Geotechnical Characterization of Copper Tailings at Zelazny Most Site

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ABSTRACT: The paper, an extended version of the 3rd Mitchell Lecture (Jamiolkowski 2014), describes the geotechnical characterization of the copper tailings at one of the world's largest tailings disposal, located at Zelazny Most, Poland. The paper covers the works carried out, over two decades, by the KGHM (the Polish Acronym for Copper Mine and Mill Company) in cooperation with a number of Polish geotechnical consultants steered by the International Board of Expert (IBE) assigned to oversee the development of the facility within the frame of the observational method [Peck (1969, 1980)]. Considering the difficulties to obtain undisturbed samples of silts and fine silty sands, major efforts were devoted to in-situ methods such as S-CPTU, S-DMT and cross-hole tests. They have allowed determining the in situ state of tailings as well as establishing the position of the saturation line in tailings and estimating their susceptibility to flow failure. The results of in-situ testing have been corroborated by laboratory tests on undisturbed specimens of the tailings retrieved from the exploratory pits excavated on the disposal beaches. Only in 2013, undisturbed sampling at depths exceeding fifty meters, were carried out using the Gel-Push sampler, recently developed by the Japanese Kiso-Jiban Ltd, that allows retrieving high quality undisturbed samples of tailings. The results of laboratory tests carried out on these samples are also anticipated.

1 INTRODUCTION

The paper summarizes over twenty years of activity in the use of in-situ combined with laboratory testing for the characterization and the monitoring of the KGHM Zelazny Most (ZM) copper tailings disposal located in South-West Poland (Fig.1).

The ZM disposal, one of the world's largest facility of this type, covers an area of 12.4 km^2, and the ring-dam (Fig.2) confining the tailings, has a total length of 14.3 km. The height of the ring-dam currently ranges between 41m and 65 m as shown in Fig.3.

The deposition of the waste mineral material started in 1977 and currently the volume of tailings already stored has approached $557 \cdot 10^6$ m^3.

The operation at the ZM disposal is planned to continue until the exhaustion of the ore body, expected in 2042, when the total volume of the tailings stored will reach about $1 \cdot 10^7$ m^3.

The ZM dams confining tailings are being raised through the upstream method, Fig.4, [Vicks (1983), Carrier (2003)]; their shell has been built using coarser tailings, separated from slimes by spigotting.

Fig. 1. Location of the Zelazny Most depository.

Ever since, the dam crest has been raised at a rate of 1 to 1.5 m/yr, maintaining an average downstream slope of 3.5 horizontal to 1 vertical. Furthermore, the distance from the dam crest to the pond edge, the beach, has been maintained with a length not less than 200 m. Moreover, to maintain depressed the phreatic surface in the dam shell, in addition to the toe drain, four levels of circumferential drains have been installed as the dam was raised, see Fig.5.

ZELAZNY MOST TAILINGS DISPOSAL
Updated as of December 2014

Maximum dam height:	61 m
Total volume stored:	558×10^6 m^3
Storage rate:	29×10^6 m^3/annum
Area covered:	14.0 km^2
Total Dam's length:	14.3 km
Operation time:	1977 throughout 2042

Fig. 2. Aerial view of the Ring Dam.

Dams Height, m	
North:	41
West:	49
South:	34
East:	65

Crest Elev., m asl	
North:	180.0
West:	177.5
South:	177.0
East:	180.0
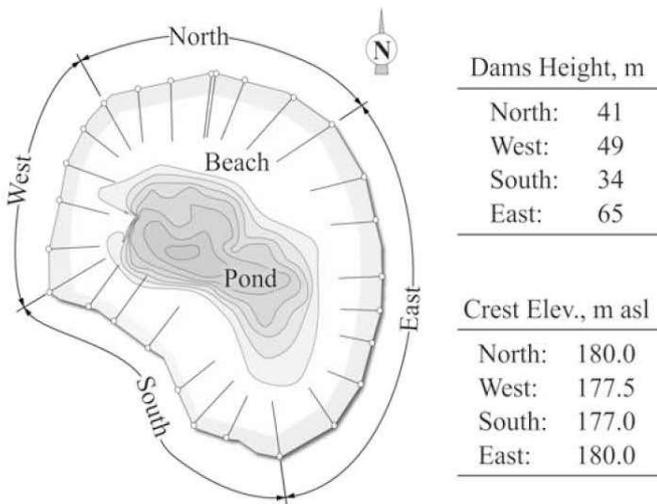
Fig. 3. Dam height and crest elevation, updated as of December 2014.
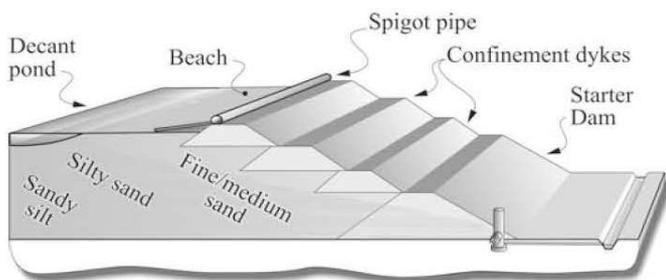
Fig. 4. Ring Dam - Schematic cross-section.
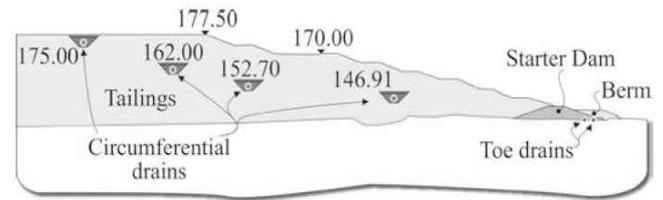
Fig. 5. Ring Dam - Circumferential drains.

This procedure will be maintained all the way through the further raising of the ring-dam whose crest, at present, has reached an elevation ranging from +177m a.s.l. to +180m a.s.l., and, by the end of the planned operation period, will exceed 205m a.s.l.. As with all tailing dams, the ZM disposal poses a number of challenges to the geotechnical engineers involved in their design and construction, particularly for the persistent risk of flow liquefaction of the stored tailings, theme of this paper. Although not related to the topic under discussion, it is crucial to mention also the potential threats to the ring dam, shown in Fig.2, deriving from the complex Pleistocene history of the area, when a succession of the ice sheets ≈1km thick, overrode, at least three times, the ZM area.

The advances of the ice sheets and their subsequent melting have generated, in the foundation high plasticity heavily overconsolidated Pliocene clay ($w_1 \geq 70\%$), the presence of glacio-tectonic shear surfaces extending to a depth up to 100m, on which the available shear strength is close to residual ($7° \leq \varphi' \leq 10°$). Such geological and geotechnical settings determine that, out of a number of geotechnical hazards, including the moderate mining induced seismicity, the stability of the confining dams is certainly the most relevant. [Jamiolkowski et al (2010), Jamiolkowski (2013)].

Considering the geotechnical hazards involved, the dimensions and the extent of the ZM disposal, the complexity of the geological and geotechnical settings, as well as the planned life time, on the World Bank recommendations, KGHM in 1992 appointed a four-member International Board of Experts (IBE): Dr. David Carrier (USA), Prof. Richard Chandler (UK), Prof. K. Hoeg (Norway), Prof. Michele Jamiolkowski (Italy). The IBE was assigned with the task, in cooperation with the Polish Geotechnical Expert (PGE), Prof. Wojciech Wolski, of overseeing the safe development of the tailings dam by applying the observational method [Peck (1969, 1980)]. Within the frame of this *on-going project*, whose overall operation will exceed 70 years thus lasting for further 30 years, this paper illustrates the experimental procedures adopted for the geotechnical characterization of the ZM tailings [Jamiolkowski (2014)].

2 GEOTECHNICAL CHARACTERIZATION OF TAILINGS

2.1 General consideration

IBE, since their involvement in the ZM project, as a routine for all the tailing dams, paid special attention to the geotechnical characterization of tailings, focusing on their susceptibility to flow failure, [Castro (1969, Mitchell (1976), (2008), Ishihara (1993), Liu and Mitchell (2006), Robertson et al (1995), Salgado et al (1997), (Jefferies and Been (2006)].

The coarser tailings from two KGHM mines (Rudna and Lubin) used to raise the ring-dam, are deposited by spigotting, on the beaches of the confining dams, whilst the much finer tailings from the third mine (Polkowice) are discharged hydraulically directly in the pond. The range of the particles size distributions of coarser tailings investigated by Lipinski (1998, 2000), is shown in Fig.6, including their mineralogical composition and the range of specific gravity, Gs.

The plasticity index (PI) of the fines contained in tailings used to raise the ring-dam, generally, does not exceed 15%. Overall, the spatial variability of the tailings grading is larger than what can be inferred from Fig.6, especially at larger depths, as one might expect when moving closer to the pond, the fines content (FC) tends to increase as a consequence of the deposition method (spigotting) in conjunction with the upstream construction method. This latter causes the reduction of the spigotting pipe distance from the pond as the dam height increases, thus affecting the distribution of FC with depth. This statement is confirmed in the following, by the Gel-Push sampling introduced at ZM since 2013. [Huang & Huang (2007), Huang et al (2008), Taylor et al (2012)]. Before 2013, the laboratory tests on tailings were carried out on "undisturbed" samples retrieved from hand-dug, up to 3m deep, pits located on the beach, at varying distances from the dam crest [Dyvik & Hoeg (1999), Hoeg et al. (2000), Lipinski (1998,2012)].

