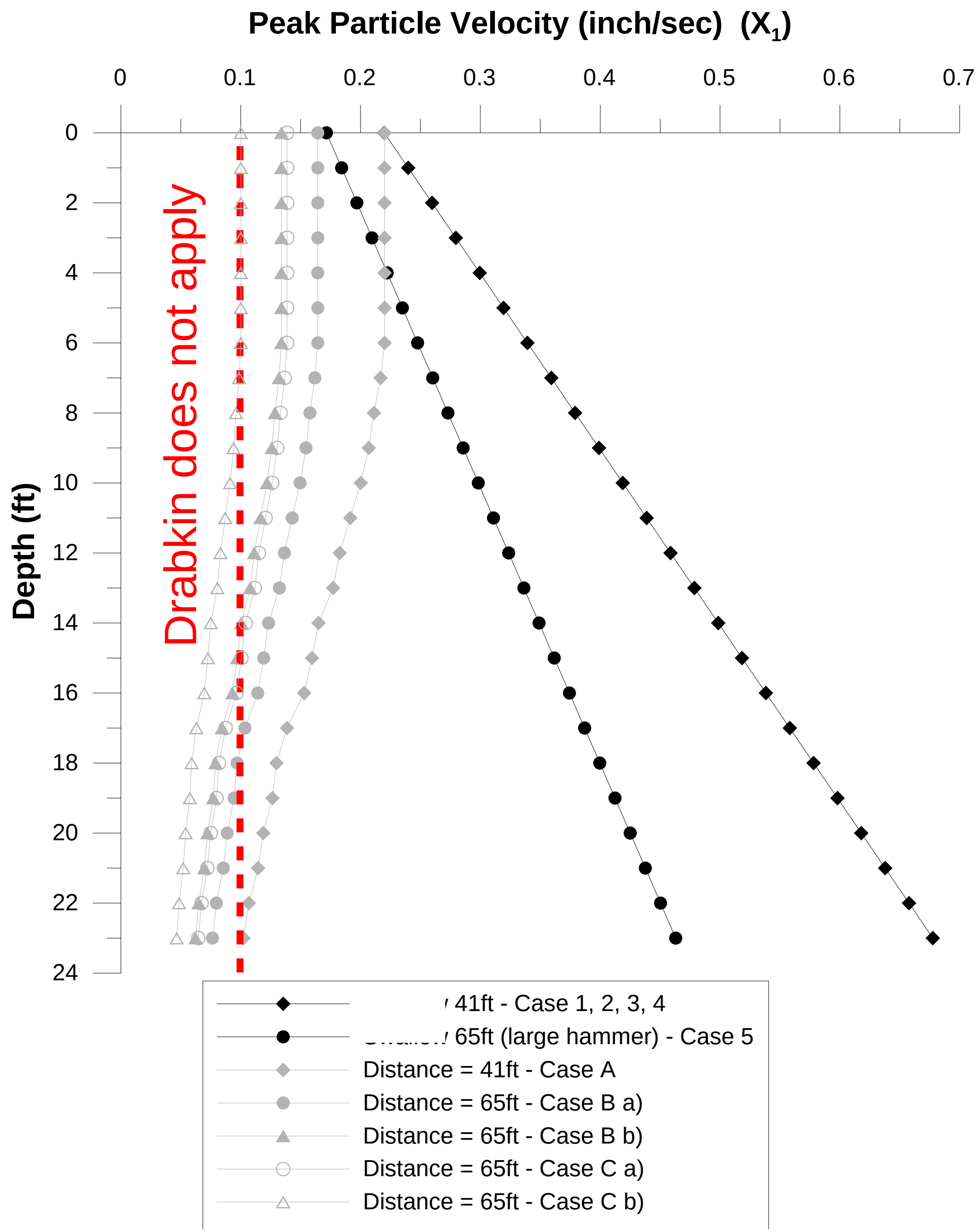
Difference in Variation of PPV w/ depth

House A allegations (dark)

