UNIVERSITÀ DI PISA
DIPARTIMENTO DI INGEGNERIA CIVILE E INDUSTRIALE
DICI

in convenzione con

SIGEA TOSCANA – Società Italiana di Geologia Ambientale

Ordine dei Geologi della Toscana

con il patrocinio di

POLITECNICO DI TORINO

UNIVERSITÀ DI PAVIA

AGI Associazione Geotecnica Italiana

REGIONE TOSCANA

con la partecipazione di

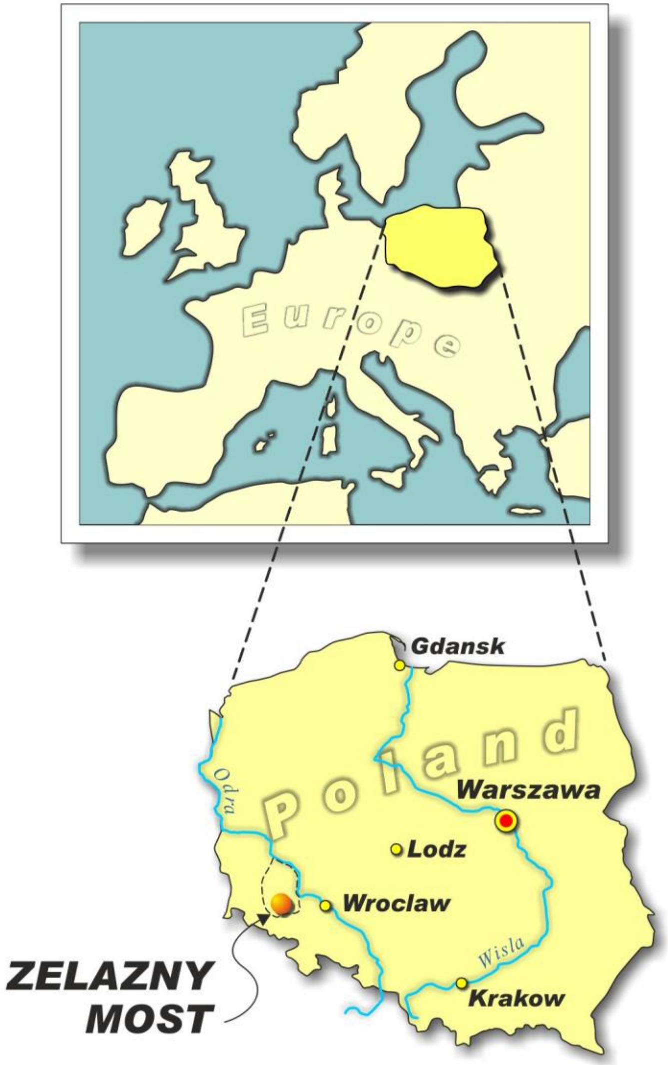
PAGANI® GEOTECHNICAL EQUIPMENT

PerlAmbiente

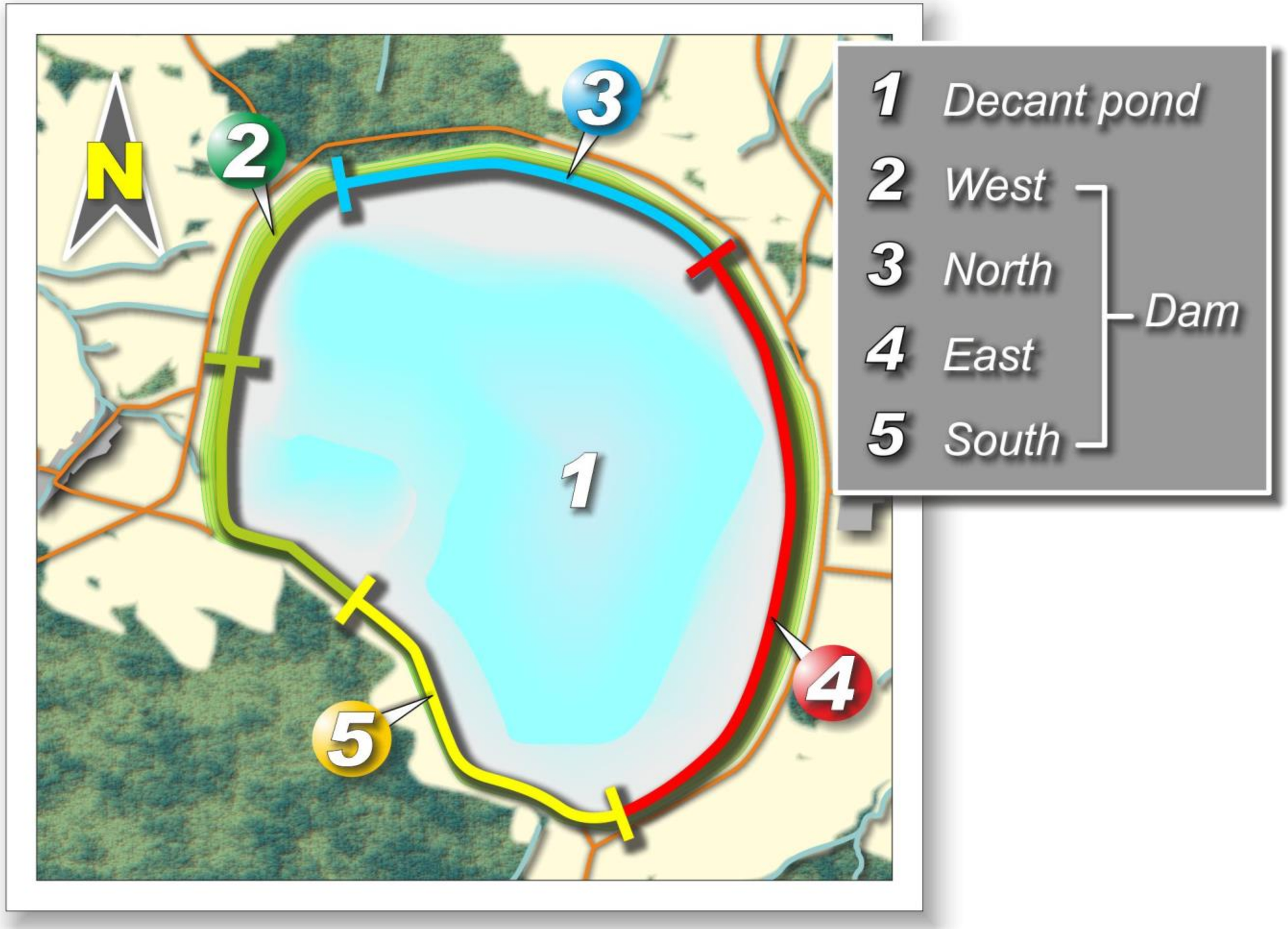
WORKSHOP
RECENTI SVILUPPI NELLE INDAGINI IN SITO
Pisa, Scuola di Ingegneria – 14 giugno 2019