2.2 In situ tests

Before 2013, due to the difficulties in obtaining undisturbed samples at greater depths, with the exception of laboratory tests on samples collected on the beach, the geotechnical characterization of tailings was mostly pursued by means of in situ testing, focusing on the following issues:

- Spatial variability.
- Depth of the saturation surface in tailing.
- In situ state of tailings and their susceptibility to static liquefaction.
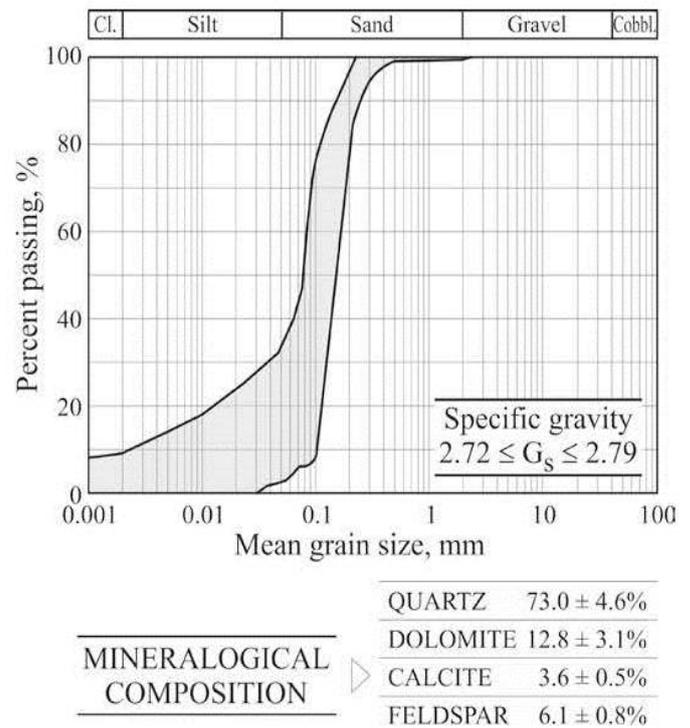
Fig. 6. Range of tailings grading and mineralogical composition - Lipinski (2000, 2012).

With this intent a large number of in situ tests have been carried out including; CPT, CPTU, DMT, S-DMT, S-CPTU, down-hole (DHT) and cross-hole (CHT) tests.

Major efforts were devoted to in-hole seismic tests (S-CPTU, S-DMT and CHT). Out of them, deserve to be mentioned the high quality, [Jamiolkowski (2012), Callerio (2013)] properly devised cross-hole tests. The CHT's throughout periodic checks, have allowed to monitor, based on the measured compression wave velocity (V_p), the location of the saturation surface in tailings at different distances from the dam crest, as well as its modification with the raise of the dam height, [Ishihara (1998, 2004), Kokusho (2000), Tsukamoto (2001), Nakazawa et al (2004), Valle Molina (2006), Takahashi et al (2006), Valle Molina & Stokoe (2012)].

This approach has been implemented at ZM, since 1993. Figs.7 to 12, report a recent series of CHT's, carried out in 2011 and 2014 respectively, on the East, North and West portions of the ring-dam. Considering that the V_p velocity in the fully saturated soil corresponds at least to that of the water ($\approx$1500 m/s), it follows that this parameter is a very accurate highlighter to single out fully saturated from near to saturated tailings.