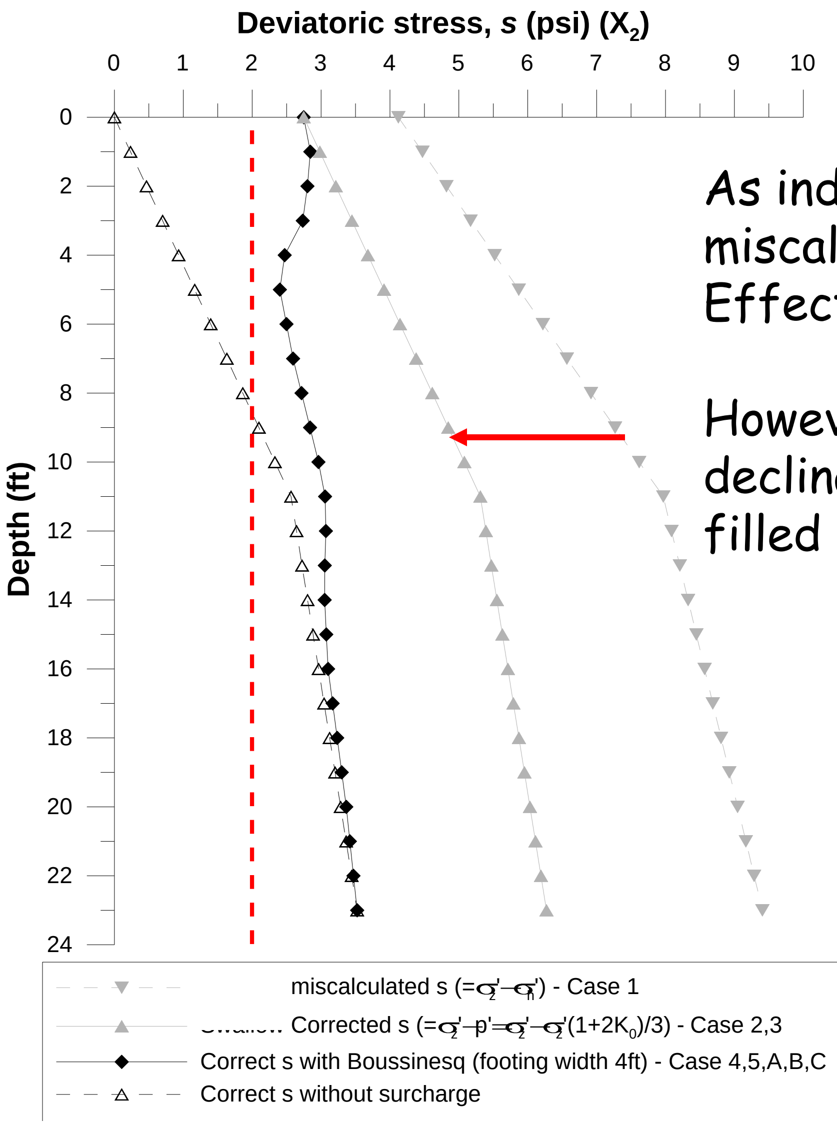
vs

Rayleigh wave (light)

15 Hz



Differences in Effect of Surcharge Load on Deviatoric Stress



As indicated by A2 in table above, House A miscalculated deviatoric stress
Effect shown by arrow

However, even that change must be corrected for declination of vertical footing stress as shown by filled diamonds ( )

Differences in
Number of Maximum Amplitude Pulses
Max Recorded PPV
Does Not Occur for the Entire Time of Vibratory Driving

