Pore-Pressure Prediction of Fluidization and Scour

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Bridge Scour - Thailand

- Bridges often remained in good shape structurally

- Patong Beach

- Ban Bangniang

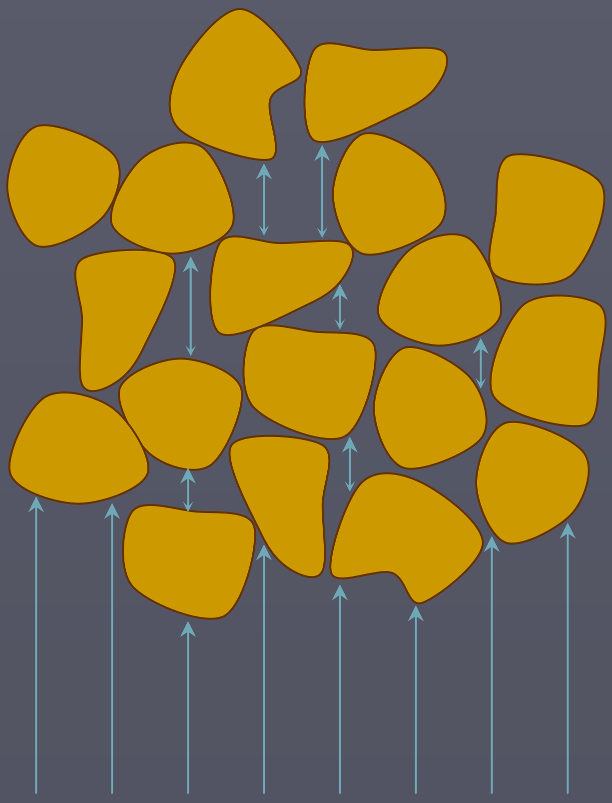
All photographs from ASCE

Bridge Scour - Sri Lanka

- Ambalangoda

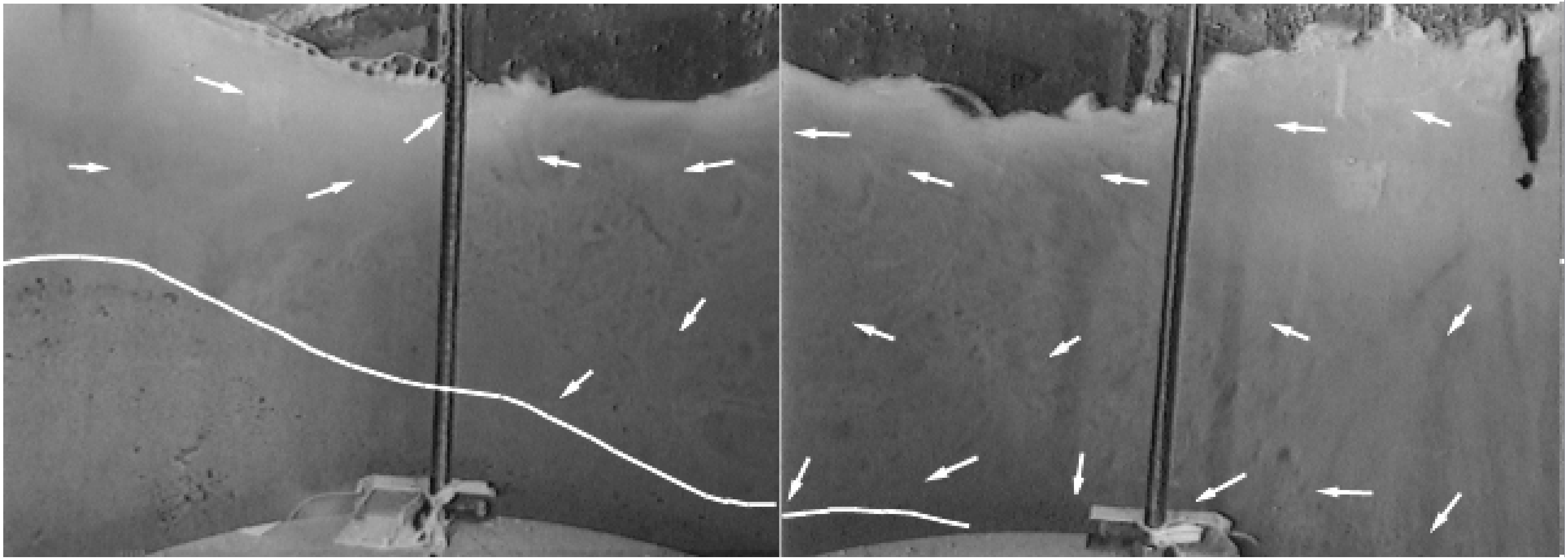
Scour Mechanisms

- Shear stress due to water motion : Shields
- Low effective stress between sand particles
  - Dependent on pore pressure gradient
  - Sediment liquefies if effective stress disappears
