PIERRE FORAY MEMORIAL
BEHAVIOR OF SOILS UNDER STATİC, CYCLİC AND DYNAMIČ LOADİNGS

ZELAZNY MOST - POLAND
TAILİNGS STORAGE FACİLITY
GEOTECHNICAL CHARACTERİZATİON
OF COPPER TAIŁİNGS

Michele Jamiolkowski – Emeritus Professor
Politecnico di Torino
Maximum dam height: 63 m
Total volume stored: 527x10^6 m³
Storage rate: ≤17.5x10^6 m³/annum
Area covered: 12.4 km²
Total length of dam: 14.3 km
Operation period: 1977 to 2042
CONSIDERING:

- DEPOSITORY OPERATION TIME: 1977 → 2042
- SCALE OF FACILITY AND LOCAL POPULATION
- RING DAM STABILITY: A GEOTECHNICAL CHALLENGE

IN 1992 POLISH GOVERNMENT AND MINE, ON WORLD BANK RECOMMENDATION, APPOINTED A FOUR-MEMBER IBE:

→ Dr. D. CARRIER, (USA) → Prof. K. HØEG (NORWAY)
→ Prof. R.D. CHANDLER (UK) → Prof. M. JAMIOLKOWSKI (ITALY)

TO OVERSEE, WITH POLISH EXPERT PROF. W. WOLSKI, THE SAFE TAILINGS DAMS CONSTRUCTION VIA OBSERVATIONAL METHOD [PECK (1969, 1980)]
GEOTECHNICAL CHARACTERIZATION OF TAILINGS

Selected Topics

In situ tests

- Spatial variability → S-CPTU, S-DMT (\(V_s\) & \(V_{s1}\))
- Location of the saturation surface → CHT (\(V_p\))
- Evaluation of in situ porosity → CHT (\(V_p\) & \(V_s\))

Laboratory tests on undisturbed samples retrieved from hand-dug pits using gel-push piston sampler

- Index properties and grading
- Monotonic undrained triaxial compression tests (TX-CIU & TX-CK\(_0\)U) → susceptibility to flow failure
2014 - Est Dam - Location of Saturation Line from $V_p$ measurements

CH-XIX-7E
CH-XIX-8E

$D = 17\text{m}$
Elev. = 163.8

$D = 242\text{m}$
Elev. = 175.0

$D = 338\text{m}$
Elev. = 174.2

$P_H \text{ = Perched water table}$

G-273
PAR-05
2014 - North Dam - Location of Saturation Line from $V_p$ measurements

ZELAZNY MOST COPPER TAILINGS POND

CH-Va-1N
CH-Va-2N

D = 40m
Elev. = 173.9

CH-Va-4N
CH-Va-5N

D = 120m
Elev. = 176.8

CH-Va-7N
CH-Va-8N

D = 200m
Elev. = 176.5

Tailings

Depth, m

$V_p$

$V_s$

PH

$V_p$, m/s

$V_s$, m/s

Horizontal Scale

0 50
0 5
10m

Depth, m

40 800 1200 1600 2000
40 800 1200 1600 2000
40 800 1200 1600 2000

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PAR-06
## Depth to Saturation Line in Tailings

<table>
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<th>Cross-section</th>
<th>Lc (m)</th>
<th>Ds (m)</th>
<th>Elev. (m asl)</th>
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*Lc = distance from the dam crest; Ds = depth to saturation line*
Alleviating Soil Liquefaction by Induced Partial Saturation

Jay Landers, ASCE Civil Engineering, N°S, 212, Research Project sponsored by U.S. NSF & NEES

Principal Researchers:
- North-Eastern University, Prof. M. Yegian & Prof. A. Alsha W. Abebekhe
- State University of NY at Buffalo, Prof. S. Thevanayagam
- University of Texas at Austin, Prof. K.H. Stokoe
- Boise State University, Prof. A. Farid

Induced Partial Saturation under existing structures

- Water storage
- Mixer and/or Chiller
- Compressor
- Gas-generating solution
- Well
- Loose sand
- PVC pipe diameter 5 cm

Injection of water containing low concentration of dissolved ecofriendly chemicals generating gas bubbles conferring a near to saturated state
MESSINA STRAIT BRIDGE – SICILY TOWER
VOID RATIO OF UNDISTURBED* SAMPLES VS. COMPUTED

In situ void ratio, \( e_0 \)

Depth, meters

\( \rho_s = \) soil particles \} mass
\( \rho_f = \) pore fluid \} density
\( K_f = \) bulk modulus of pore fluid
\( \nu_s = \) Poisson ratio of soil skeleton

\( n = \frac{4(\rho_s - \rho_f)K_f}{V_p^2 - 2\left(1 - \frac{1}{1 - 2\nu_s}\right)V_s^2} \)

\( 0.5^{**} \)

(*) Retrieved by means of in situ freezing; (**) Foti et al. (2002) formula

- Green dots: Laboratory tests
- Red dots: From \( V_s \) and \( V_p \), CH tests

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LIS-19
PISA CLAY - POROSITY FROM CH TESTS