PROF. MICHELE JAMIOLKOWSKI

ZELAZNY MOST COPPER TAILINGS DISPOSAL

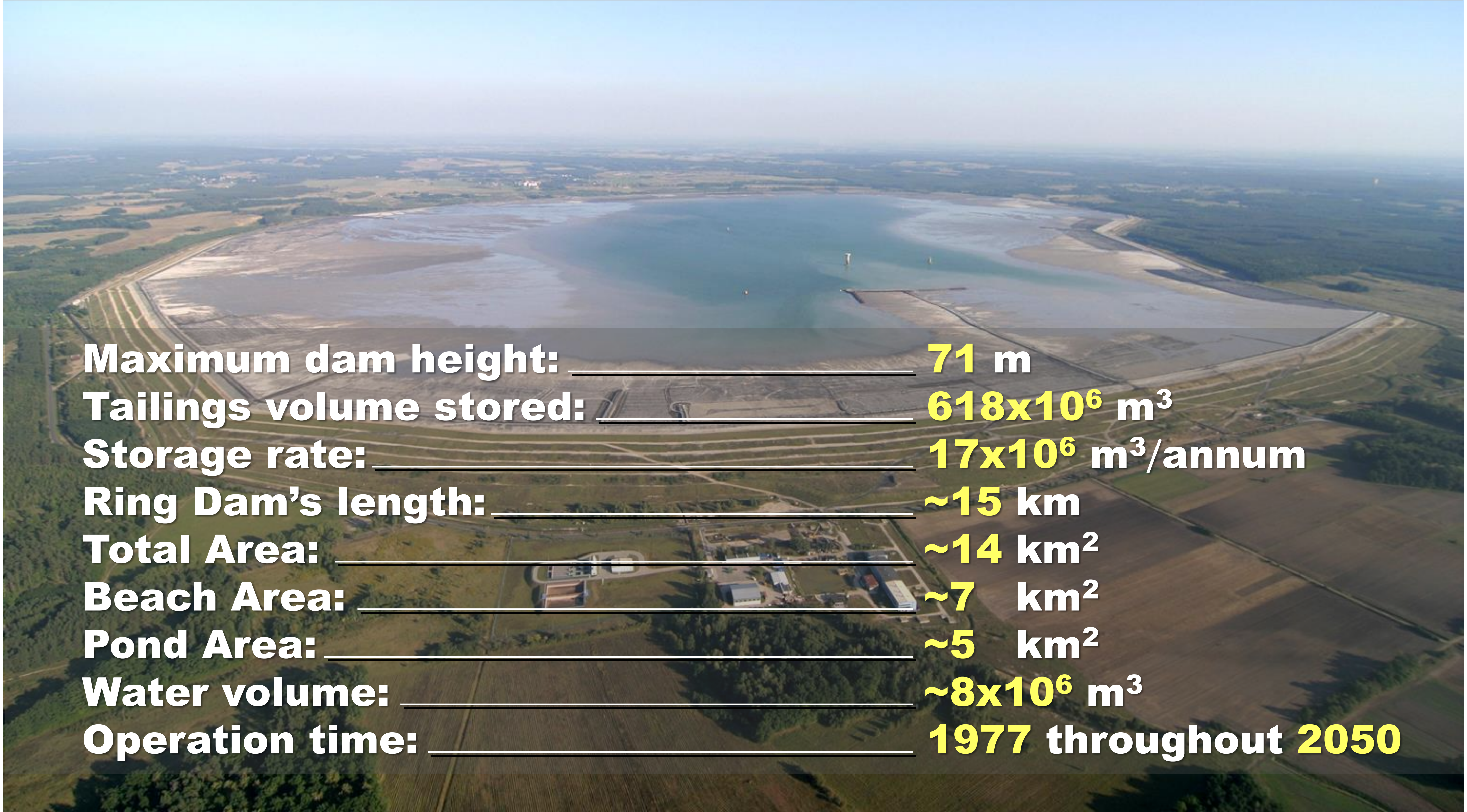


Plan of depository



ZELAZNY MOST TAILINGS DISPOSAL

Updated as of March 2018

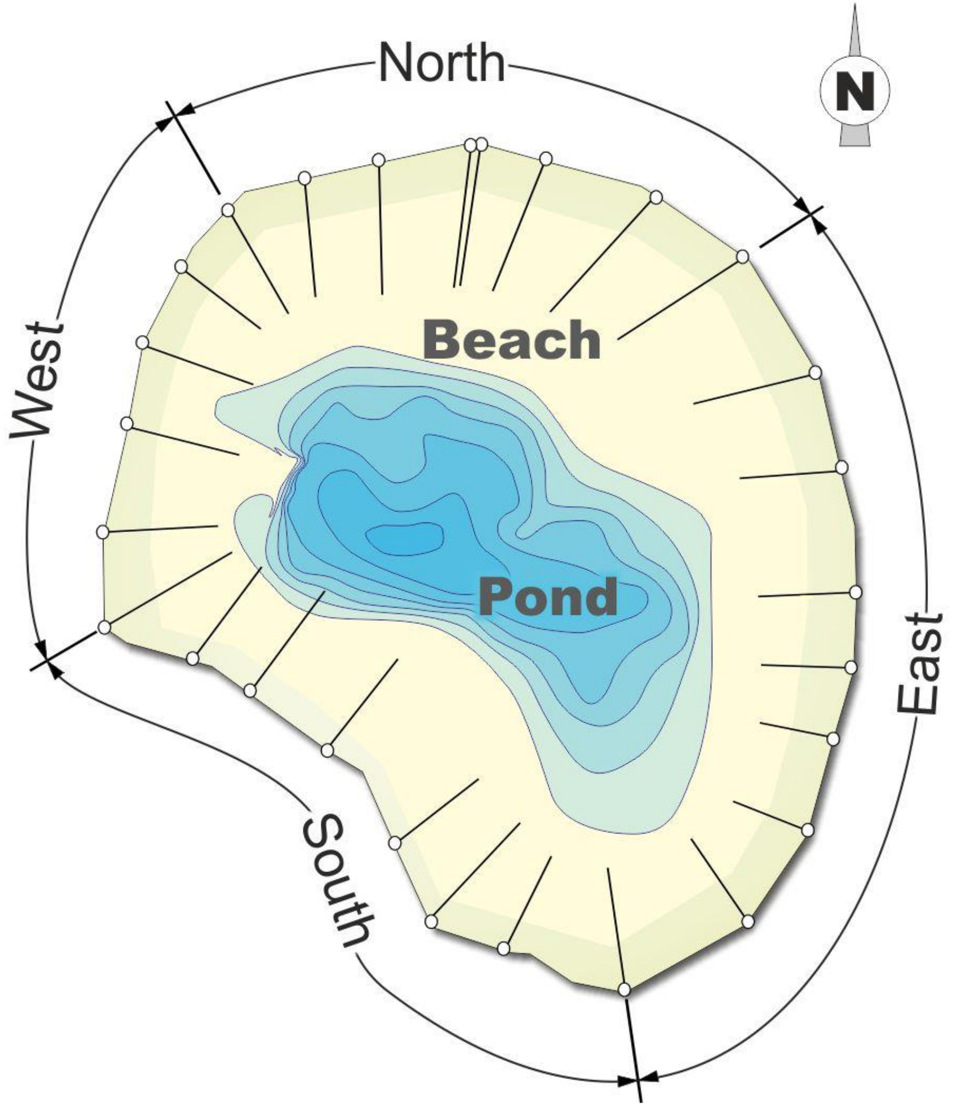


- **Maximum dam height:** ______ 71 m
- **Tailings volume stored:** ______ $618x10^6$ m^3
- **Storage rate:** ______ $17x10^6$ m^3/annum
- **Ring Dam's length:** ______ ~15 km
- **Total Area:** ______ ~14 km^2
- **Beach Area:** ______ ~7 km^2
- **Pond Area:** ______ ~5 km^2
- **Water volume:** ______ $\sim 8x10^6$ m^3
- **Operation time:** ______ 1977 throughout 2050

LECTURE OUTLINE

- Zelazny Most Tailings Disposal
- Role of seismic body wave tests
- Mapping location of phreatic surface
- Undisturbed sampling

DAM HEIGHT AND CREST ELEVATION
Updated at March 2018



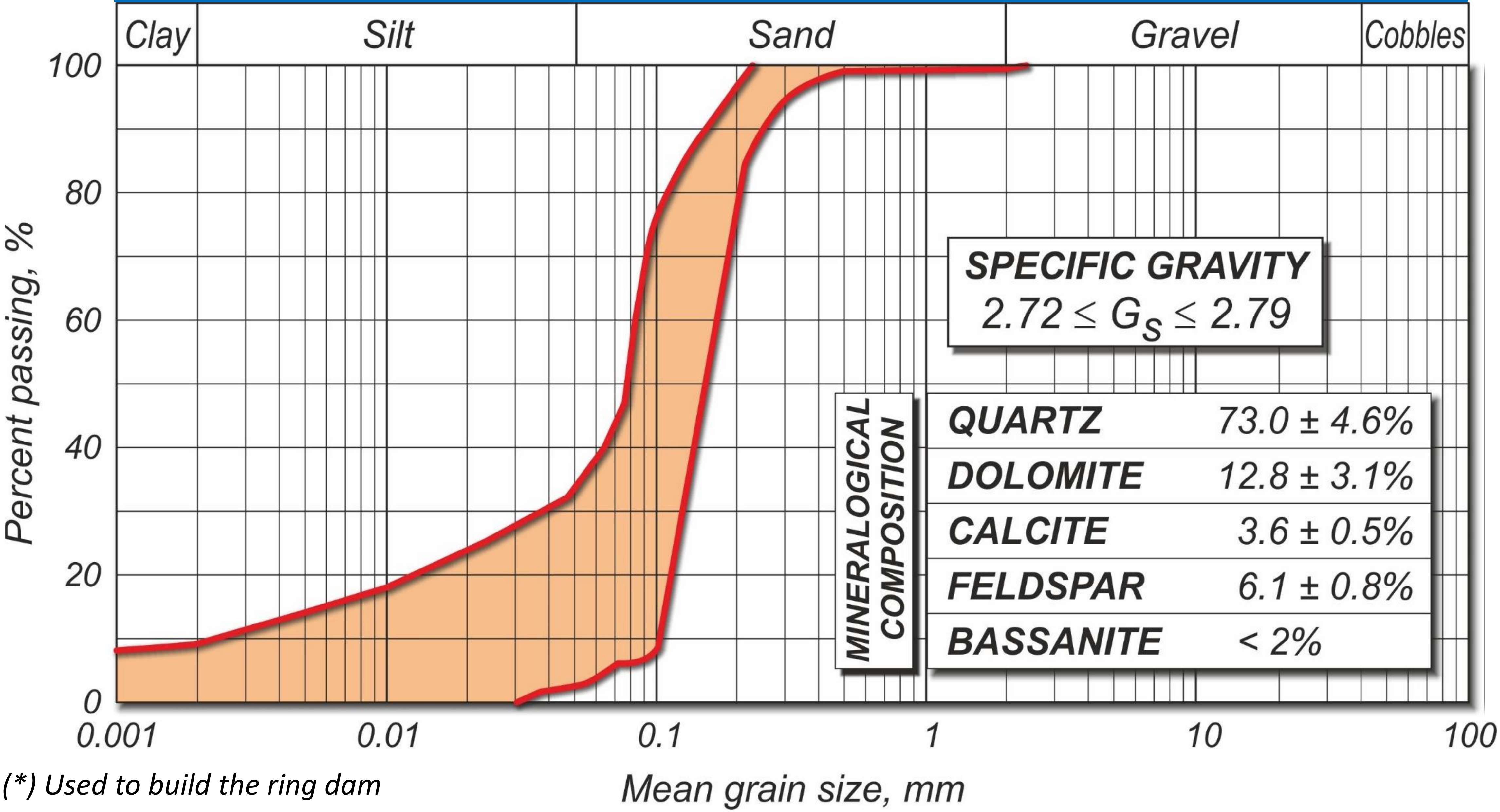
Dams Height, m

North:	49
West:	58
South:	41
East:	71

Crest Elevation:

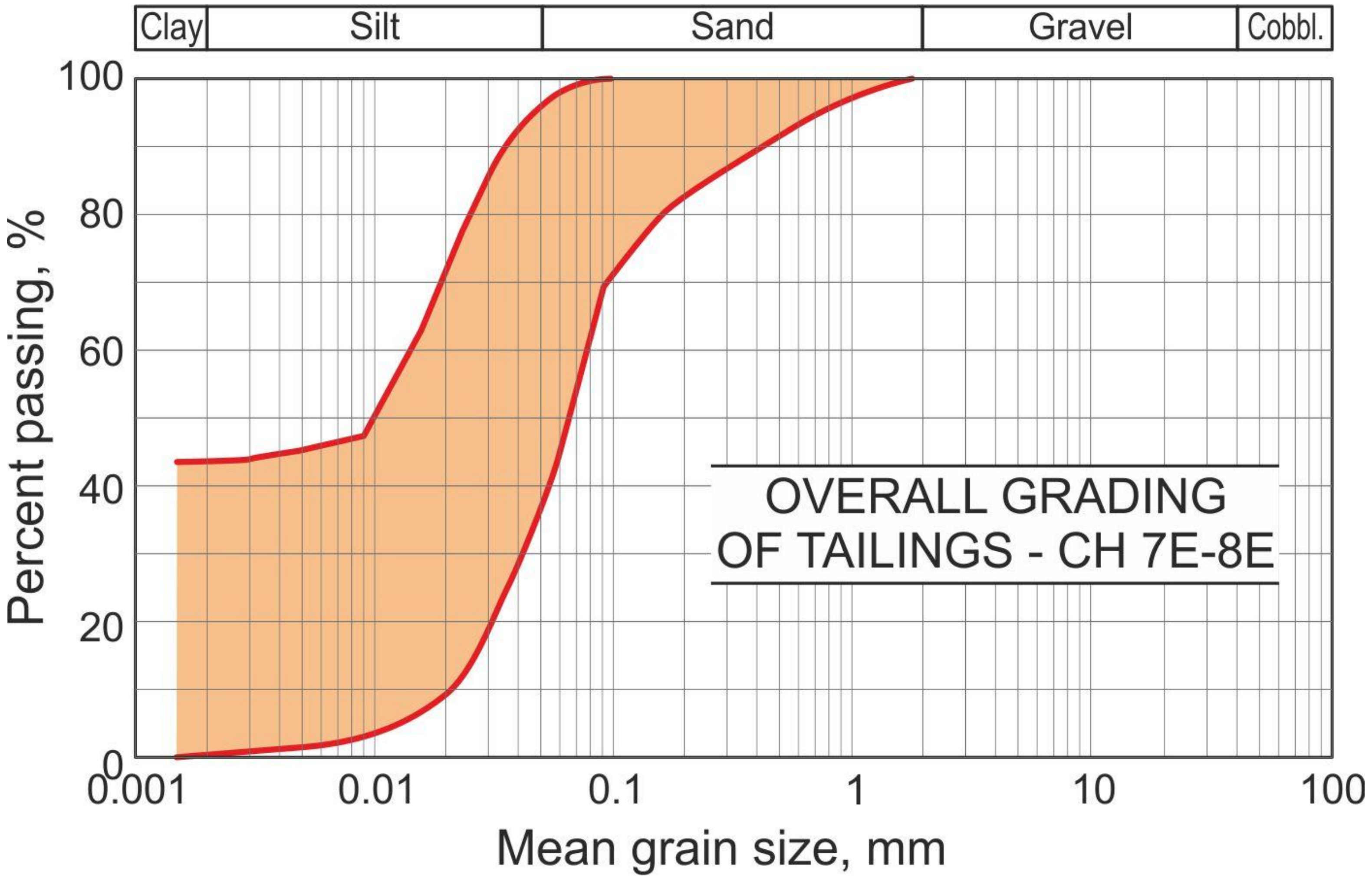
180 to 182 m asl

GRADING OF COARSE TAILINGS*



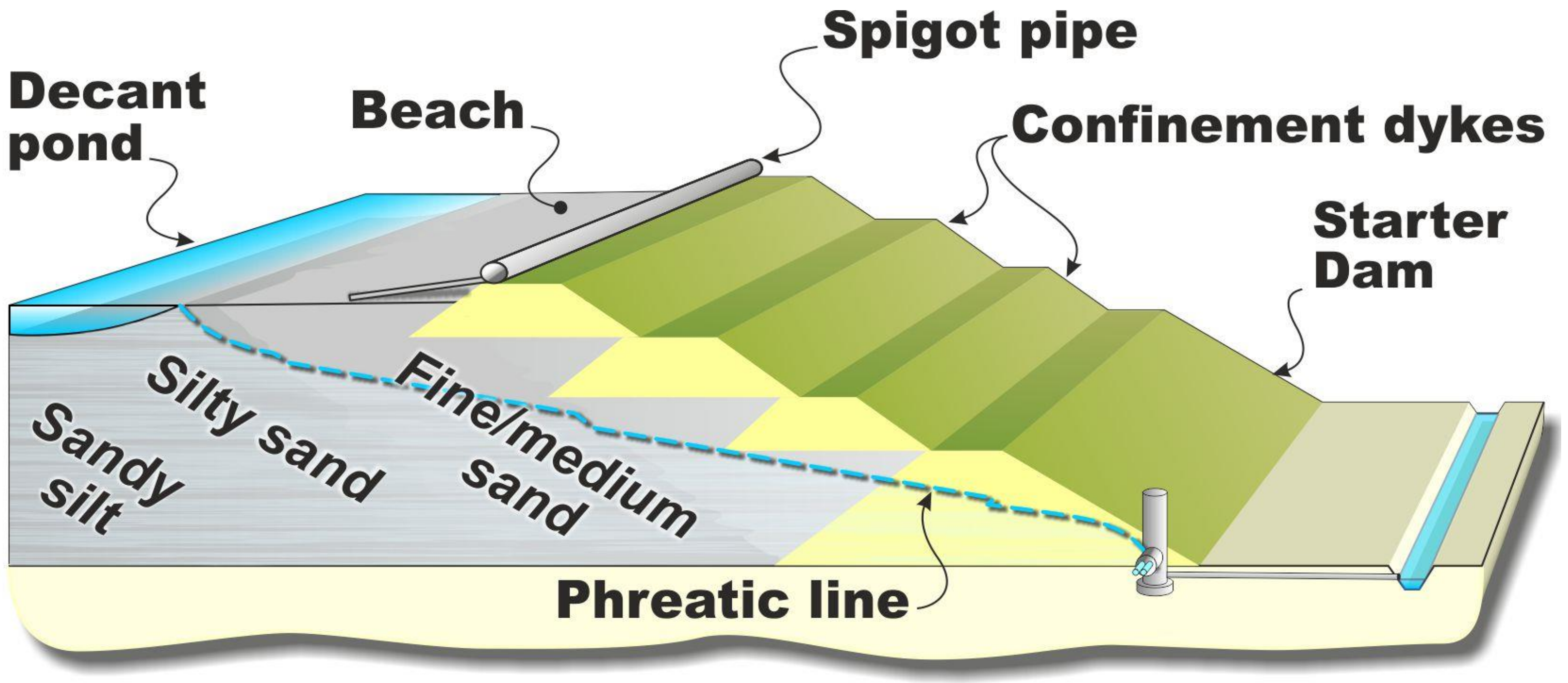
(*) Used to build the ring dam

OVERALL GRADING OF TAILINGS



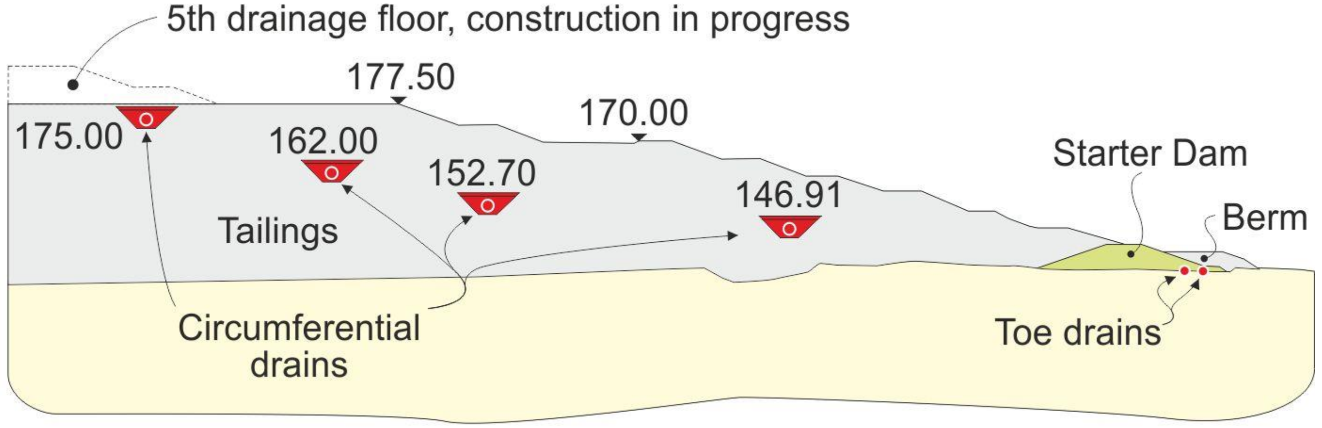
RING DAM - SCHEMATIC CROSS-SECTIONS

UPSTREAM METHOD

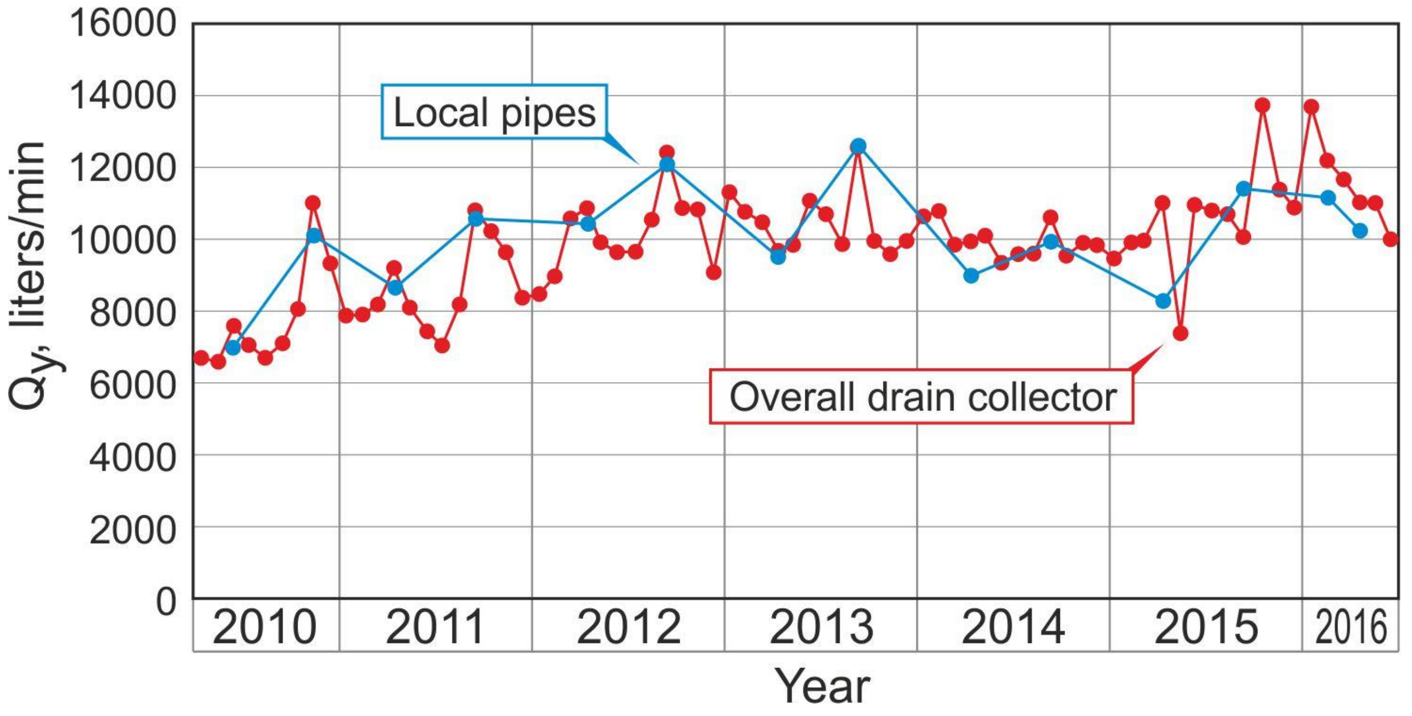


REASONS FOR PARTIAL SATURATION

CIRCUMFERENTIAL DRAIN SYSTEM



CIRCUMFERENTIAL DRAINS YIELD



THE INTERNATIONAL BOARD OF EXPERTS (IBE)

THE TEAM

W.D. Carrier, IBE
M. Jamiolkowski, IBE
R. Chandler, IBE (retired in 2016)
J. Standing, IBE (took over R. Chandler)
K. Høeg (IBE)
W. Wolski (PGE)

IBE was appointed in 1992 by Polish Government and KGHM to oversee, via observational method, the safe operation and development of TSF Zelazny Most,

GEOLOGICAL AND GEOTECHNICAL SETTINGS

TSF Zelazny Most jeopardized by:

- Foundation hazard, due to extremely complex geological and geotechnical settings

- Hazard of spontaneous flow failure (static liquefaction)

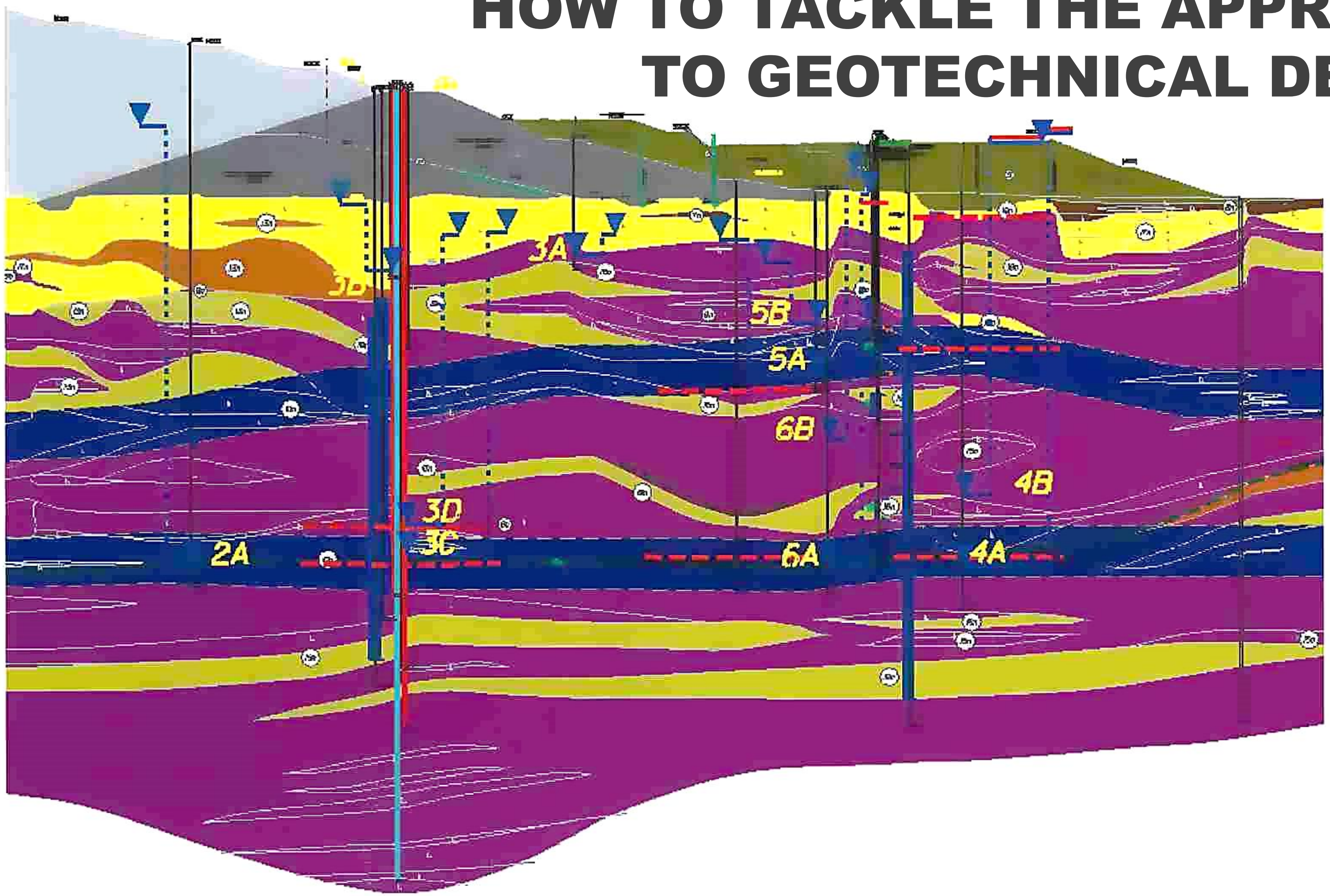
Threats strictly linked:

→ Foundation failure can trigger flow failure

→ Flow failure can trigger dam failure

GEOTECHNICAL PROFILE DOWNSTREAM OF THE EAST DAM

HOW TO TACKLE THE APPROACH TO GEOTECHNICAL DESIGN



COPPER TAILINGS

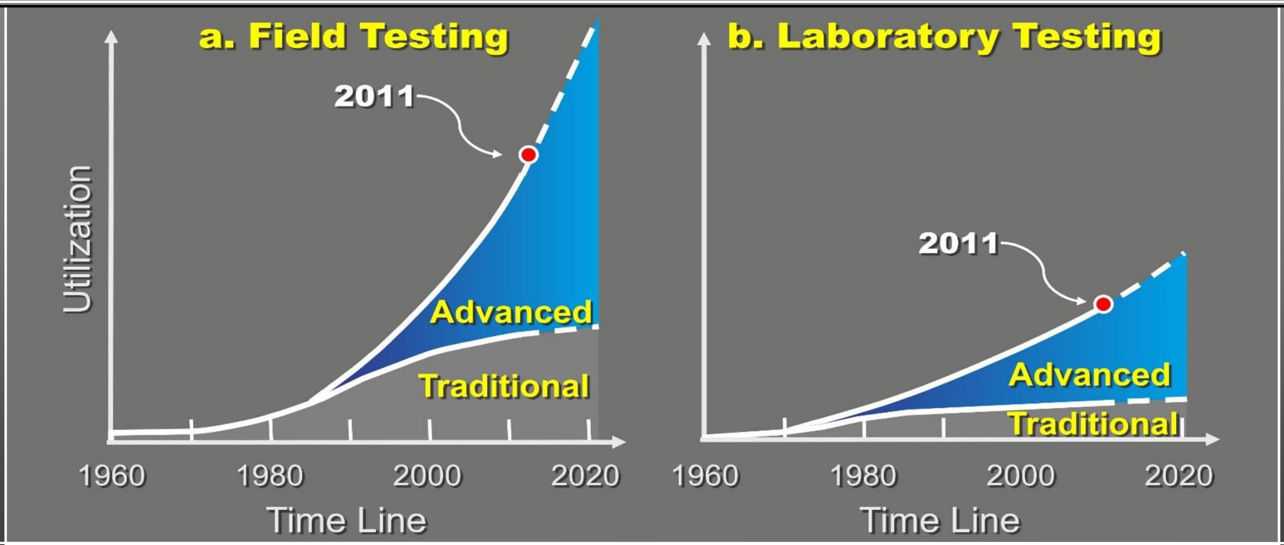
Main Focus - Liquefaction Hazard

- Tailings characterization, role of in-hole geophysical tests.
- Mapping the partial saturation of tailings in situ.
- Effect of partial saturation on liquefaction resistance of sand-like soils.

INTEGRATION OF SEISMIC MEASUREMENTS IN GEOTECHNICAL DESIGN
SELECTED TOPICS DEALING WITH IN-HOLE TESTS IN SAND-LIKE SOIL
(After Prof. K. H. Stokoe

- **Focusing on material properties and design parameters**
- **Dealing mainly with sand-like soils**
- **In-hole seismic tests considered***

(*) CHT,
DHT,
S-CPT,
S-DMT



SEISMIC BODY WAVES VELOCITY AID IN GEOTECHNICAL DESIGN

- V_p → Distinction between fully and partly saturated soils
- V_s → Appraisal of undisturbed samples quality
- $V_s + V_p$ → Assessment of porosity in situ
- V_s → Soil stiffness at small strain, $\gamma \leq 10^{-5}$ %

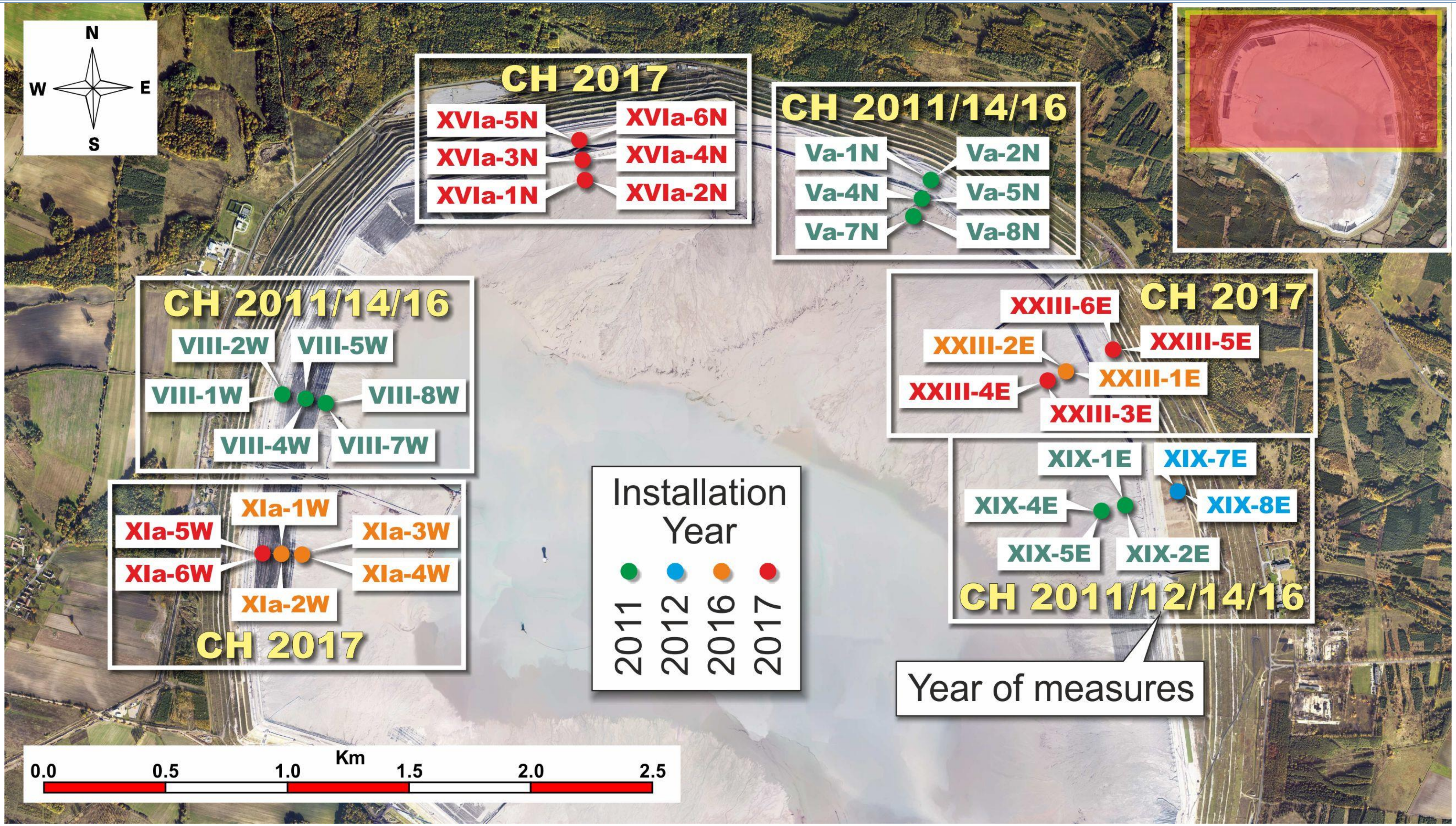
Type of in-hole generated seismic waves:

- **Cross-Hole tests:**

  P-wave velocity $V_p(H)$, S-wave velocity, $V_s(HV)$ & $V_s(HH)$
- **S-CPTU & S-DMT:**

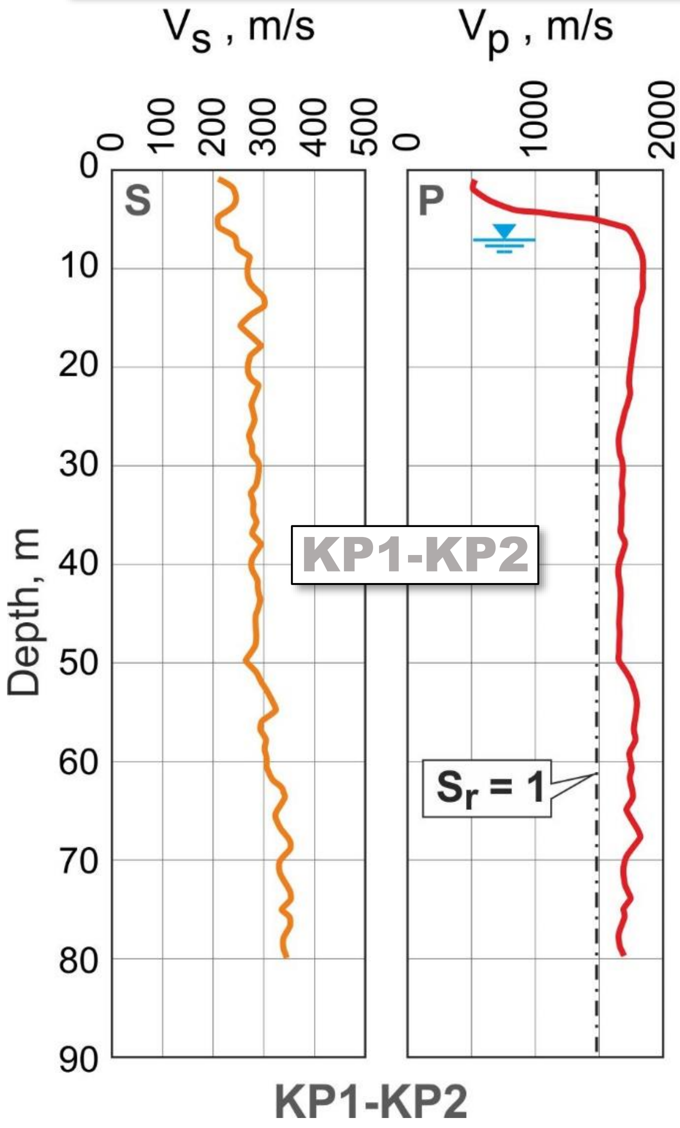
  P-wave velocity $V_p(V)$; S-wave velocity, $V_s(VH)$