What can be inferred from the above figures is that, thanks to the effectiveness of the drainage system implemented by the KGHM on the depository, the position of the saturation surface, especially closer to the dam crest, is maintained well beneath the beach level.
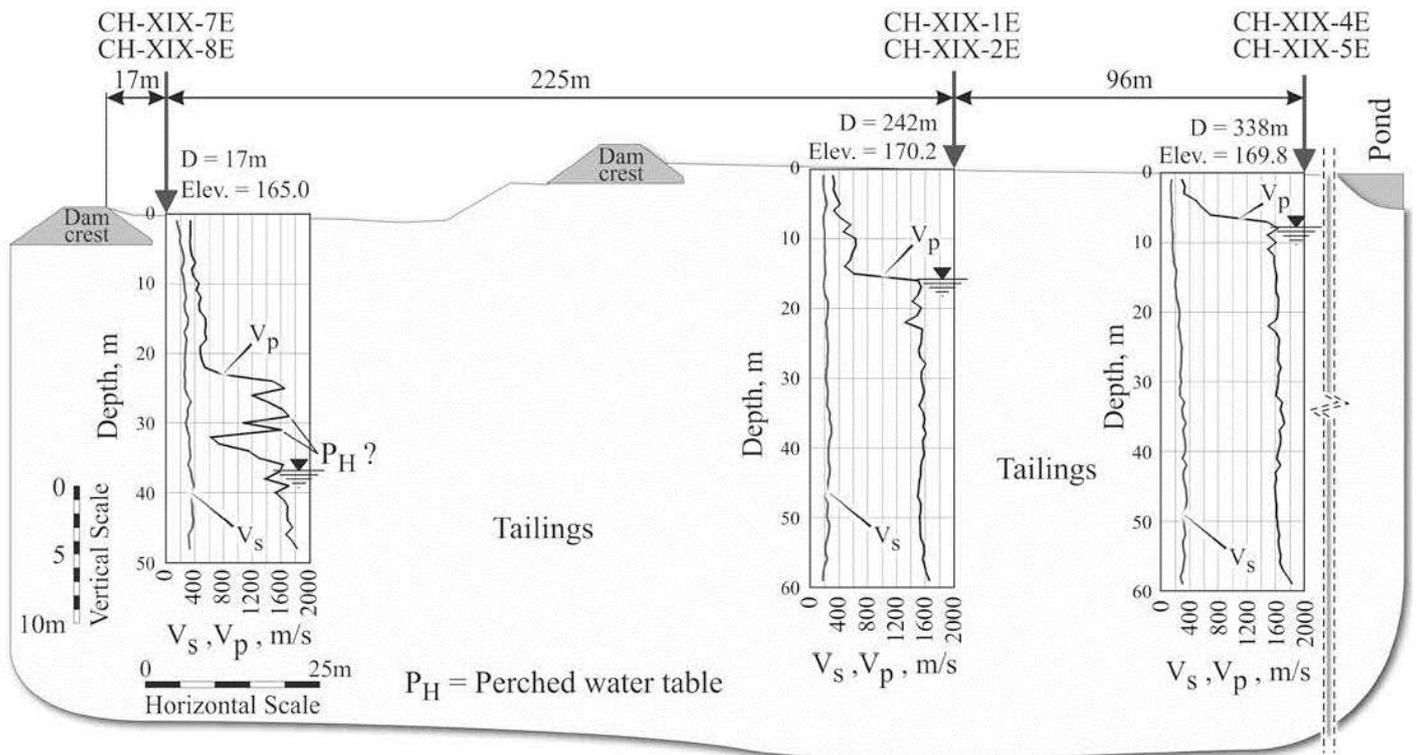
Fig. 7. 2011 - Est Dam - Location of saturation depth from Vp measurements.
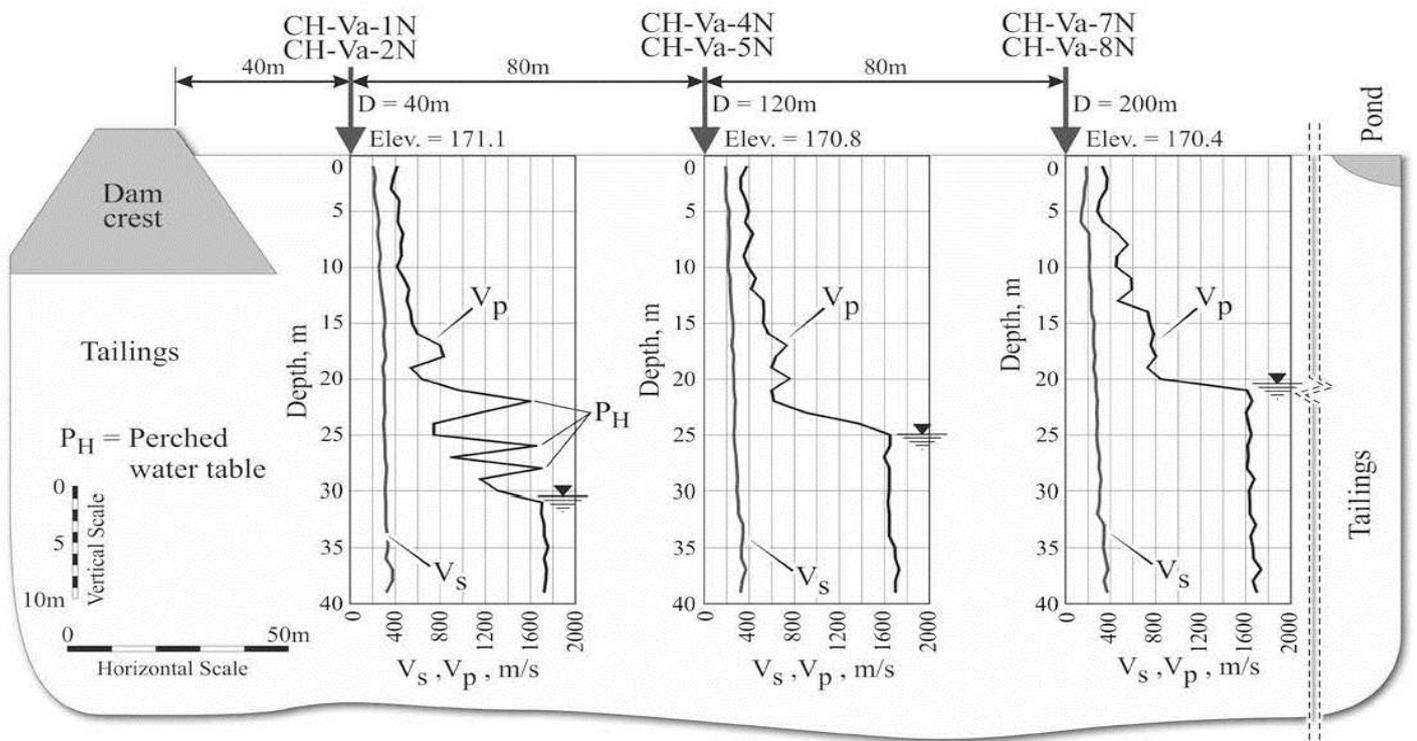
Fig. 8. 2011 - North Dam - Location of saturation depth from Vp measurements.
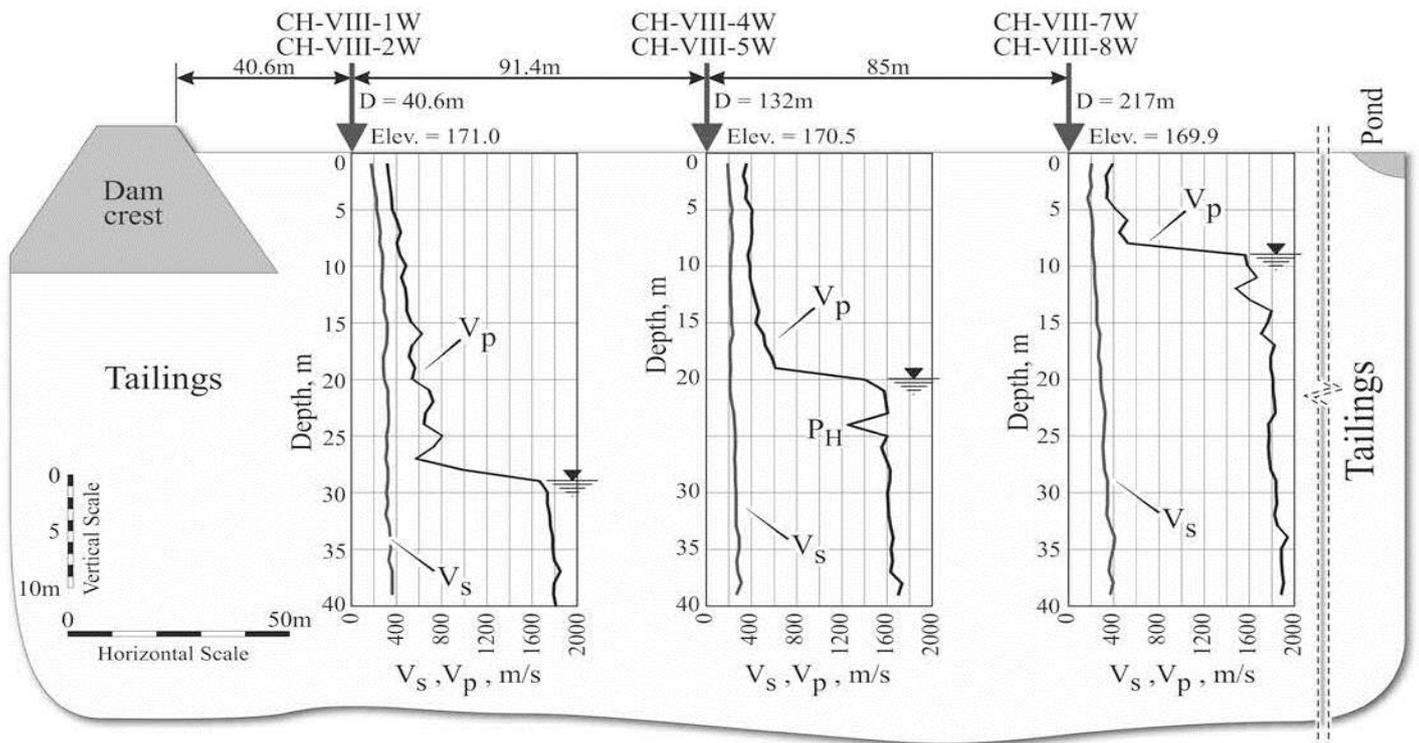
Fig. 9. 2011 - West Dam - Location of saturation depth from Vp measurements.
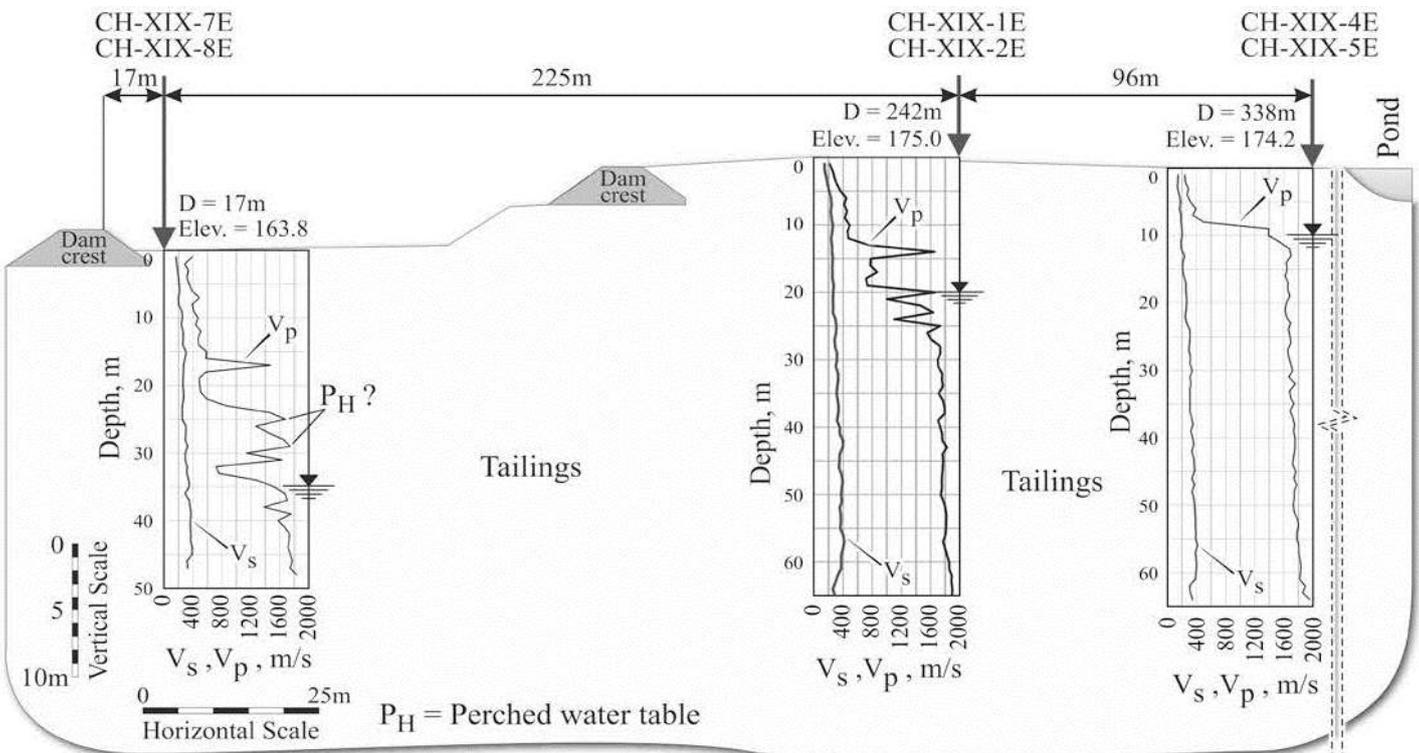
Fig. 10. 2014 - East Dam - Location of saturation depth from Vp measurements.
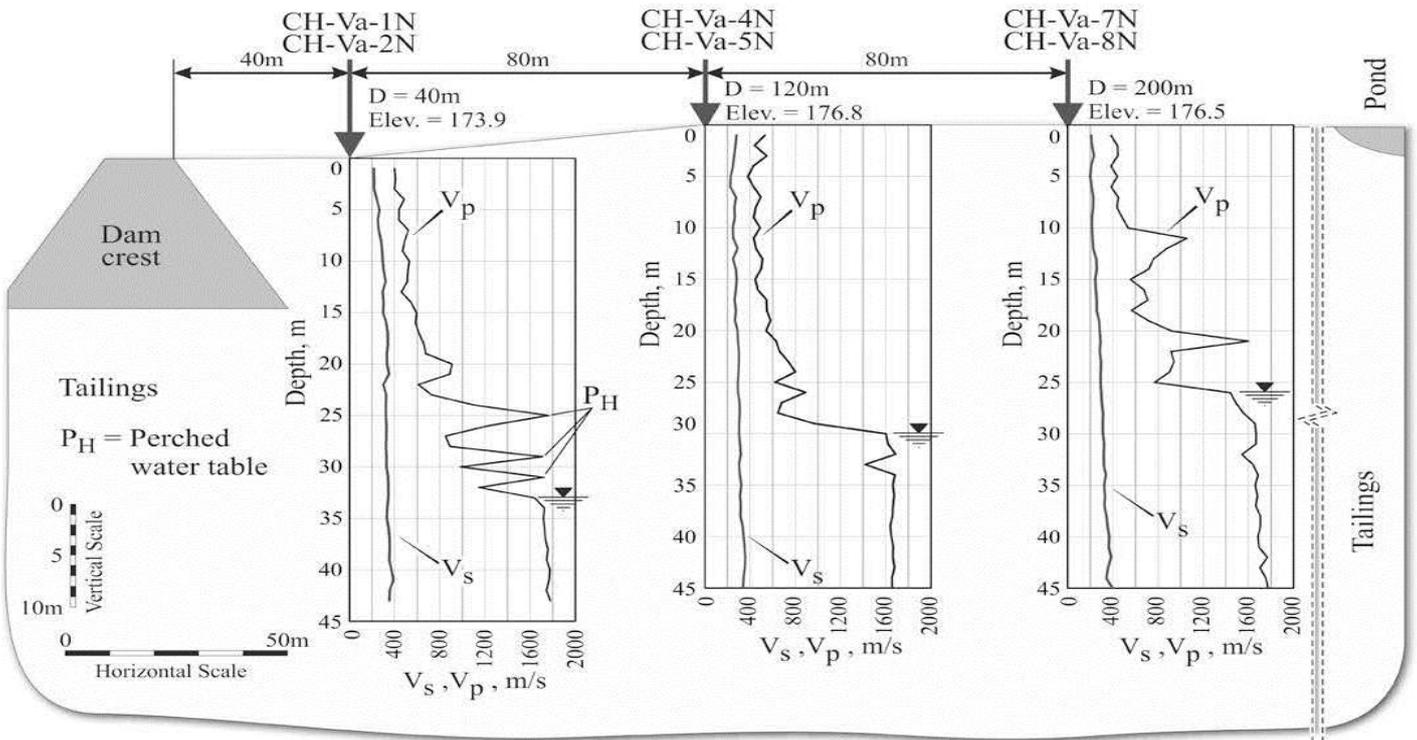
Fig. 11. 2014 - North Dam - Location of saturation depth from Vp measurements.
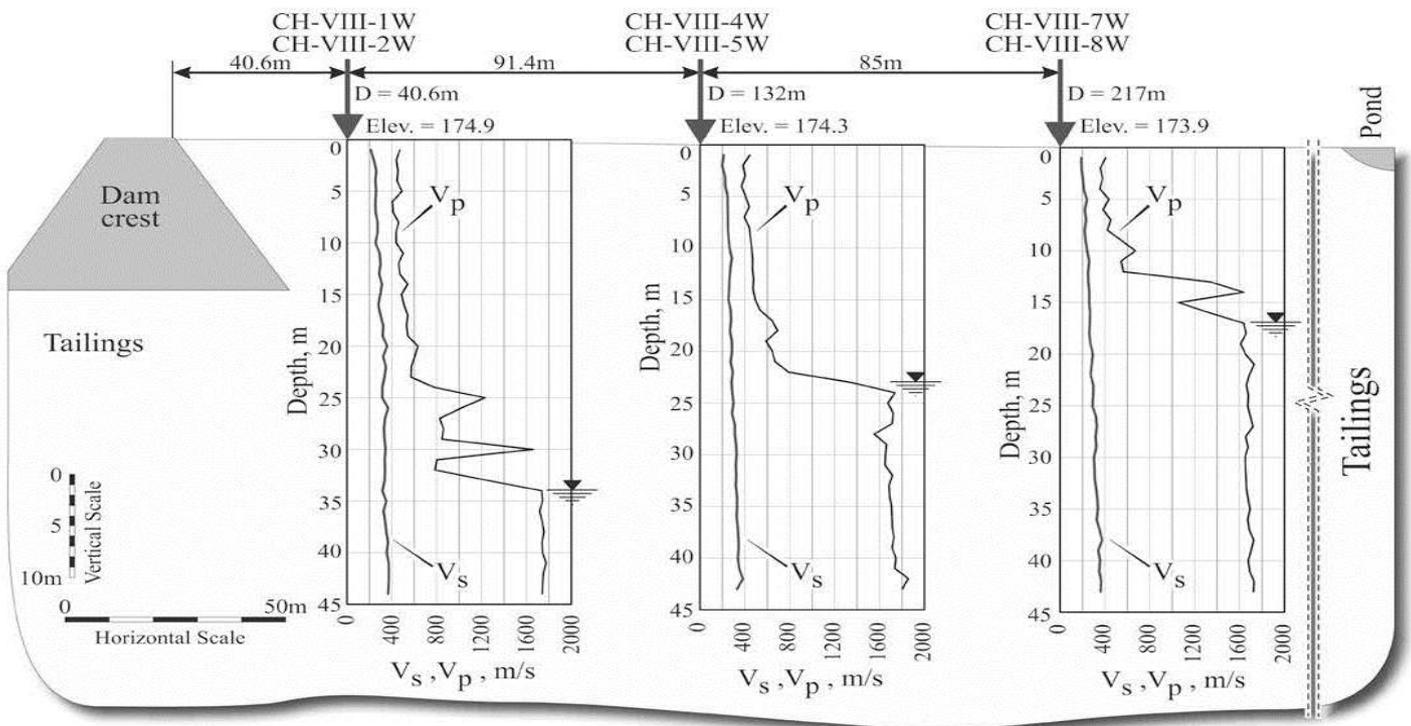
Fig. 12. 2014 - West Dam - Location of saturation depth from Vp measurements.