- Man made ground
- Sandy silt
- Clayey sandy silt
- Medium sand
- Upper silty clay (Pancone)
- Intermediate silty clay
- Intermediate sand
- Lower silty clay
- Lower sand
- Lightly cemented silty sand
- Organic silt
- Lower sand

Porosity, n

Undisturbed samples

LAB. (Laval)
LAB. (Osterberg)
SAMPLING OF TAILINGS FROM THE BEACH

- 3m deep trenches excavated in the beach
- Thin wall (2mm) stainless steel cylinders (D=70mm, H=140mm) with sharp cutting edges pushed into the soil
- Retrieved samples subject to consolidated undrained triaxial tests

GEOTEKO (2011)
GEL PUSH SAMPLER

a) Lowering down the sampler to the bottom of borehole

Outer head
Spring
Bearing
Inner head
Outer tube
Inner tube
Stainless steel
Free piston
Cutting shoe

b) During sampling (flow of drilling fluid and polymer solution)

Drilling fluid
Discharge polymer

Polymer solution
Free piston
Sampler

Flow of drilling fluid
Flow of polymer solution
OVERALL GRADING OF TAILINGS

GEL-PUSH SAMPLE OF SILTY SAND – 3rd TRIAL*

\[e_0 = 0.895; \quad \gamma = 18.6 \text{kN/m}^3; \quad G = 2.745; \quad 5.25 \leq SFR \leq 7.62\]

Lenght 520 mm; Diameter 72 mm

Coarse tailings used to build the dam shell

(*) 3rd trial, carried out close to the dam crest, Section XVIE

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PAR-12
UNDISTURBED TAILINGS CORES
RETRIEVED USING G-P TR SAMPLER

(* 3rd Trial, January 2014)
Index properties of ZM tailings of G-P

- FC, %
- γ, kN/m³
- e₀

Depth, m

- 1st trial
- 2nd trial
VOID RATIO OF G-P SAMPLES and COMPUTED FROM CHT

According to Foti et al (2002)

1st and 2nd trial

0 0.4 0.8 1.2 1.6
Void ratio, e

0 1 2 3 4
Depth, m

16.7 18.4 31
75.8 80.6 10
45.5 68.5 90.9 92.6
17.7 78.7
97.9 61.3
94.8 78.1 99.9 99.2
44.6 87.7
95.4 73.5
99.8 95.6
99.6

G-P specimens

FC%
INDEX PROPERTIES OF ZM TAILINGS

Tr GEL-PUSH SAMPLER, 3rd Trial, ≈ 20m from dam crest

<table>
<thead>
<tr>
<th>FC, %</th>
<th>PI, %</th>
<th>( e_0 )</th>
<th>( \left( \frac{S_u}{\sigma'<em>{vo}} \right)</em>{pt} )</th>
<th>( \gamma ), kN/m³</th>
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Depth m

3rd trial
POROSITY OF SATURATED SOILS
FROM SHEAR AND COMPRESSION WAVES VELOCITY

- Poroelasticity theory approach, \cite{Foti2002, Foti2004} to assess in situ porosity based on measured $V_p$ and $V_s$ velocities
- As to inverse problems, reliability of obtained results controlled by key input parameters, $V_p$ and, to a lesser extent, $V_s$
- Carried out properly devised cross-hole tests, most suitable to obtain independent, highly accurate $V_p$ and $V_s$ measurements
- Quantifying uncertainties involved in assessing picking arrival time and travel distance can enhance computed porosity reliability
TX-$CK_0$U-C tests on undisturbed G-P specimen

Geoteko (2014)

Axial strain $\varepsilon_a$, %

Excess pore pressure $\Delta u$, kPa

Mean effective stress $p'$, kPa

Principal stress ratio, $c'/c''$

3rd trial

 Depth 5.5m; Fine silty sand: $\gamma = 18$ kN/m$^3$; $e_0 = 0.861$; FC = 11%; $V_s = 240$ m/s
**UNDISTURBED TAILINGS RESPONSE TO UNDRAINED SHEARING**

**GEOTEKO (2012)**

<table>
<thead>
<tr>
<th>$\sigma_a^{'}, \text{kPa}$</th>
<th>50</th>
<th>200</th>
<th>400</th>
<th>700</th>
<th>1000</th>
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<td>Frequency of occurrence, %</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>90.8%</td>
<td>7.2%</td>
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**ZELAZNY MOST COPPER TAILINGS POND**

**TX-CK$_{0}$U - K$_{0}$ = 0.5 - 84 tests**

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**Graph and Diagrams**

- **Dilative**: $q$ vs. $S_u$; $S_u^{(ss)}$, $p^{'ss}$
- **Contractive Dilative**: $q$ vs. $S_u$; Yield, $p^{'ss}$
- **Contractive**: $q$ vs. $S_u$; $p^{'ss}$

**Legend**:
- Dilative
- Contractive Dilative
- Contractive

**Axes**:
- $q$, $S_u^{(ss)}$, $p^{'ss}$
- $q$, Yield, $p^{'ss}$
- $q$, $p^{'ss}$

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\text{G-254, ZM-76}
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THANK YOU FOR YOUR ATTENTION