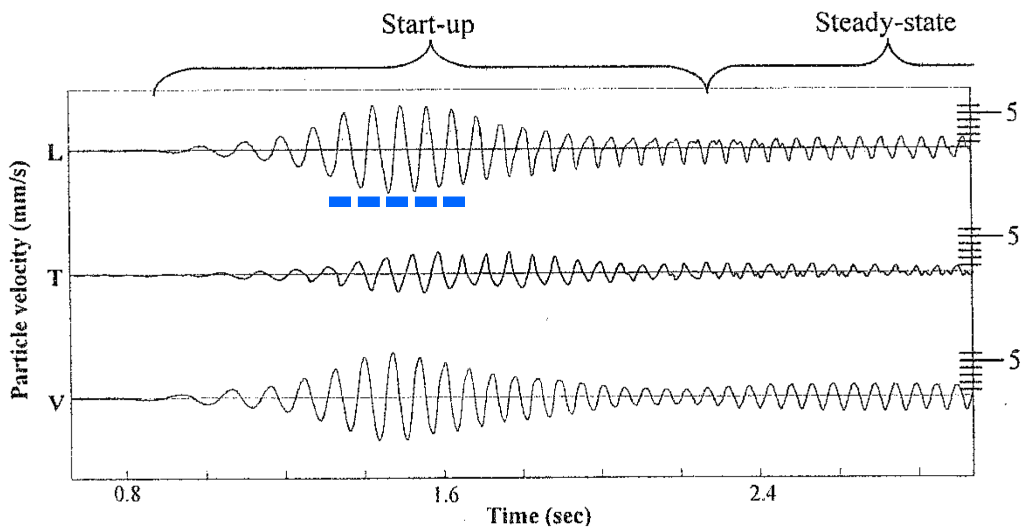


FIGURE 2. Typical Velocity Waveform

N is not Time/Frequency but more likely
2 x 7 -- x number of piles and then
only for the closest at the max PPV

Differences in Settlement Calculated w/ Other Assumptions:

far less to no settlement (0.086in) fits w/ measured floor tilt

1	House A	0.24(top)-0.68 (bottom)	500000	23	1	0.76	1. ground water table at 12ft 2.Surcharge = 7.78 psi 3. Atwell-Farmer anttenuation from the bottom 4.K0 = 0.47	miscalculated s, p' Confirmed with Dowding's recalculation
2	House A2	0.24(top)-0.68 (bottom)	500000	23	1	1.36	Same as case 1	corrected s and p' Dowding's recalculation S = 1.41
2B	Dowding	0.24(top)-0.68 (bottom)	500000	23	1	0.756	Same as case 1 but surcharge is redistributed by Boussinesq (footing width 4ft)	
2N	Dowding	0.24(top)-0.68 (bottom)	600 or1200	23	1	0.552 (0.553)	Same as case 1	N=600 (min) or 1200 make little difference
2R	Dowding	0.22 ips (top) with R-wave attenuation	1200	23	1	0.083	Same as case 1	Rayleigh wave (15 Hz assumed) attenuation
2BNR	Dowding	0.22 ips (top) with R-wave attenuation	1200	23	1	0.086	Same as case 1 but surcharge is redistributed by Boussinesq (footing width 4ft)	Rayleigh wave (15 Hz assumed) attenuation

Sand Stiffness/Shear Wave Velocity

House A estimate of low propagation velocity (450 fps) is low. Should have been

C_s	Elev (ft)	N
500	25-29	7
500-550	20-25	12
600-625	< 20	>20

Density immediately below house A > than that outside because of vibrations from construction of the House A .

Can round, beach sand exist at a density (e) with a shear wave propagation velocity (PV) < 500 ft/s