  - Smaller pore pressure gradients can enhance scour due to shear stress



  - Distinct from liquefaction under cyclic loading

Experimental / Analytic Approach



Excess Pore Pressure

- Define excess pore pressure p_e:

$$p_e(z,t) = p(z,t) - \rho_w\, g\,[h - z]$$

- Sediment liquefies/fluidizes when:

$$\left.\frac{\partial p_e}{\partial z}\right|_{z=z_0} \geq -(\rho_{sat} - \rho_w)g \equiv -\gamma_b$$

- Define scour enhancement parameter:

$$\Lambda(z) = \frac{p(z) - p(z_0)}{\gamma_b |z - z_0|}$$

Analytic Model - 1

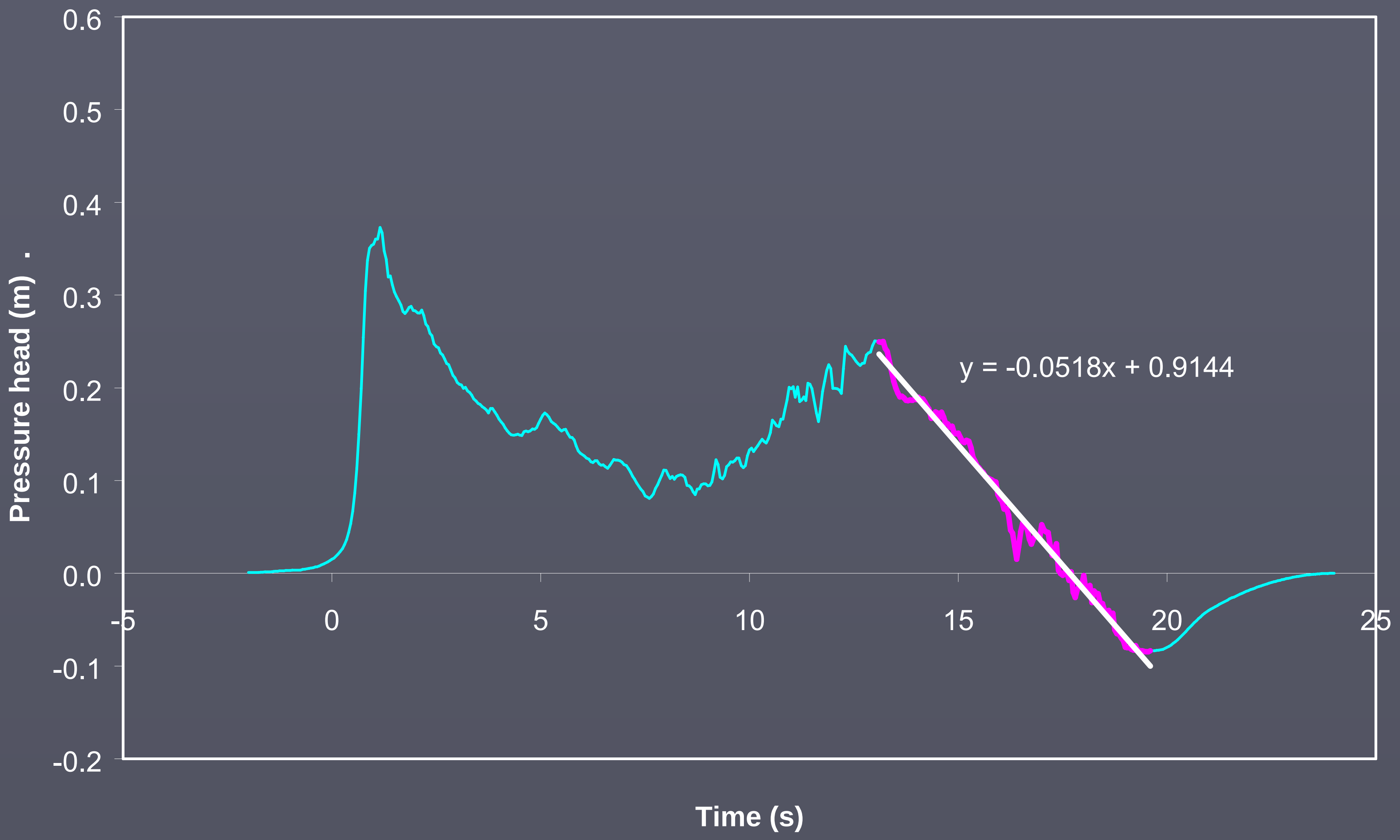
- Terzaghi (1925) diffusion model, used in geotechnical engineering:

$$\frac{\partial p_e}{\partial t} = c_v \frac{\partial^2 p_e}{\partial t^2}$$

- Coefficient of consolidation c_v:

$$c_v = \frac{k}{\gamma_w} . \frac{1+e_0}{a_v} \quad \text{where} \quad a_v = -\frac{de}{d\sigma'}$$

Linear Drawdown of Water Level



Analytic Model - 2

- At the end of drawdown, the excess pore pressure becomes:

$$p(z) = 4\,\Delta p\; i^2 erfc\left(\frac{-z}{2\sqrt{c_v\,\Delta T}} \right)$$

- The scour enhancement parameter becomes:

$$\Lambda(d_s) \equiv \frac{p_e(-d_s) - p_e(0)}{\gamma_b d_s}$$

$$= \frac{\Delta p}{\gamma_b d_s}\left(1 - 4\mathrm{i}^2\mathrm{erfc}\left[\frac{d_s}{2\sqrt{c_v \Delta T}} \right] \right).$$

Analytic Model - 3

- The scour enhancement parameter at the surface becomes:

$$\Lambda(0) = \frac{2}{\sqrt{\pi}} \frac{\Delta p}{\gamma_b \sqrt{c_v \Delta T}}.$$

- Fluidization occurs to depth d if $\Lambda(d) = 1$
- Experiments suggest enhanced scour (beyond Shields-type modeling) if $\Lambda(d) > 0.5$

Analytic Model - 4

h (m)	H (m)	ΔT (s)	ΔP (kPa)	ΔH_p (m)	$\Lambda(0)$	Measured scour depth d_s (m)	$\Lambda(d_s)$
Values at Cylinder Front							
2.65	0.13	4.5	1.28	0.13	0.26	0.000	-
2.65	0.24	6.5	1.77	0.18	0.30	0.025	-
2.65	0.34	6.0	1.96	0.20	0.35	0.043	-
2.45	0.22	3.0	1.37	0.14	0.35	0.024	-
Values at Cylinder Back							
2.65	0.13	4.5	1.67	0.17	0.35	0.026	-
2.65	0.24	6.5	3.34	0.34	0.57	0.144	0.52
2.65	0.34	6.5	3.63	0.37	0.62	> 0.2	< 0.55
2.45	0.22	6.5	3.34	0.34	0.57	0.145	0.52