CROSS-HOLE STATIONS GENERATING THE SEISMIC BODY WAVES

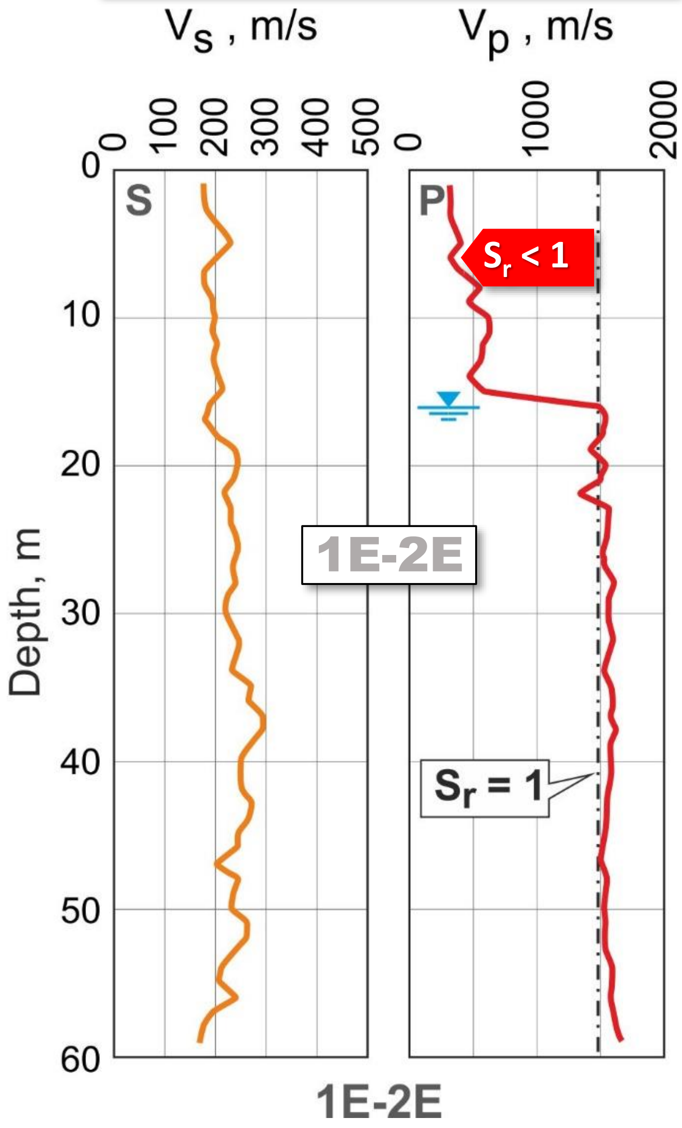


SATURATION DEDUCED FROM PROPAGATION OF P-WAVES

FOUNDATION SOILS



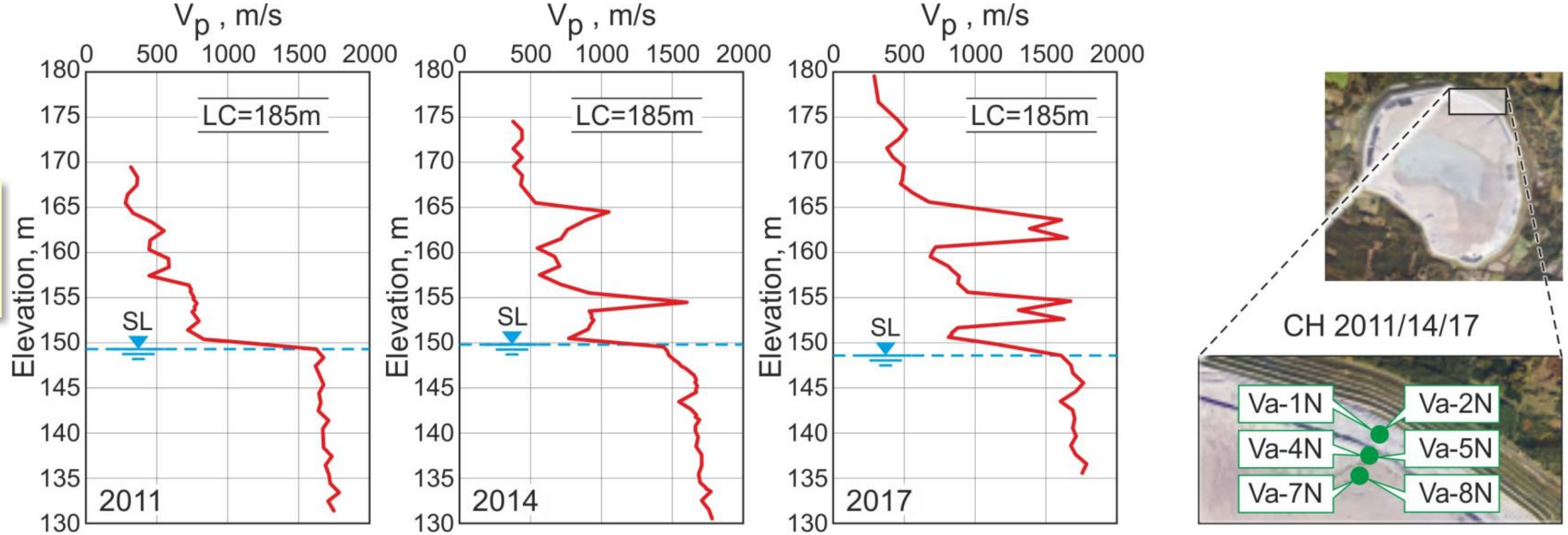
TAILINGS*



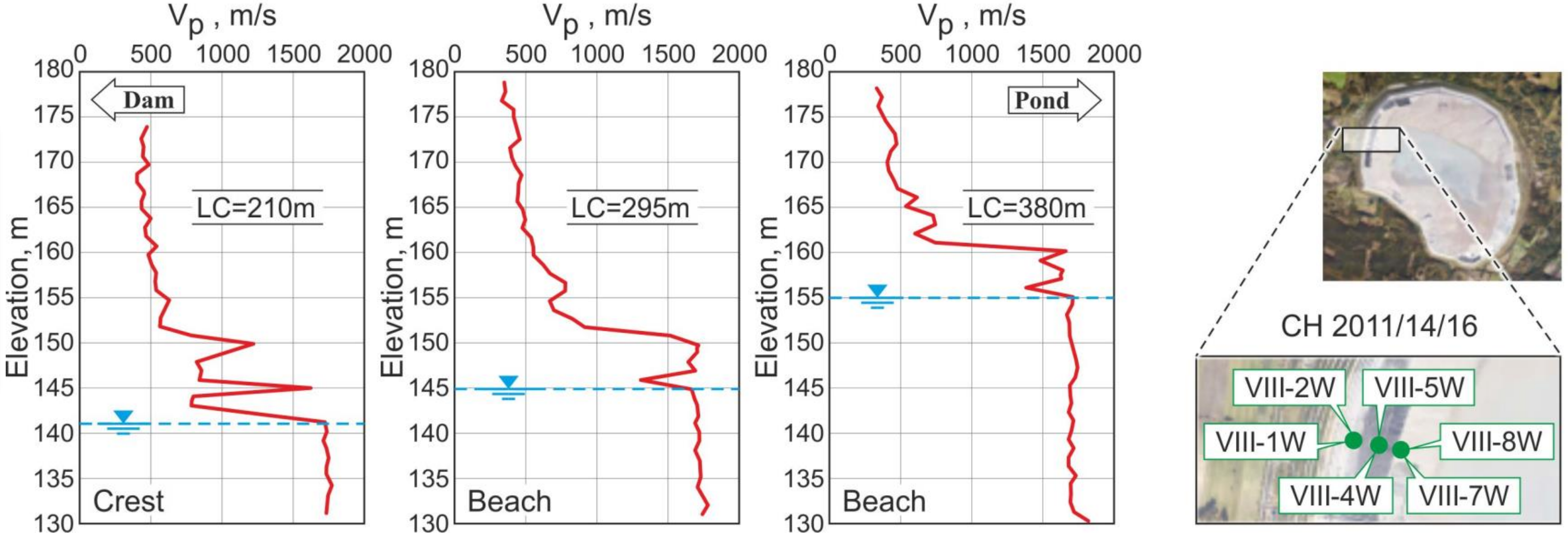
(*) 363m from starter dam

MAPPING LOCATION OF PHREATIC BY PROPAGATION OF P-WAVES

AS FUNCTION OF TIME



AS FUNCTION OF DISTANCE FROM STARTER DAM



Zelazny Most Tailings Disposal
DEPTH OF THE PHREATIC SURFACE

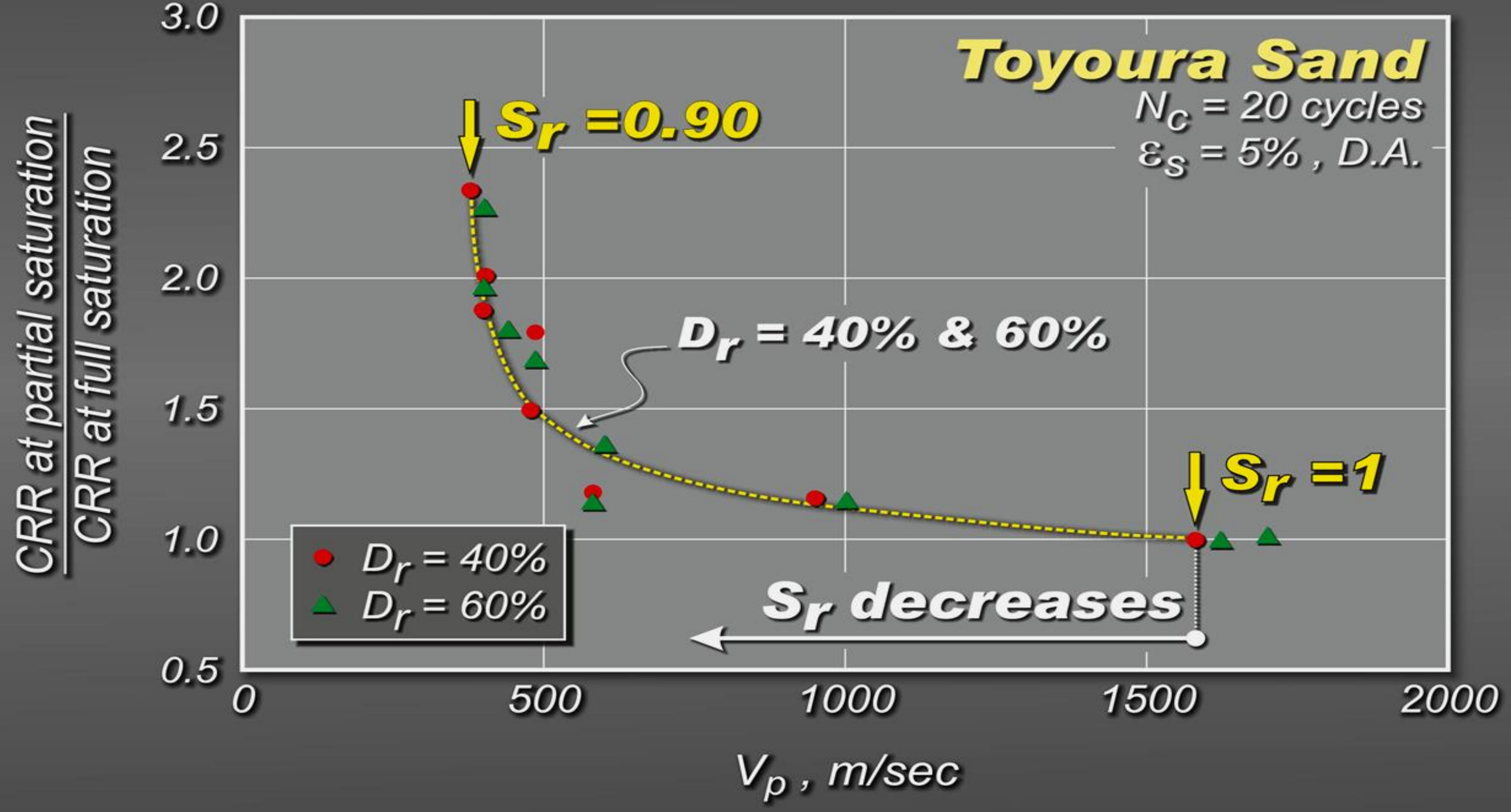
Dr. A. Callerio SGI, Milano

Geodetic Cross-Section -	CH -Survey Year -	CH-BH's -	Distance from starter dam m	Dam Crest m a.s.l.	Beach elevation m a.s.l.	Depth of phreatic surface from beach m
W-VIII	2016	7W-8W	380	185 (2015)	178.0	24
W-VIII	2016	4W-5W	295	185 (2015)	179.0	30
W-VIII	2016	1W-2W	210	185 (2015)	183.0	42
W-XIa	2017	3W-4W	380	180 (2017)	152.1	28
W-XIa	2017	1W-2W	300	180 (2017)	148.7	32
W-XIa	2017	5W-6W	200	180 (2017)	143.9	37
N-XVIa	2017	1N-2N	340	185 (2017)	138.0	42
N-XVIa	2017	3N-4N	265	185 (2017)	137.9	46
N-XVIa	2017	5N-6N	190	185 (2017)	130.5	> 44
N-Va	2016	7N-8N	345	185 (2017)	180.0	33
N-Va	2016	4N-5N	265	185 (2017)	182.0	39
N-Va	2016	1N-2N	185	185 (2017)	171.0	32
E-XVIII	2017	3E-4E	450	185 (2017)	159.6	21
E-XVIII	2017	1E-2E	365	185 (2017)	151.7	29
E-XVIII	2017	5E-6E	150	185 (2017)	134.1	37
E-XIX	2016	4E-5E	465	185 (2015)	170.0	15
E-XIX	2016	1E-2E	365	185 (2015)	179.0	31
E-XIX	2016	7E-8E	145	185 (2015)	164.0	37