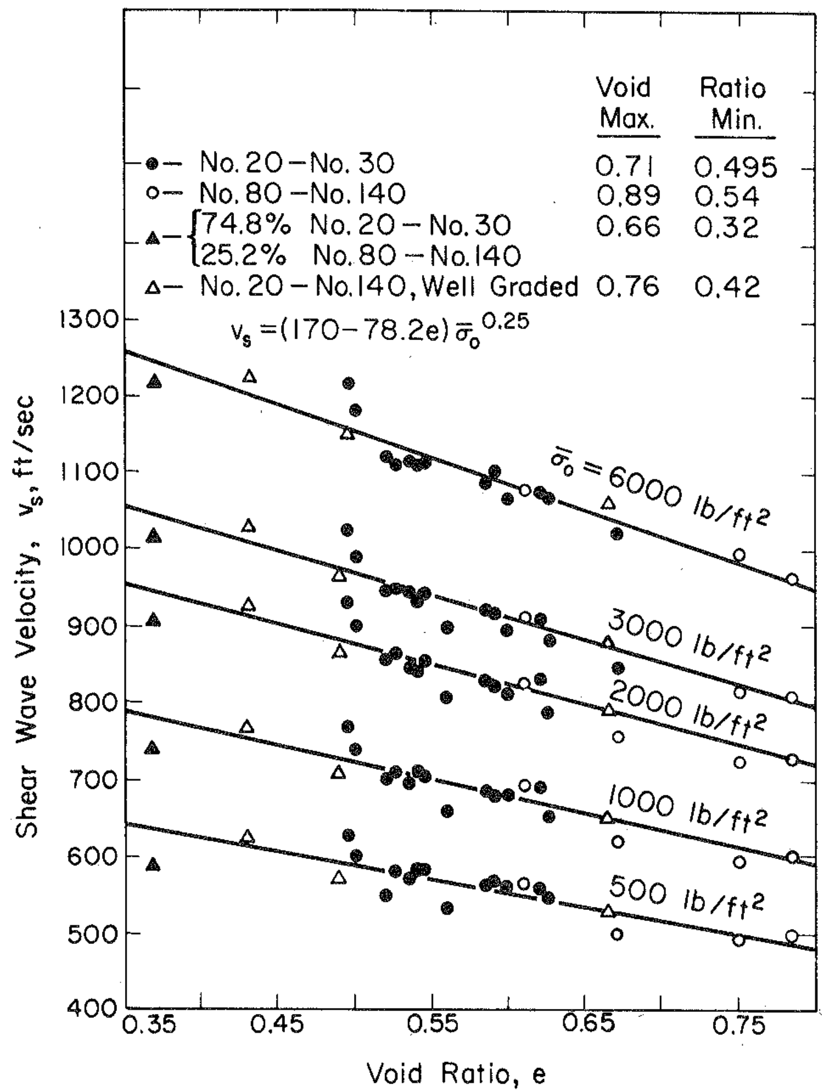


Figure 6-7. Variation of shear-wave velocity with void ratio for various confining pressures, grain sizes, and gradations in dry Ottawa sand (*from Hardin and Richart, 1963*).

Stresses or Strains Must be Measurable as with CTS and TS tests

Vibration control

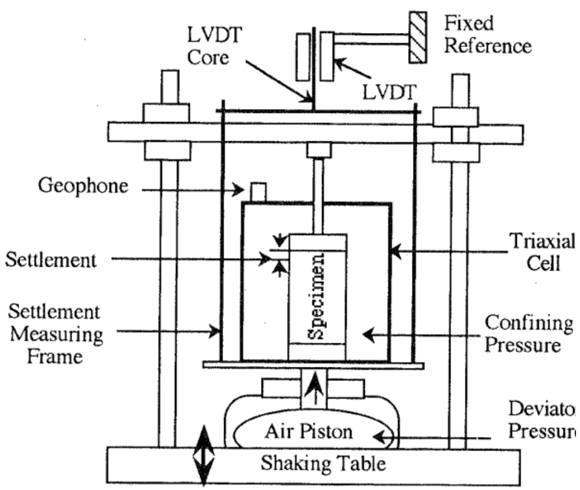
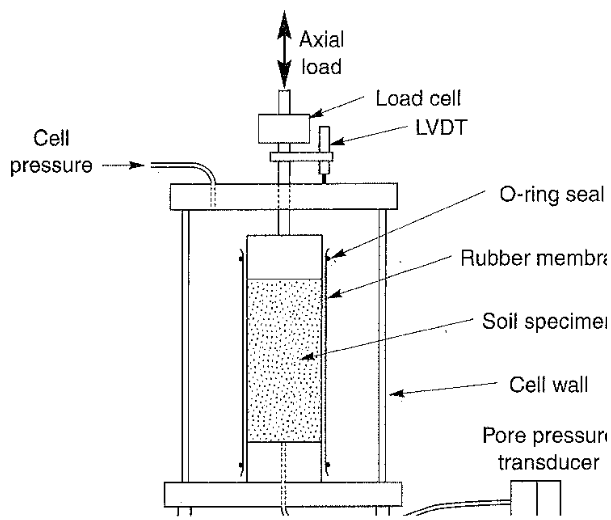