Criteria for Enhanced Scour

Criteria for enhanced scour at depth d_s, from

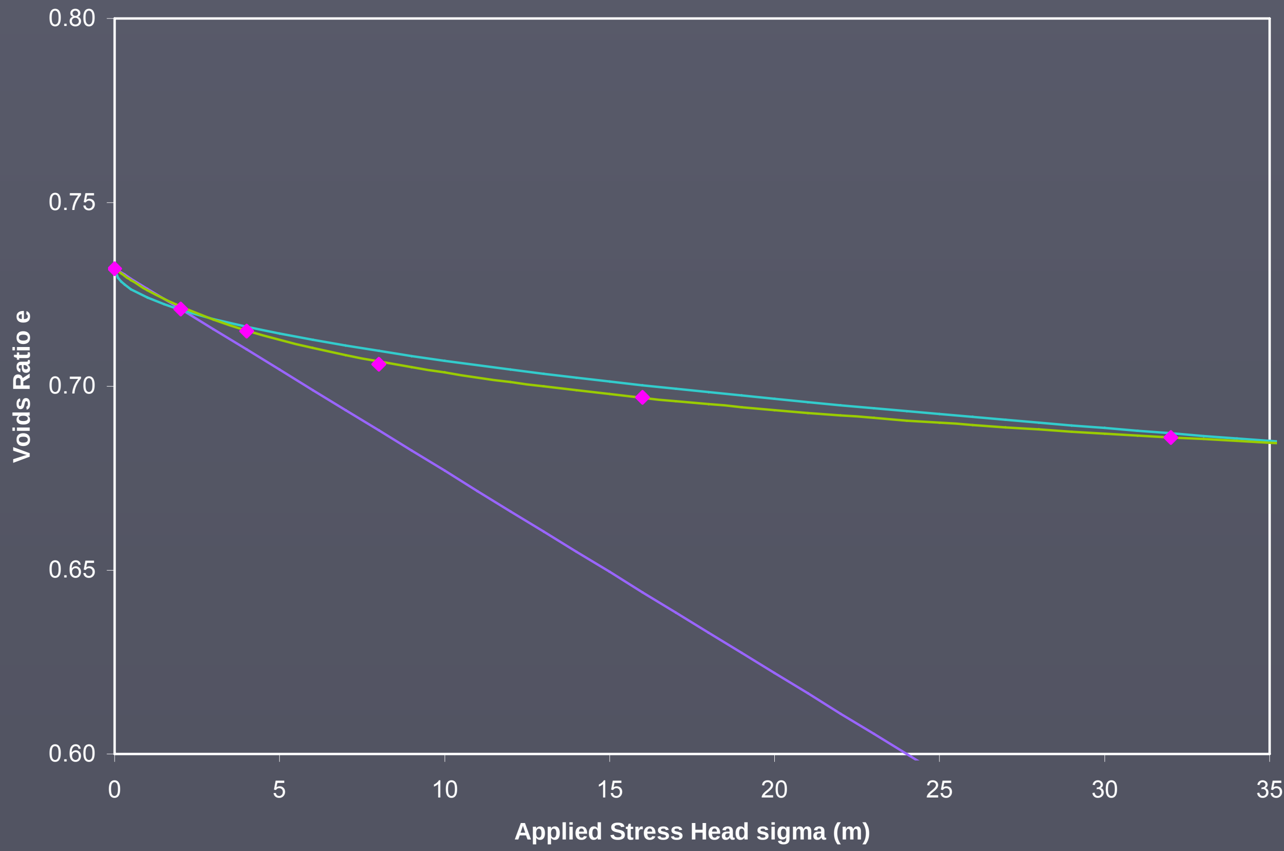
$$\Lambda(d_s) = \frac{\Delta p}{\gamma_b d_s}\left(1 - 4\mathrm{i}^2\mathrm{erfc}\left[\frac{d_s}{2\sqrt{c_v \Delta T}}\right]\right).$$

- Drop in water level / pressure head ΔP:
  At least ~ $\gamma_b d_s$ to allow sufficient pore pressure gradient to build up

- Time scale of drawdown ΔT:
  No more than ~ d_s^2/c_v so the excess pore pressures do not dissipate over depth