LOCATION OF PHREATIC SURFACE IN TAILINGS

- Propagation of the longitudinal seismic body P-waves velocity V_p from 18 CH to map location of phreatic surface below the beach at different distance from the dam confining tailings.
- Measured values of V_p , the most reliable tool to distinguish fully saturated from near to saturated tailings.
- Continued validity of current drainage conditions assured by installation of circumferential drains at ~ 6m vertical spacing and repeated CH testing.
- $V_p \geq 1550$ m/s, velocity of P-wave in water, threshold of full saturation.

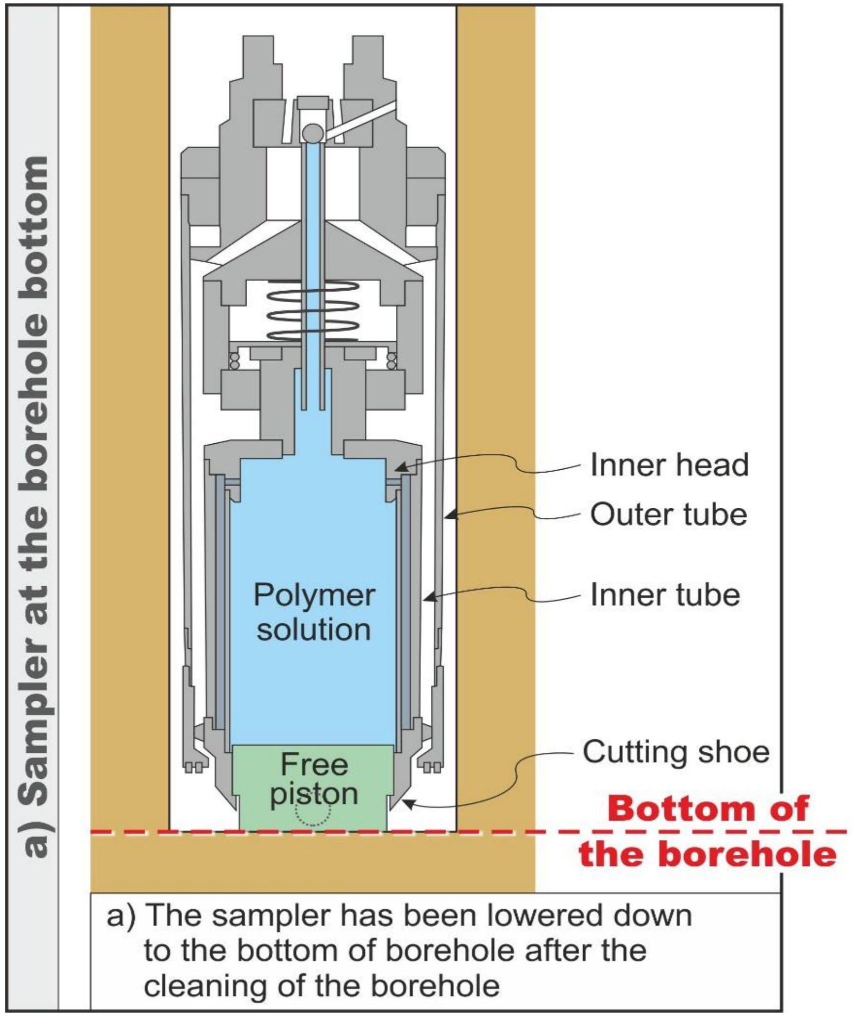
NORMALIZED CRR IN NEARLY SATURATED SAND vs. COMPRESSION WAVE VELOCITY

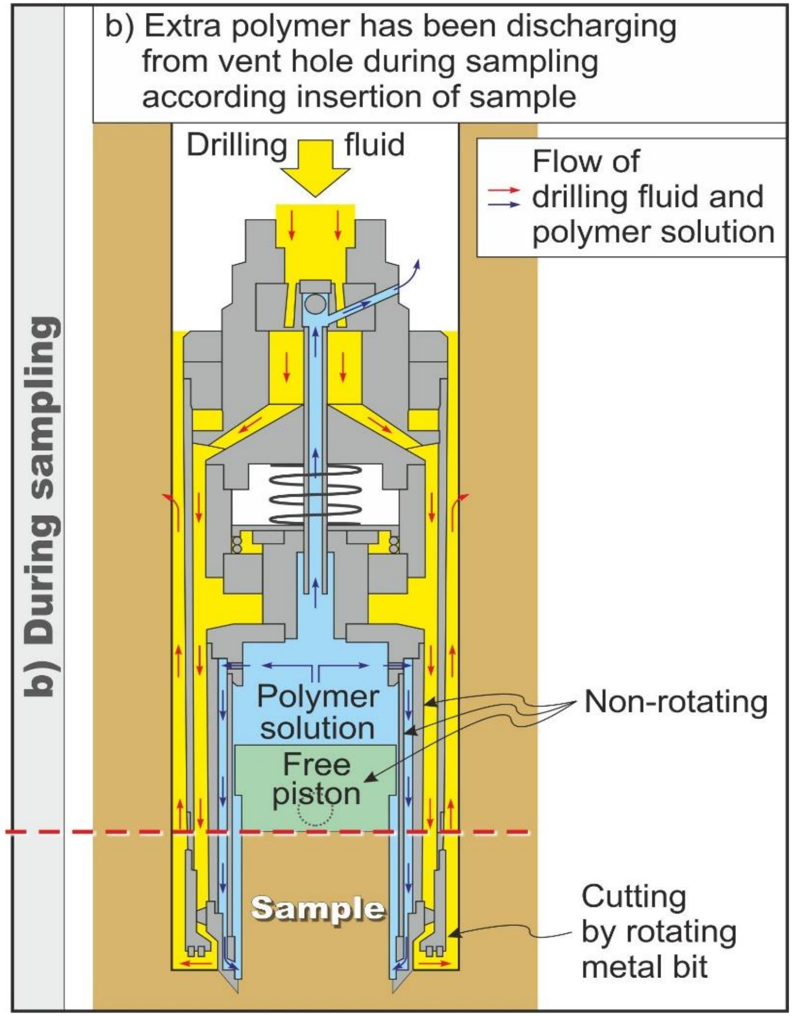


UNDISTURBED SAMPLING OF TAILINGS

GEL-PUSH SAMPLER

- Procedure developed jointly by Japan and Taiwan under prof. K. Ishihara guidance
- To date used in Japan, Taiwan, Poland, Bangladesh, New Zealand, Italy
- Gel reduces friction between soil and internal liner during sampling, forming thin gel layer around the sample
- Polymer soluble gel removable after sample extrusion



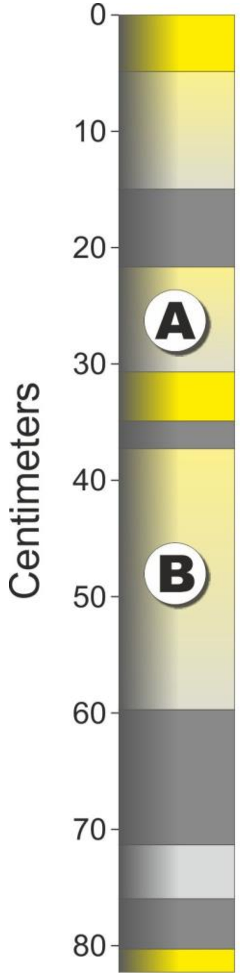


UNDISTURBED TAILINGS CORE RETRIEVED USING G-P TR SAMPLER

(*) 4° Trial

Section XIXE - CH 4E-5E

Geoteko, 2015



		A	B
FC	%	70.0	32.0
γ_n	kN/m³	19.60	18.40
G_s	(-)	2.74	2.77
e_0	(-)	0.712	0.865

Depth 34.5m, Distance from the dam crest: 340m

CRITERIA TO EVALUATE SAMPLE DISTURBANCE

- **$p_s / p'_0 \rightarrow$ Skempton (1961), Chandler et al (2011);**

  p_s = suction measured immediately after retrieval of the undisturbed sample

  p'_0 = the **best estimate** of in situ mean effective stress

- **$\Delta e / e_0 \rightarrow$ Lunne et al (1997,2006), De Groot et al (2011);**

  Δe = reduction of void ratio after 1-D recompression of laboratory sample consolidated to the **best estimate** of in situ effective stresses

  e_0 = in situ void ratio

- **$V_{s1}(L)/V_{s1}(F) \rightarrow$ Sasitharan et al (1994), Landon et al (2007);**

  $V_{s1}(L)$ = normalized S-wave velocity measured on the laboratory sample consolidated to the **best estimate** of in situ effective stresses

  $V_{s1}(F)$ = normalized S-wave velocity measured in situ*

(*) CH, DH, S-CPTU, S-DMT

FIELD vs. LABORATORY S-WAVE VELOCITY AN INDEX OF SAMPLE QUALITY

- V_s(F) reflects soil: state, fabric, aging, bonding,……
- V_s (L), determined on specimen reconsolidated to the in-situ geostatic stresses
- Higher V_s (L)/V_s (F), better quality of the tested specimen
- Main uncertainty, selection of laboratory horizontal consolidation stress (σ'_{ho}). Empirical, applicable to all kind of soils. Qualitative criteria need to be established