Moreover, as can be observed from the measured V_p, they allow perceiving the presence of a number of perched water level horizons that, based on the piezometers readings, can be difficult to detect in a complex ground water regime of such a large disposal as ZM is. Table 1 compares the location of said saturation surface as inferred from a series of CHT's carried out from 2011 to 2014.

Overall this comparison suggests an almost steady location of the saturation of the tailings in spite of the dam height increase.

The nearly to saturated state of tailings in the vicinity of the ring dam shell, together with the values of the normalized shear wave velocity V_{s1}, inferred from seismic tests, discussed in the following, have attenuated, to some extent, the concern regarding the susceptibility of tailings to flow failure. Since the last two decades there have been increasing experimental evidences supporting the beneficial effects of the nearly to saturated state $(0.9 > S_r \leq 1)$ on the resistance of loose to medium sands to cyclic liquefaction. As an example, Fig.13 summarizes the results of cyclic triaxial tests carried out on nearly to saturated Toyoura sand [Ishihara et al (1998, Tsukamoto et al (2002)].

More recently, the results of the monotonic undrained triaxial compression and extension tests on loose to medium sands presented by He et al (2014) who, based on his own experiments conducted on the Ottawa sands and summarizing the results obtained by others [Yang et al (2004), Okamura and Soga (2006), Yegian et al (2007), Okamura et al (2011), He et al (2013)], have demonstrated, also for static liquefaction, that the nearly to saturated state alleviates the risks of flow failure of sands in the manner quite similar to what has been previously established for the cyclic liquefaction. As to fully saturated ZM tailings, in order to estimate their susceptibility to flow failure, dozens of the penetration tests (S-CPTU, S-DMT) and many CHT's have been carried out offering to the designers the opportunity to use the q_c and V_s based empirical correlations to assess the risk of flow failure. This presentation will be limited to discussing the V_s measured during penetration tests and those resulting from CHT's.

Table 1. Depth to saturation line in tailings.

Cross-section	Lc (m)	Ds (m)	Elev. (m asl)	Lc (m)	Ds (m)	Elev. (m asl)
Year		2011			2014	
XIXE	17	37	165	17	35	165
	242	16	170	242	20	175
	338	8	170	338	11	175
VaN	40	31	171	40	33	174
	120	25	171	242	30	177
	200	21	170	338	26	177
VIIIW	41	29	171	41	34	175
	132	20	171	242	24	174
	217	9	170	338	17	174

Lc = distance from the dam crest
Ds = depth to saturation line

Figs.14 to 17 compare the shear waves profiles as measured in the CHT's 4E-5E and 7E-8E, whose location is shown in Fig.18, against those obtained by Tschuschke et al (2012) from S-CPTU and S-DMT's carried out nearby. These figures display both the V_s measured and the normalized V_{s1} with respect the appropriate ambient stresses computed by means of the following formula [Roesler (1979), Lee (1985), Lee and Stokoe (1986)].

$$V_{s,1} = V_s \cdot \left[\left(\frac{p_a}{\sigma'_a} \right)^{n_a} \cdot \left(\frac{p_a}{\sigma'_b} \right)^{n_b} \cdot \left(\frac{p_a}{\sigma'_c} \right)^{n_c} \right] \qquad (1a)$$

being: σ'_a = principal stress in the direction of wave propagation; σ'_b = principal stress in the direction of particles motion; σ'_c = "out of plane" principal stress, perpendicular to the plane made by σ'_a and σ'_b; n = experimental exponents referred to the principal stresses listed above.

Equation 1a can be rewritten, for shear waves propagated in the down-hole mode, polarized on the horizontal plane V_s (vh), as well as those propagated in the cross-hole mode, polarized on the vertical plane V_s (hv), referring to the geostatic effective stresses as shown below:

$$V_{s,1} = V_s \cdot \left[\left(\frac{p_a}{\sigma'_{vo}} \right)^n \cdot \left(\frac{p_a}{\sigma'_{ho}} \right)^n \right] \qquad (1b)$$

or, alternatively,

$$V_{s,1} = V_s \cdot \left[\left(\frac{p_a}{\sigma'_{vo}} \right) \cdot \left(\frac{p_a}{(k_0 \cdot \sigma'_{vo})} \right) \right]^{2n}$$

being: p_a = reference stress, 98.1 kPa; σ'_{vo} = effective vertical stress; σ'_{ho}=corresponding to horizontal effective stress, assuming the coefficient of earth pressure at rest (K_0) equal to 0.5; n = empirical exponent, assumed equal to 0.125.

In less frequent cases, when during the CHT, the horizontally propagated shear wave is polarized on the horizontal plane Vs (hh), equation 1b) reduces into:
$V_{s,1}$

$$= V_s \cdot \left[\left(\frac{p_a}{\sigma'_{ho}} \right)^n \right] \qquad (1c)$$

Both equations 1b and 1c omit the negligible effect that the out of plane geostatic effective stress ($\sigma'_c \approx 0$) has on the magnitude of V_{s1}. The exam of the data shown in Figs.15 to 17, computed from Eq. 1b, displays a consistent picture of V_{s1} yielded by different kind of tests, corroborating the use of the normalized shear wave velocity as an empirical index in evaluating the risk of cyclic liquefaction of sands and silty sands [Andrus and Stokoe (2000), Andrus et al (2004), Idriss and Boulanger (2009)].
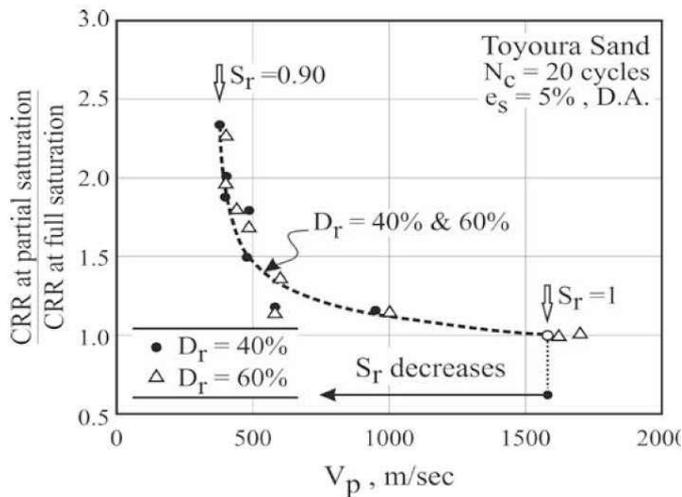
Fig. 13. Effect of partial saturation on the cyclic resistance ratio (CRR) of Toyoura sand - Ishihara et al (1998), Tsukamoto et al (2001).