Standard Measurement of c_v

- Measure void ratio against effective stress
- Effective stress head: 0 to 64 m



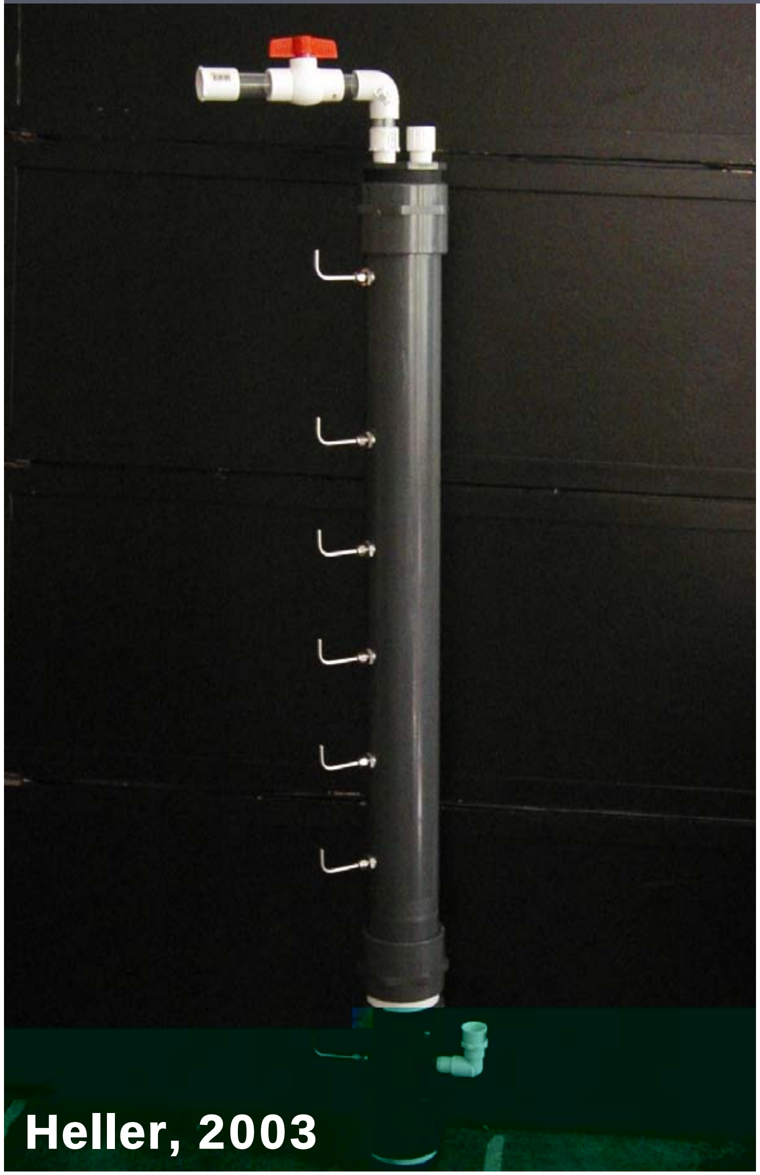
- Different low-stress models: Hicher (1996)