Field Test

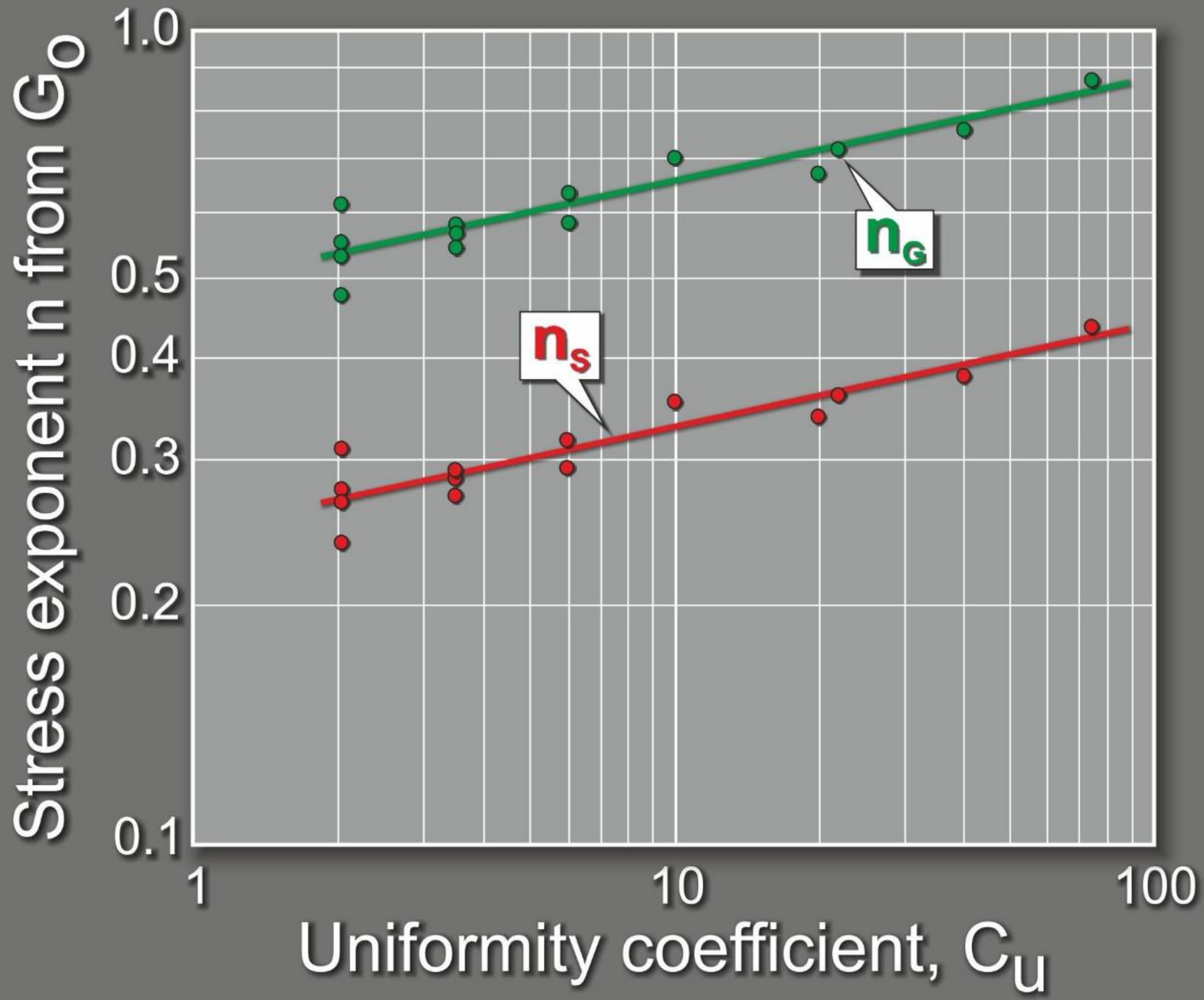
$$V_{s1}(F) = V_s\left(\frac{2p_a}{\sigma'_a + \sigma'_b}\right)^{ns}$$

Lab Test

$$V_{s1}(L) = V_s\left(\frac{2p_a}{\sigma'_{vo} + \sigma'_{ho}}\right)^{ns}$$

STRESS EXPONENT vs UNIFORMITY COEFFICIENT FOR GRANULAR SOILS

Stokoe et al (1996)



RETRIEVED GEL-PUSH SAMPLES

RETRIEVED SAMPLE

SPECIMENS FOR TX-CIU AND TX-CK$_0$U TESTS

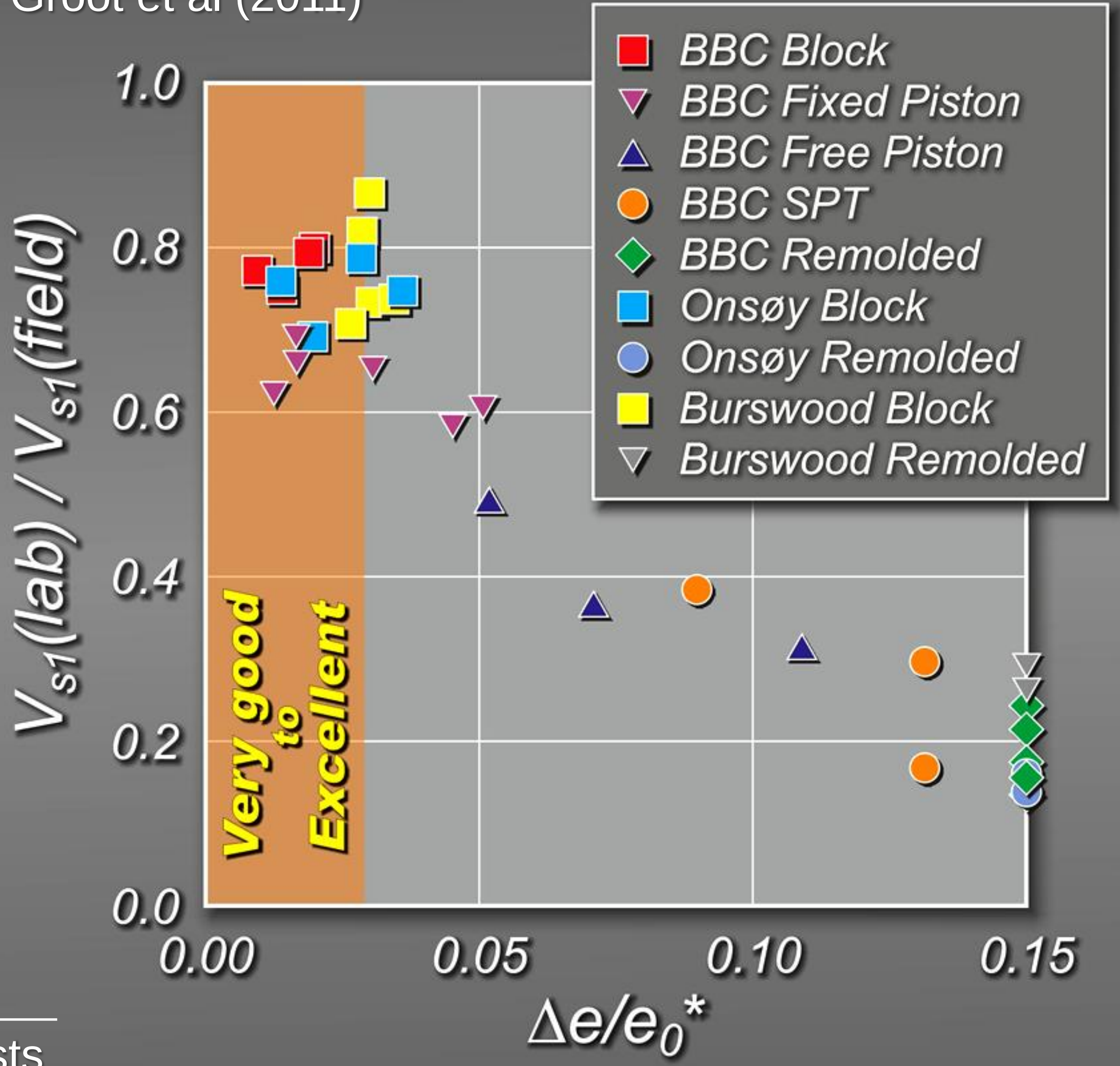
Geoteko (2015)

$$\frac{V_{s1}(L)}{V_{s1}(F)} = 0.82$$

$$\frac{V_{s1}(L)}{V_{s1}(F)} = 0.70$$

UNDISTURBED CLAY SAMPLES QUALITY LABORATORY vs FIELD CRITERION

Lunne et al (2006), De Groot et al (2011)

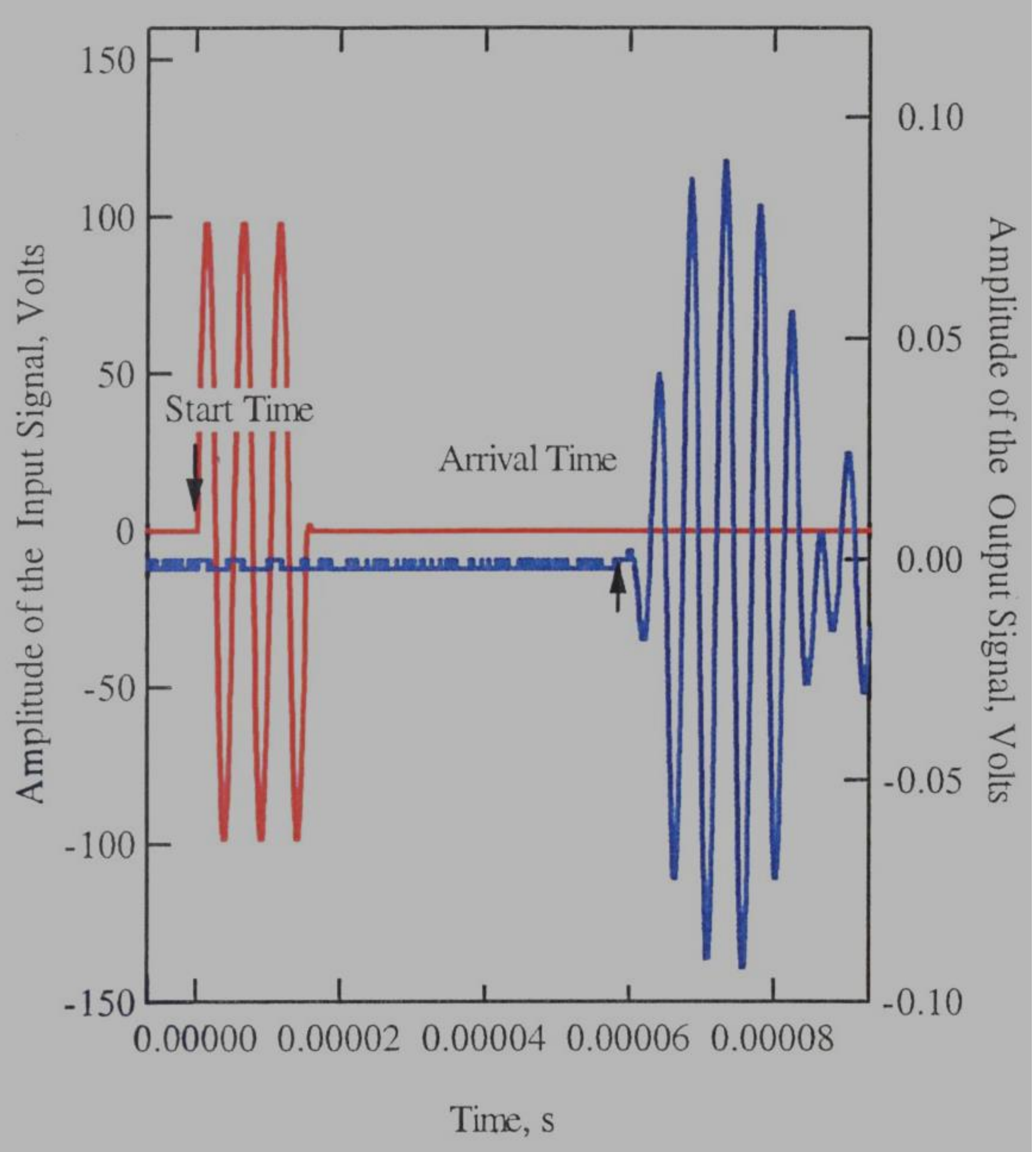


(*) from oedometer tests

PORTO EMPEDOCLE HARD PLIOCENE CLAY
MULTIPLE APPROACH to SAMPLE QUALITY ASSESSMENT

Depth (m)	$\frac{\Delta e}{e_0}$	$\frac{V_{s1}(L)}{V_s(F)}$	$\frac{p'_k}{p'_0}$
28.6	0.0093	0.79	0.983
31.3	0.0069	0.69	1.078
31.2	0.0059	0.74	1.082
49.8	0.0112	0.82	0.852
53.1	0.0032	0.81	0.938
56.1	0.0052	0.78	0.991