On the contrary as to cyclic liquefaction, there are relatively limited case records attempting the empirical correlations of V_{s1} [Robertson et al (1995)] with respect soils susceptibility to the static liquefaction, considering in this case the state parameter approach more reliable as having better grounded theoretical basis [Jefferies and Been (2006), Robertson (2010)].

2.2.1 *Laboratory Tests*

As previously observed, the Gel-Push Sampler was first employed for undistorted sampling at ZM in 2013, aimed at a more rigorous evaluation of the static liquefaction hazard at depth. Its use not only has offered the possibility, throughout laboratory tests, to achieve more comprehensive and reliable data about the undrained strength of tailings during monotonic shearing, but also to compare the obtained results against those yielded by the specimens retrieved on the beach from hand-dug pits [Dyvik (1998), Hoeg et al (2000), Lipinski (1998, 2012)]. Fig.19 shows an example of the specimens retrieved on the beach which, after saturation and reconsolidation to the best estimate of the in situ ambient stresses, have been subject to monotonic undrained triaxial compression tests (TX-CK$_0$U-C) test. The obtained values of undrained shear strength (S_u) at locations of the phase transformation threshold [Ishihara (1993)] normalized with respect to the axial consolidation stress (σ'_a) are shown in the same figure. Fig.20 presents the frequency histograms for all TX-CK$_o$U-C tests run by Lipinski (2012) on the specimens retrieved from the pits, subdivided depending on the value of consolidation stress σ'_a. The results are classified according to the three possible modes of behaviour during undrained shear [Robertson (1994)]; Fig. 20 confirms that even fully saturated ZM tailings are

barely susceptible to flow failure even under axial stress as high as 1 MPa.
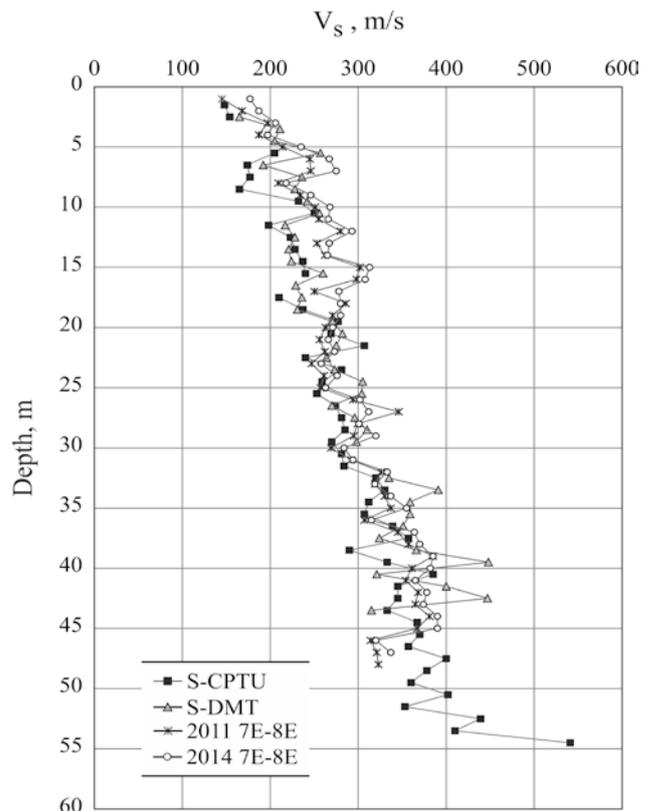
Fig. 14. Shear wave velocity profiles of tailings obtained from cross-hole test*, S-DMT** and S-CPTU**.
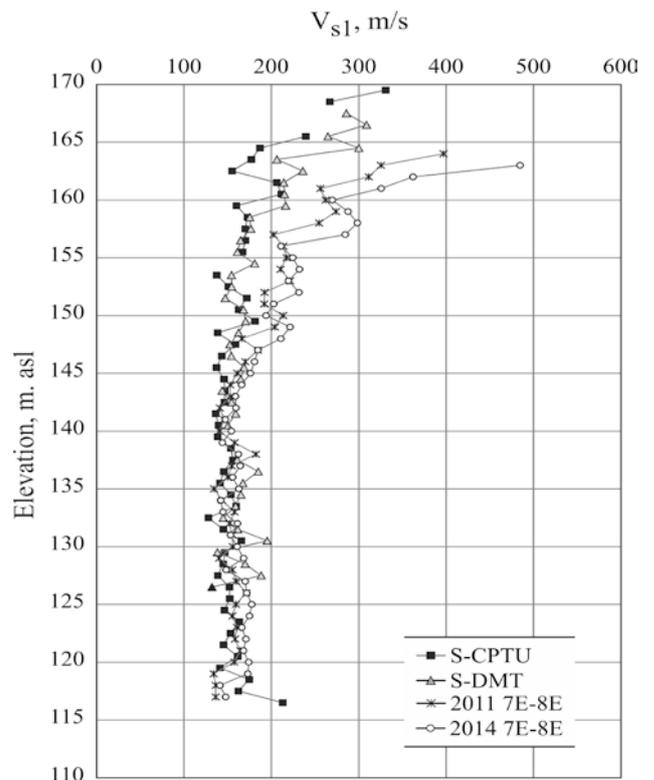
Fig. 15. Normalized shear wave velocity profiles obtained from CH test*, S-DMT** and S-CPTU**.

(*) CH 7-8, (**) Adapted from Tschuschke et al (2012).
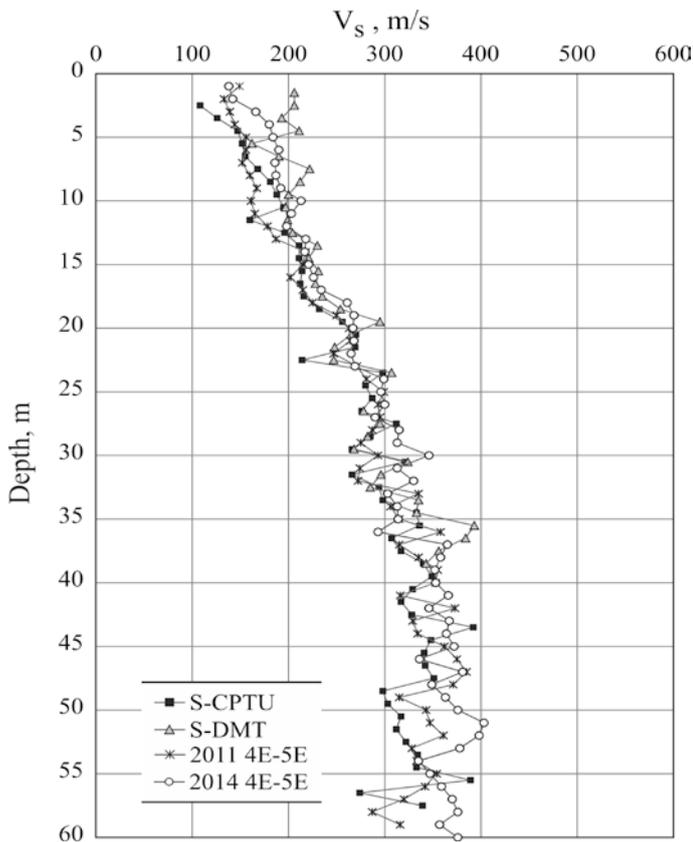
Fig. 16. Shear wave velocity profiles of tailings obtained from cross-hole test*, S-DMT** and S-CPTU**.
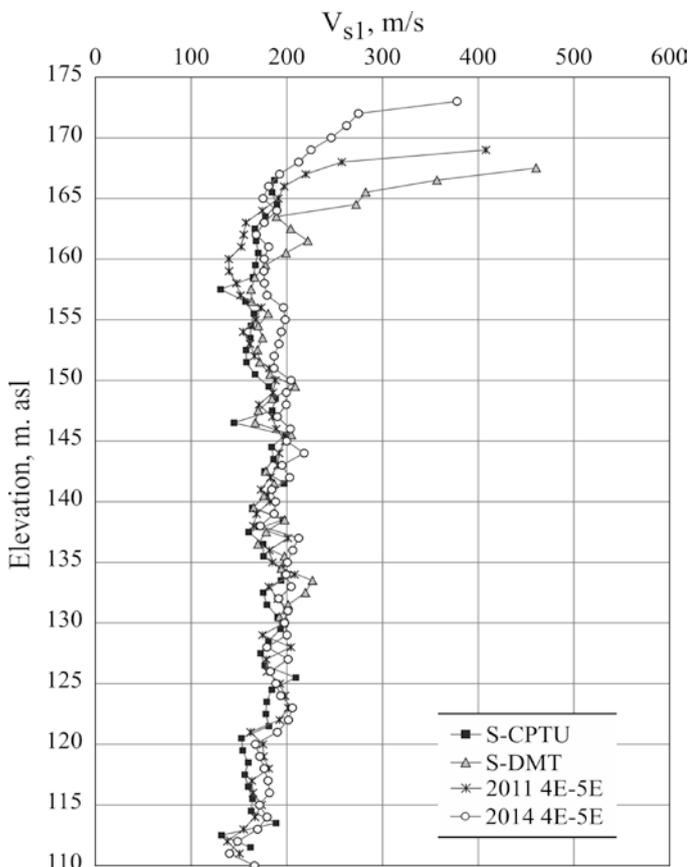
Fig. 17. Normalized shear wave velocity profiles obtained from CH test*, S-DMT** and S-CPTU**.