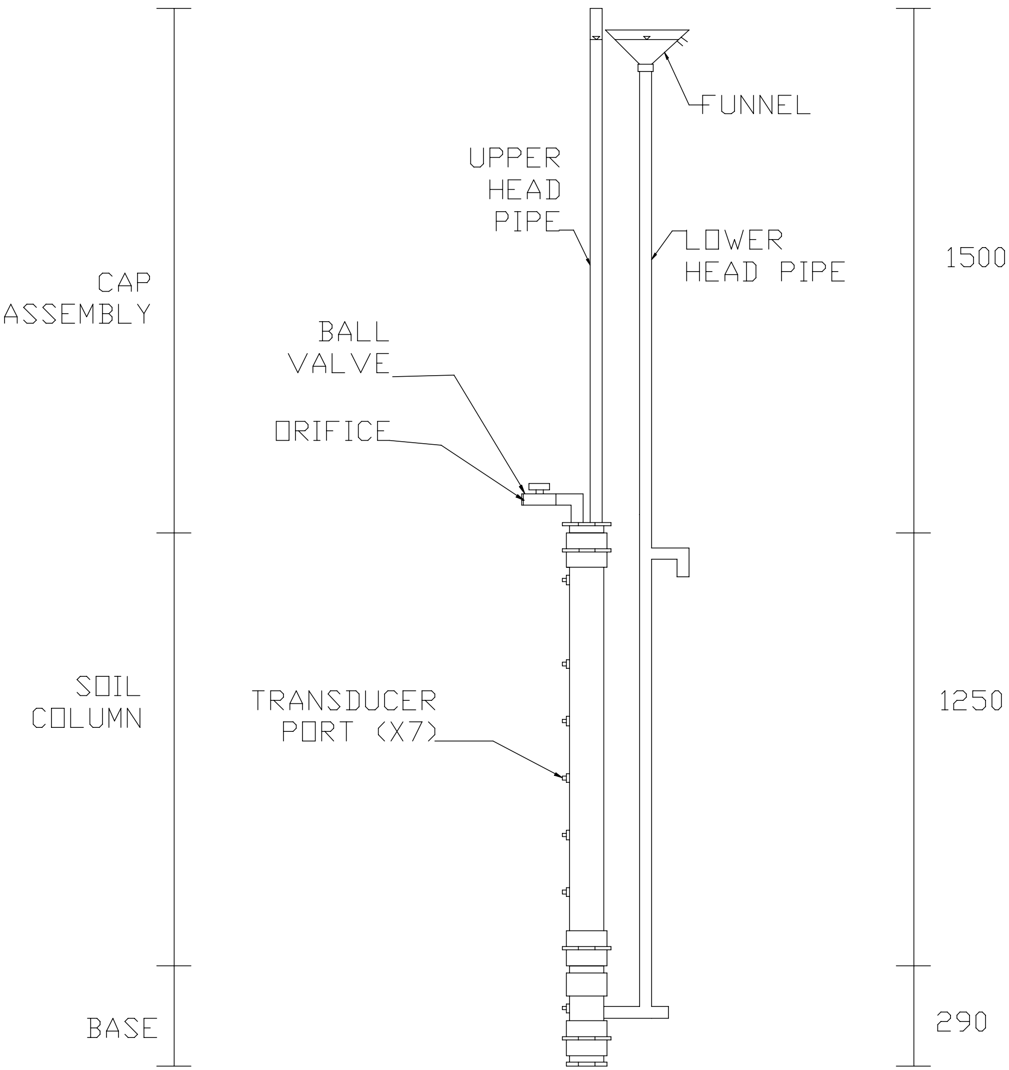
Coefficient of Consolidation c_v

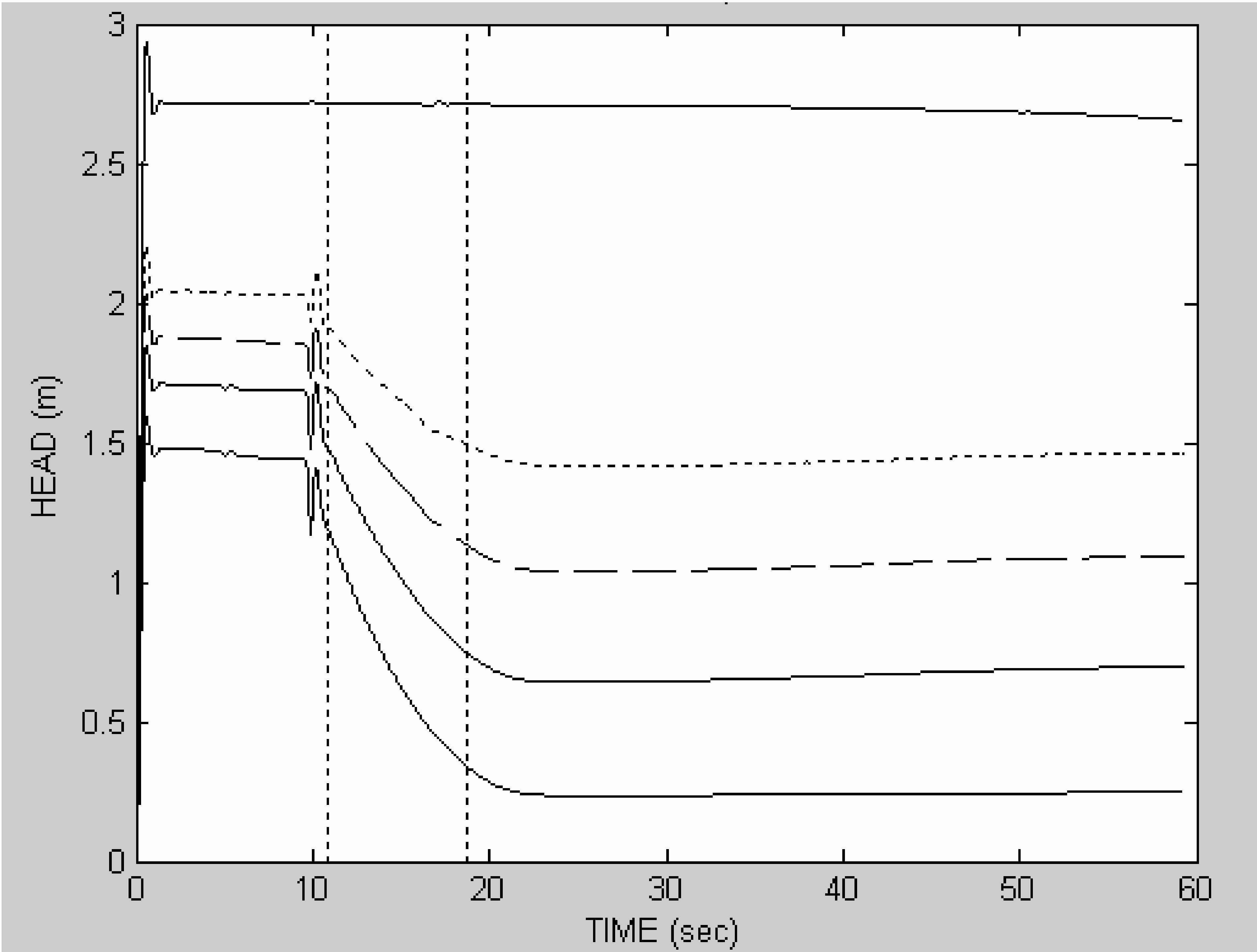
Soil Description	D_{50}(mm)	c_v(cm^2/s)	Ref
Hazaki sand	0.16	7,180	1
Hazaki sand	0.16	11,520	1
Toyoura sand	0.18	12	2
Fine sand	0.26	1300	3
Beach Sand: 1	0.35	840	4,5
Beach Sand: 2	0.35	1,225	4,5
Beach Sand: 3	0.35	10,000	1