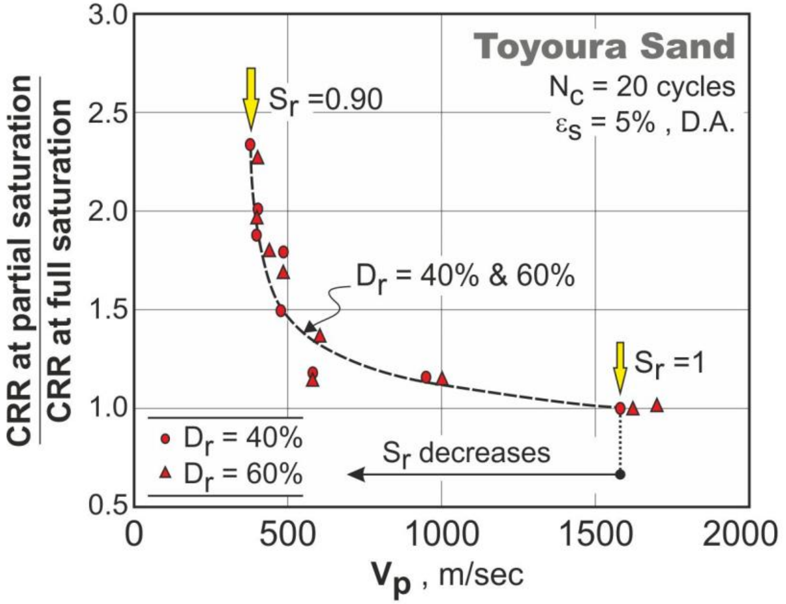

THANK YOU FOR
YOUR ATTENTION


Start Time
Arrival Time
Amplitude of the Input Signal, Volts
Amplitude of the Output Signal, Volts
Time, s
150
100
50
0
-50
-100
-150
0.10
0.05
0.00
-0.05
-0.10
0.00000
0.00002
0.00004
0.00006
0.00008

NORMALIZED LIQUEFACTION RESISTANCE OF PARTIALLY SATURATED SAND-LIKE SOILS

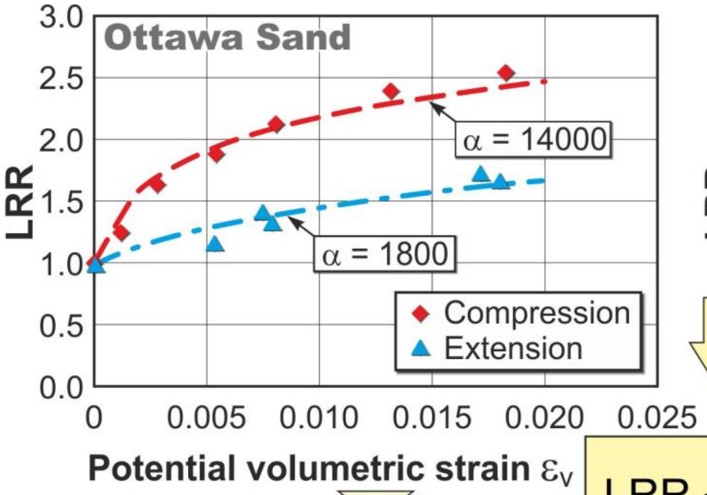
CYCLIC LABORATORY TESTS

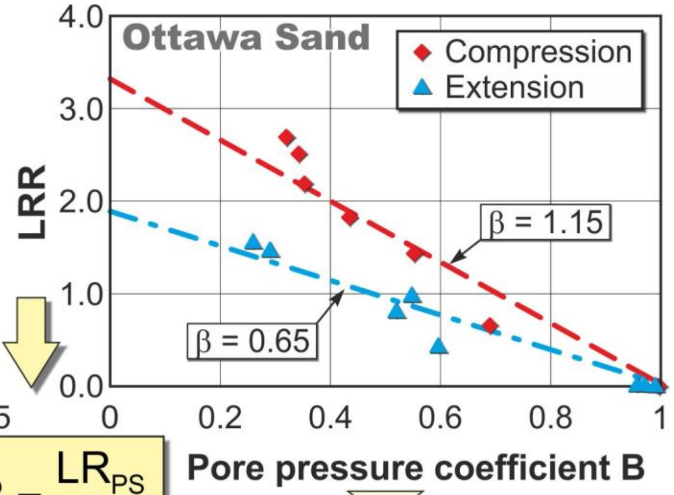
Ishihara et al. (1998)
& Tsukamoto et al. (2001)



MONOTONIC LABORATORY TESTS

Okamura and Soga (2006),
*Yang et al. (2004), He et al. (2014)**





$$LRR = \frac{LR_{PS}}{LR_{FS}}$$

$$\varepsilon_v^* = \frac{\sigma_c'}{p_0 + \sigma_c'}(1 - S_r)\frac{e_0}{1 + e_0}$$

Okamura and Soga (2006)

$$LRR_{PS} = LRR_{FS} \exp\left[\beta(1\text{-}B)\right]$$

Yang et al (2004)

(*) Could overestimate LRR in extension loading

PARTIAL SATURATION
VS
LIQUEFACTION RESISTANCE

- **In sand-like soils the liquefaction resistance increases as the values of S_r and B decrease.**
- **Both S_r and B cannot be monitored in field. The P-wave velocity V_p is that used to identify the in-situ soil state and the conditions of specimens in laboratory, Ishihara (2001).**
- **To assess liquefaction resistance of partly saturated soils, it is required to couple field and laboratory V_p-values, supported by dedicated laboratory tests carried on fully and partly saturated specimens.**

NGI CRITERIA FOR SAMPLE QUALITY

Lunne et al (1998, 2006)

APPLICABLE IN FINE GRAINED SOILS

OCR	$\frac{\Delta e}{e_0}$ at p'_0 *			
1→2	< 0.04	0.04→0.07	0.07→0.14	> 0.14
2→4	< 0.03	0.03→0.05	0.05→0.10	> 0.10
4→6	< 0.02	0.02→0.035	0.035→0.07	> 0.07
Quality	1	2	3	4

Quality: 1 - Good to excellent 3 - Poor
2 - Good to fair 4 - Very poor

(*) p'_0= laboratory consolidation stress, close to that in situ

GEL-PUSH SAMPLES - PRECAUTIONS

BOREHOLE DRILLING PROCEDURE:
Bentonite or polymer mud+casing if necessary.

DELIVERY TO LABORATORY:
Samples should be transported in subvertical position, accelerometers suggested to monitor vibrations.

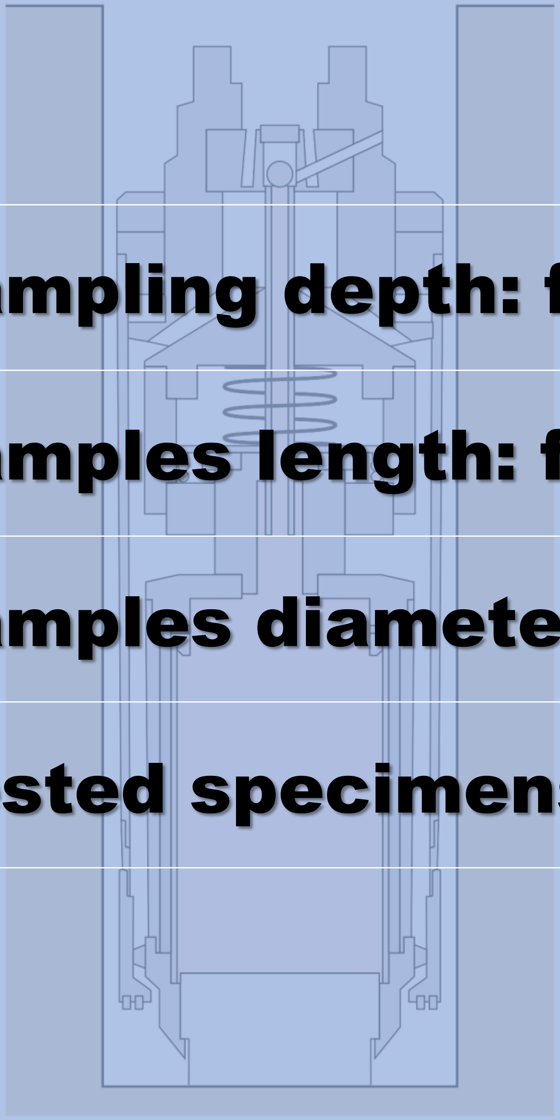
SAMPLES HANDLING:
Complex handling samples in laboratory:
- **Upright core extrusion, gel-cover removal***
- **Specimen preparation and saturation.**

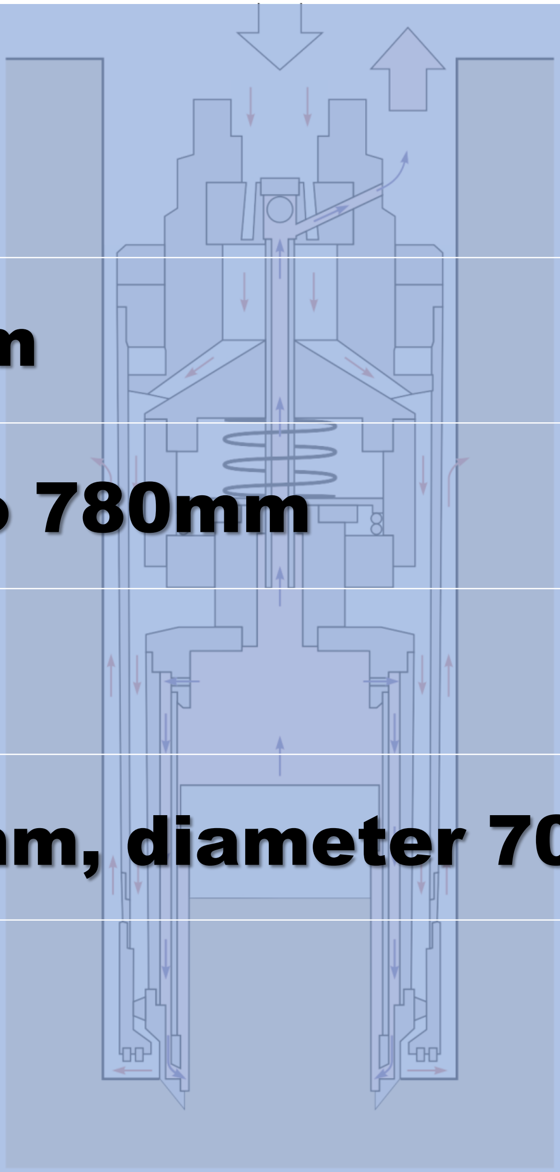
(*) not later than 10 to 15 days after sampling

RELEVANT FEATURES of GEL-PUSH Tr SAMPLER

- Triple core barell sampler
- Cutting shoe: diameter inner core-liner = 72.1mm; cutting shoe diameter = 70mm
- Incorporates anti-shock/vibration spring
- Operates, by rotation, at low rate of the outer bit-tube, collecting the soil core in the non-rotating inner tube
- Polymer lubricant between soil core and inner tube wall reducing friction improves retrieved sample quality

GEL-PUSH SAMPLER Tr TYPE





- **Sampling depth: from 2m to 53m**
- **Samples length: from 350mm to 780mm**
- **Samples diameter: 72mm**
- **Tested specimens: height 140mm, diameter 70mm**

UNDRAINED SHEAR STRENGTH and INDEX PROPERTIES of ZM TAILINGS

Tr GEL-PUSH SAMPLER, 3rd Trial, ≈ 20m from dam crest Geoteko (2014)