(*) CH 4-5, (**) Adapted from Tschuschke et al (2012).
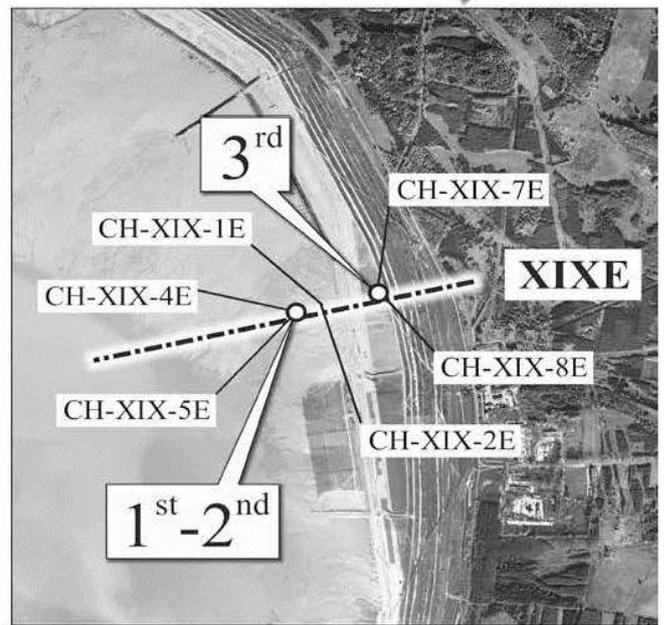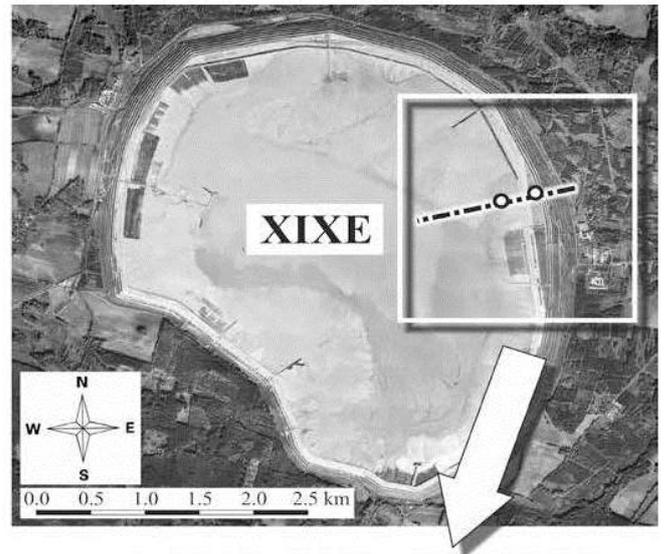
Fig. 18. East dam - Locations of cross-hole tests.
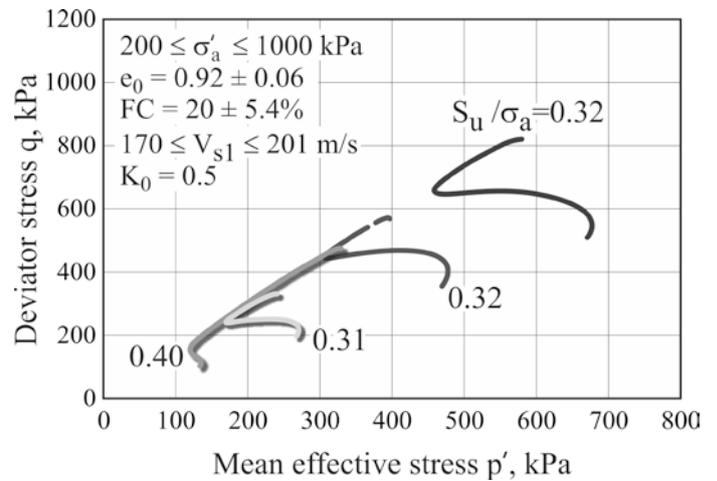
Fig. 19. East Dam, Geodetic section XIX-E.
TX-CK$_0$U on saturated tailings "undisturbed" specimens, Lipinski (2012).
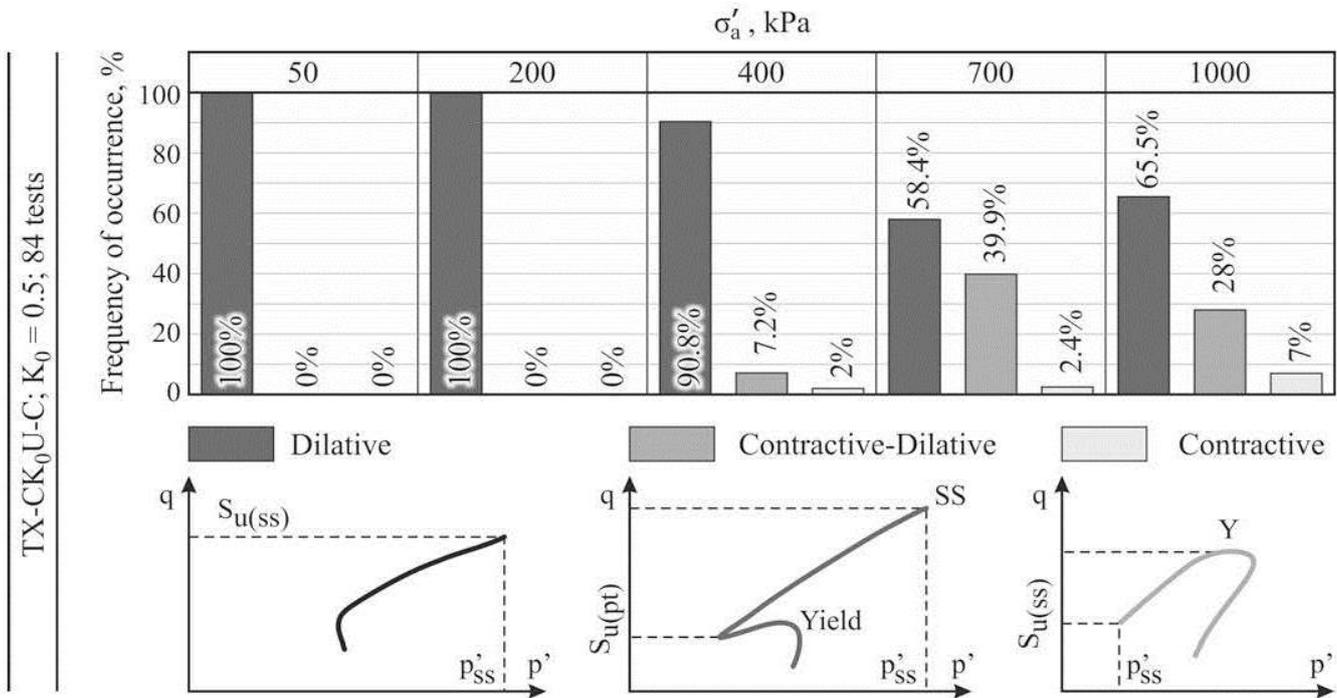
Fig. 20. "Undisturbed" tailings response to undrained shearing - Lipinski (2012).

For more comprehensive information Tab.2 reports examples of the index properties of tailings specimens collected by Lipinski (2012) from hand-dug pits at location close to the crest of East dam.

The step forward for a more rigorous characterization of the ZM tailings becomes possible thanks to a number of sampling campaigns using Gel-Push Sampler.

Up to the writers knowledge, this is the only available tool to attempt good quality undisturbed samples in the so called "intermediate soils" like silts and sandy silts. Although requiring a lot of precautions as regards drilling procedure, samples transportation to the laboratory; their handling in laboratory and a limited time interval between sampling and testing, the first three campaigns conducted on the ZM depository, considered as a learning process, succeeded in retrieving good quality undisturbed samples from large depths.

Table 2. East dam - Tailings samples from trial pits: summary of index properties. Lipinski (2012).

$32° \leq \varphi'_{cv} \leq 34°$		$2.69 \leq G_s \leq 2.72$			
L_C	FC*	e_0	e_{max}	e_{min}	D_R
m	%	-	-	-	%
40	14.5±4.9	0.798±0.055	1.023±0.028	0.531±0.028	46.4±8.2
100	18.9±7.5	0.797±0.032	1.034±0.037	0.513±0.036	45.6±8.2
140	24.7±11.2	0.847±0.032	1.076± NA	0.510± NA	36.3±5.8
200	24.8±6.3	0.897±0.077	1.076±0.049	0.513±0.034	29.3±7.5

L_C=distance from the dam crest; (*) low plasticity silt

Some of the results of laboratory tests carried out in the soil mechanics laboratory of Geoteko Ltd, Warsaw, Poland on tailings specimens retrieved by means of the Gel-Push Tr Sampler (Fig.21) are presented in [Reports: N° 263/3607/13 (December (2013), (February 2014) and (September 2014)].

Fig.22 shows the photo of an undisturbed sample relevant to the silty sand layer, collected from a boring located in the vicinity of CHT 7E-8E, at a depth of 34.5m below the beach. Moreover, this figure shows the grading of the sample in question as well as the grading range of the tailings encountered along the entire boring length up to the depth of 53m.

The Gel-Push sampling campaigns have permitted to determine that, by reason of the deposition method by spigotting and because of the upstream construction method of the ring dam, the deposited tailings exhibit highly pronounced variability, both as function of the depth and of the distance from the ring dam crest see Fig. 23. This figure illustrates the heterogeneity of three Gel-Push samples tested by Geoteko (2014). Fig.24 reports the overall variation of the tailings index properties with depth as obtained on G-P specimens taken from the borehole above mentioned and located in the vicinity of the East Dam crest. Since the samplings were carried out in boreholes located nearby the cross-holes, it was possible to assess the quality of the tested samples comparing the V_{s1} (L) measured in laboratory against V_{s1} (F) inferred from CHT's [Sasitharan et al (1994), Landon et al (2007), De Groot et al (2011), Fioravante et al (2012), Jamiolkowski (2012)] at the depth where they were retrieved, see Fig.25.

Fig. 21. Gel push sampler.