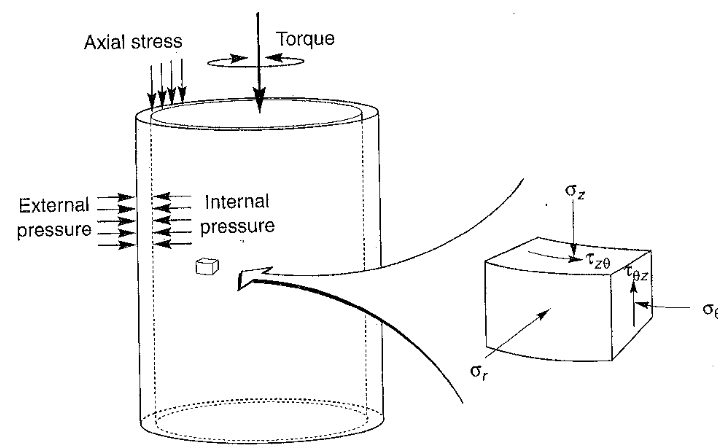
FIG. 1. Schematic Diagram of Testing Equipment

Kim-Drabkin Device

Kim et al (1994) ASCE GSP 40

Stress Control





Cyclic Triaxial Shear or Torsional Shear

Kramer (1996) Geotechnial Earthquake Engineering, Prentice Hall

Threshold, or minimum vibratory strain necessary to induce volume change ~ 0.01%

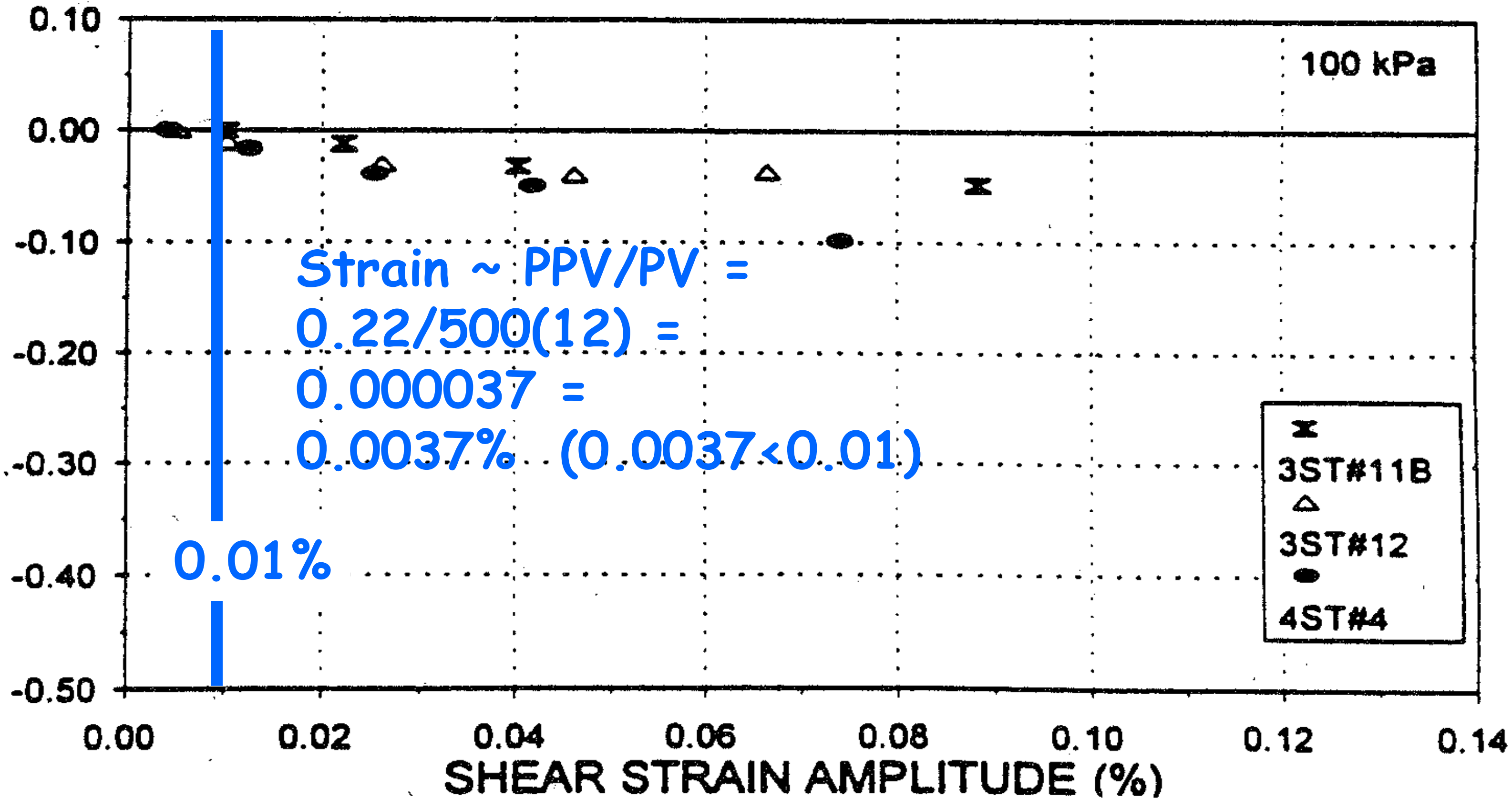