1. Zen & Yamazaki, 1991
2. Zen & Yamazaki, 1990
3. Heller, 2003
4. Tonkin 2001
5. Tonkin et al, 2002

Direct c_v Determination: Apparatus



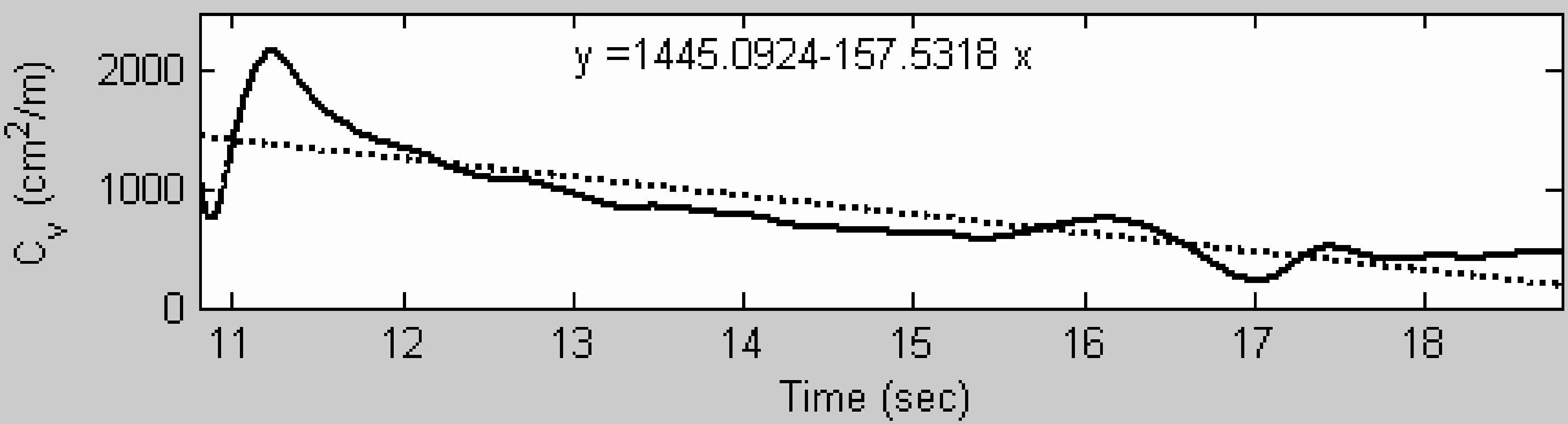




HEAD (m)
TIME (sec)
0
0.5
1
1.5
2
2.5
3
0
10
20
30
40
50
60

Direct c_v Determination: Results

- ►Measured c_v decreased during drawdown



- ►Average values agreed with cylinder experiments

Conclusions

- Most fluidization occurs near the end of drawdown
  - After greatest velocities occur
  - Extremely turbulent, three-dimensional
- Defined scour enhancement parameter
  - Enhanced scour if $\Lambda > 0.5$
  - Liquefaction if $\Lambda > 1$
- Need to understand

[illegible]