Labels in figure:

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

Polymer solution
Free piston

Drilling fluid
Discharge polymer
Polymer solution
Free piston
Sampler
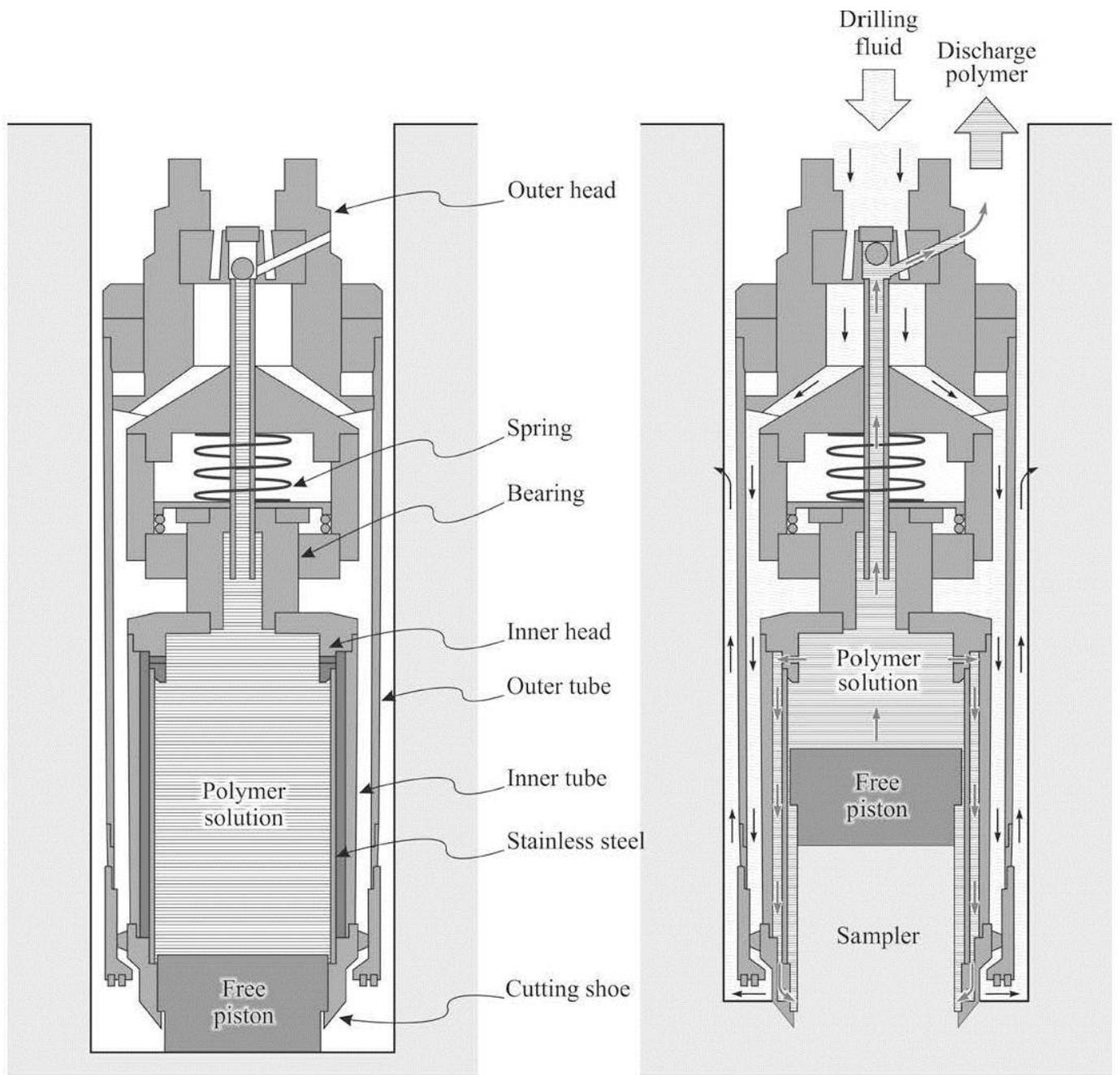
a) Lowering down the sampler to the bottom of borehole

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

→ Flow of drilling fluid   → Flow of polymer solution
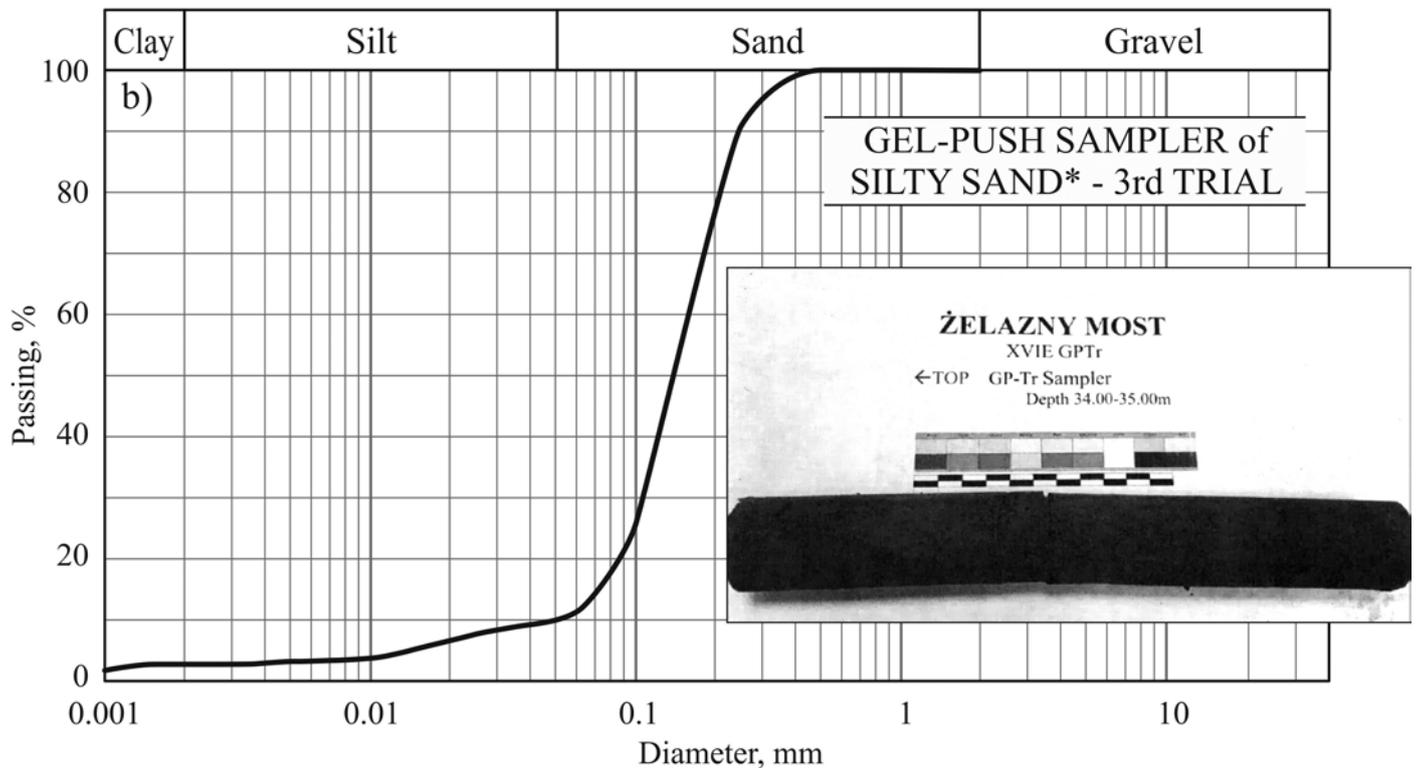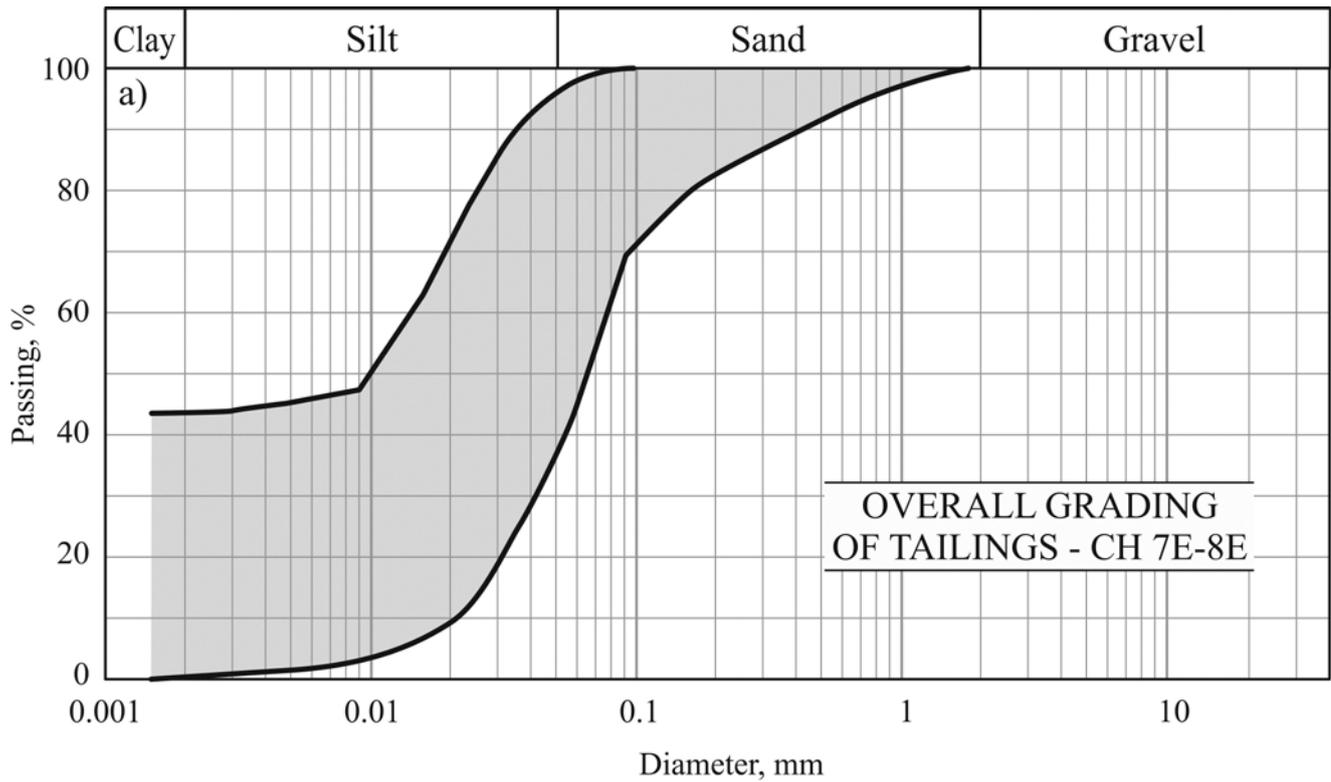
(*) Used to build the dam shell