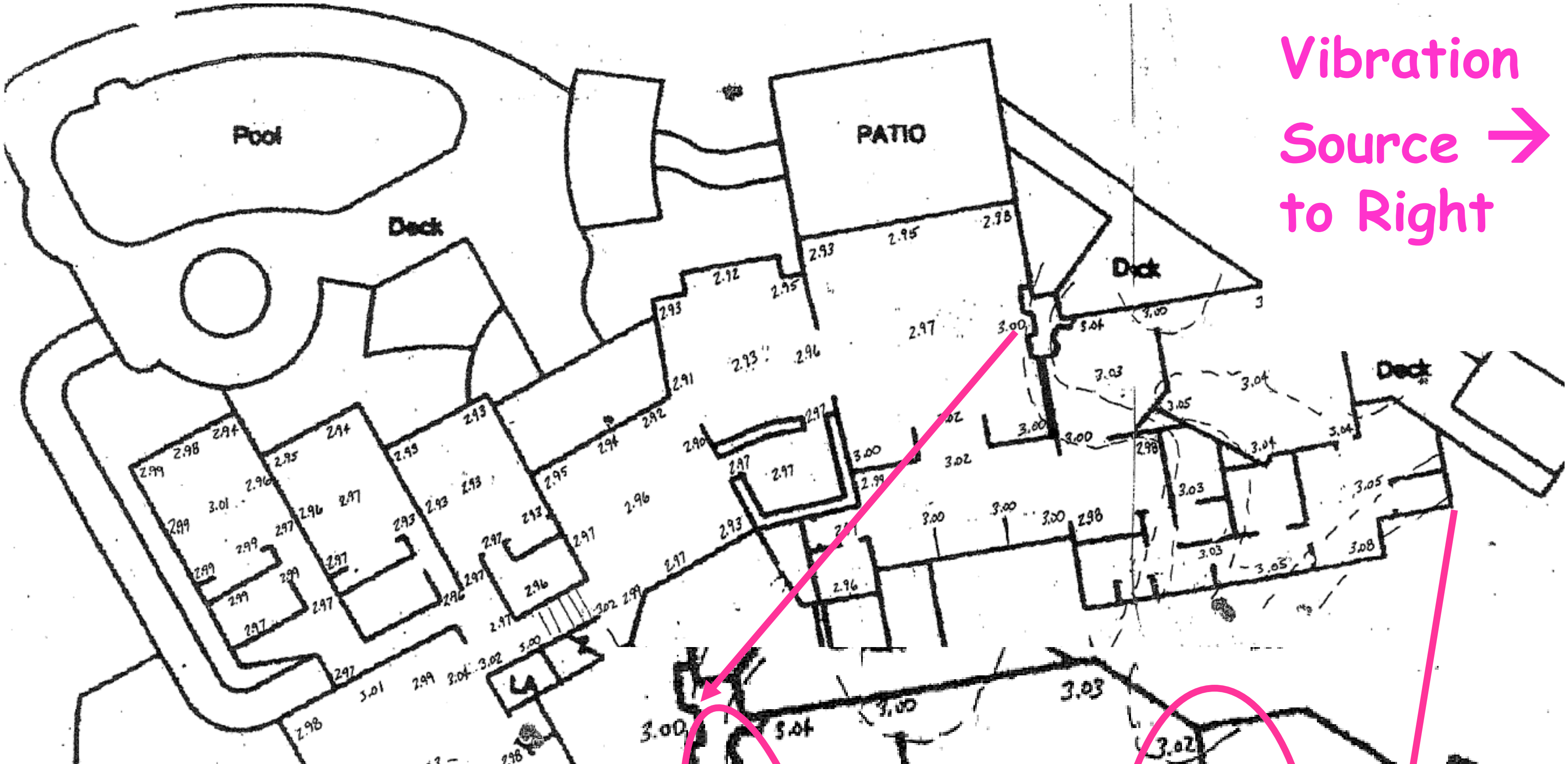
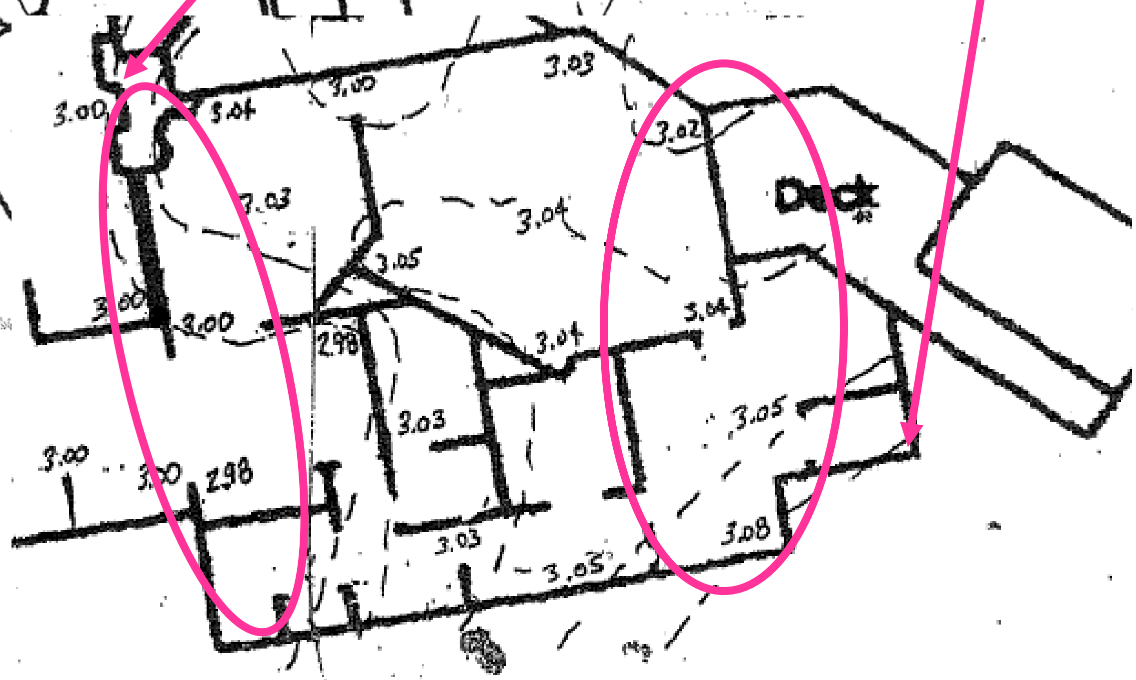


Figure 4.23 Dynamic Volumetric Strain for 1000 Cycles as a Function of Shear Strain Amplitude for Specimens Tested during Phase II (b) and (c)

Borden, Shao, & Gupta (1994) Construction Related Vibrations, NCSU, FHWA/NC/94-007

Vibration Source → to Right





Measured floor elevations of nearest room show ~0.1 ft (1 in) tilt AWAY from vibration source

Conclusions

- Avoid signing indemnification clauses
- Scale and relative size are important
- Low hanging fruit research project
  - Motions at depth at distance
- Understand limitations of polynomial factor analyses
- Develop 3D, physics-based, simulation models
- Conduct experiments with
  measurable/controllable stresses or strains
- **Its all about strain**