$e_0=0.895$; $\gamma=18.6$ kN/m^3; G=2.745; $5.25 \leq SFR \leq 7.62$; Length 520mm; Diameter 72mm

Fig. 22. a) Overall grading of tailings. b) Gel-push sample of silty sand, 3rd trial - Geoteko (2014).
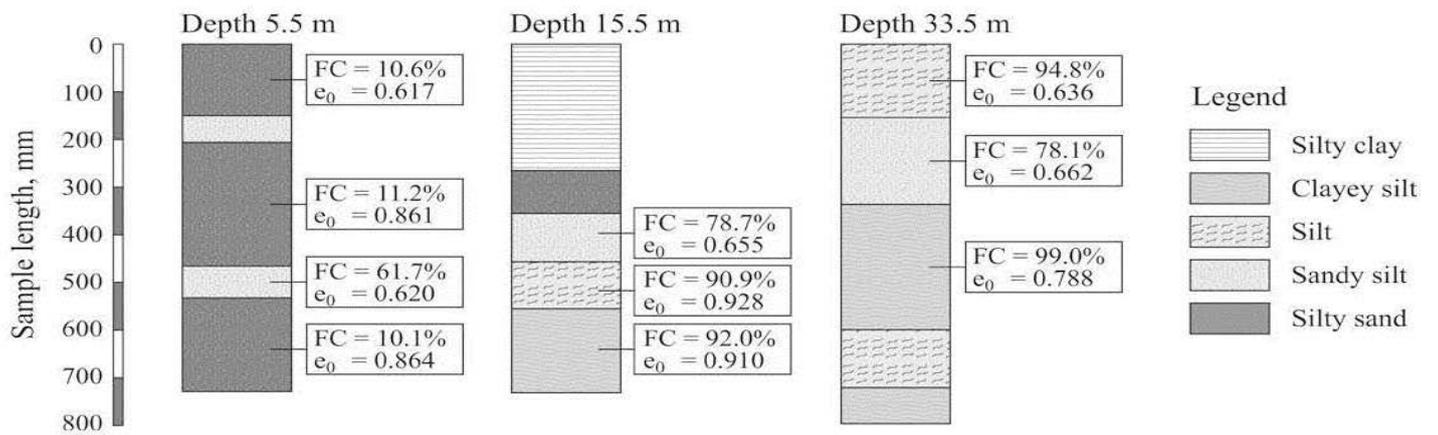
Fig. 23. Undisturbed tailings cores retrieved using G-P Tr sampler - 3rd Trial, Geoteko (2014).
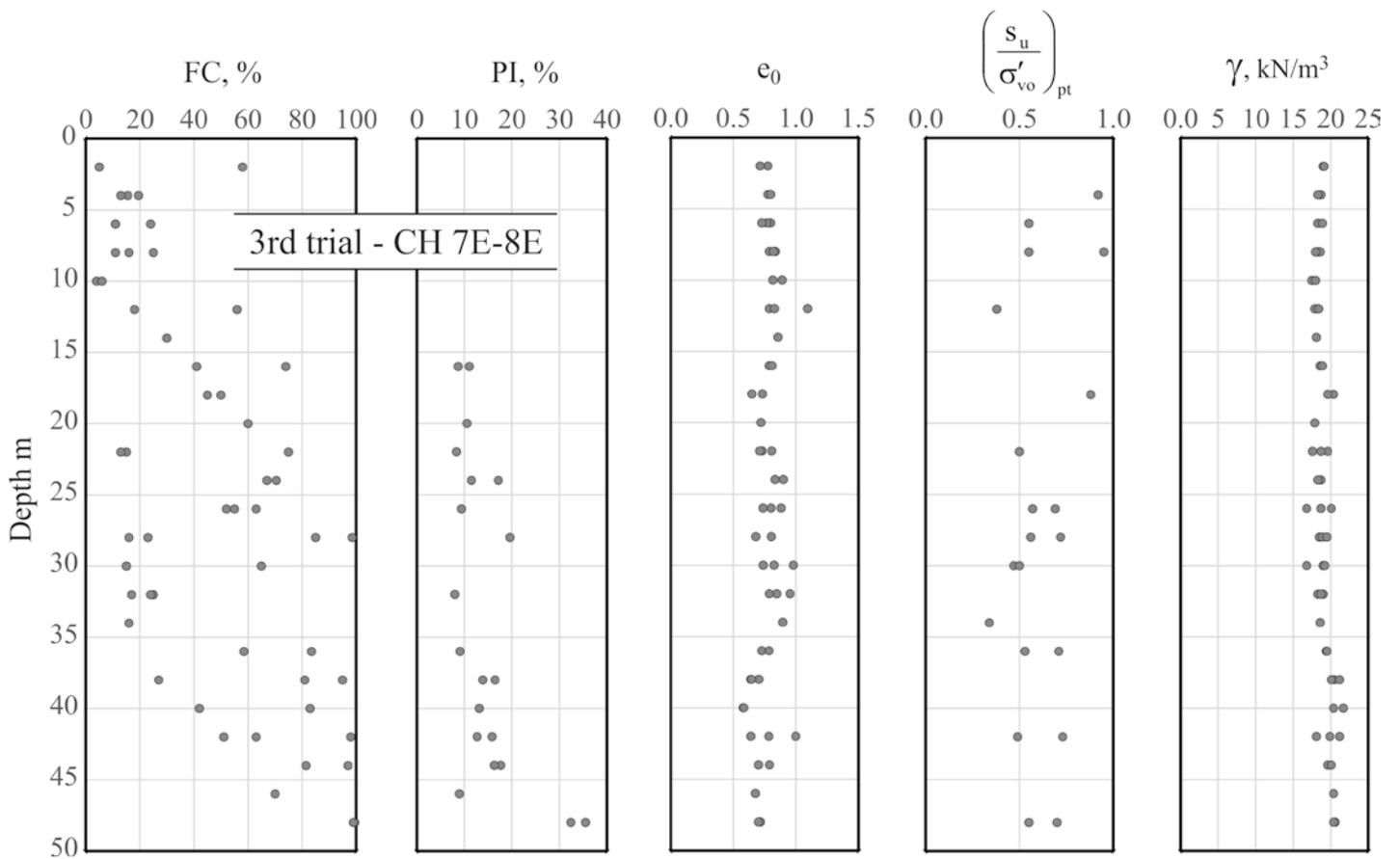
Fig. 24. Index properties of ZM tailings - Tr gel-push sampler, 3rd trial, ≈ 20m from dam crest. Geoteko (2014).
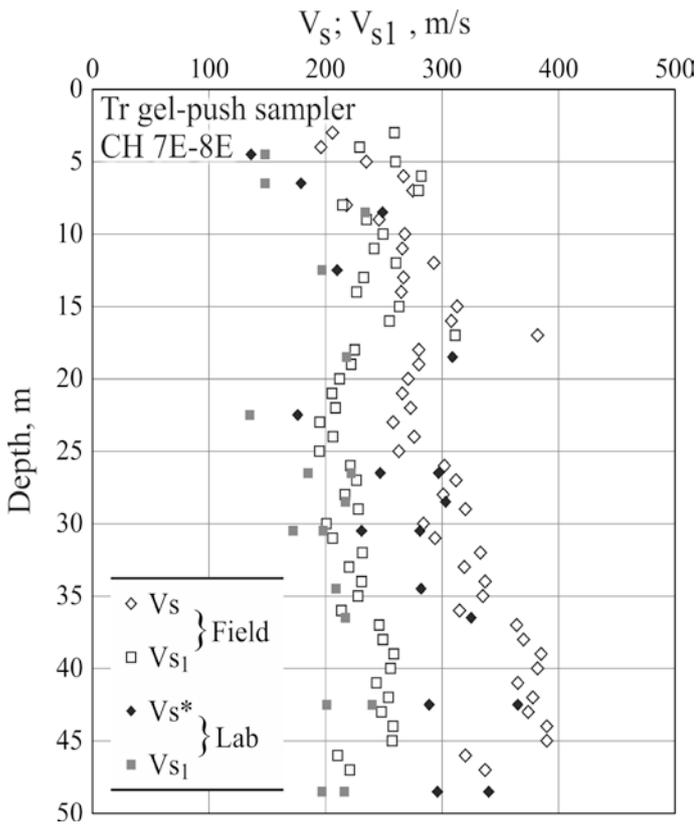
Fig. 25. East dam - Comparison $V_{s1}(F)$ vs. $V_{s1}(L)$. (*) Bender element test, Geoteko (2014).

The specimens of Gel-Push samples were subject to numerous TX-CK$_o$U-C tests; an example is shown in Fig.26. Likewise the specimens retrieved from the hand-dug pits on the beaches, all the Gel-Push specimens, during undrained shearing, exhibited dilative or contractive-dilative behaviour. In the latter case the contractive response was generally less pronounced than for specimens taken on the beaches.

Furthermore, despite the remarkable high spatial variability of tailings disclosed by Gel-Push samples and corroborated by the results of seismic penetration tests, the writers have attempted to compare, see Fig.27, the in situ void ratio e_0 computed on the basis of CHT's results using the formula by Foti et al (2002). Such formula, exposed below, is applicable to fully saturated geomaterials only, against that measured in laboratory on Gel-Push specimens.

$$n = \frac{\rho_s - \left[\rho_s^2 - \frac{4(\rho_s - \rho_f)B_f}{V_p^2 - 2\left(\frac{1 - \nu_s}{1 - 2\nu_s}\right)V_s^2}\right]}{2(\rho_s - \rho_f)} \quad (2)$$

being: n = porosity; ρ_f = pore fluid mass density; ρ_s = soil particles mass density; B_f = bulk modulus of pore fluid; ν_s = Poisson ratio of soil skeleton.

The data reported in Fig. 27 show that the values of the e_o computed from CHT interpretation, on the whole, match with those measured on Gel-Push specimens by Geoteko (2013, 2014). Considering the pronounced spatial variability of tailings and taking into account that the laboratory tests were carried out on a much smaller volume of soil than that involved when measuring V_p and V_s in cross-holes, this result appears encouraging as it regards the evaluation of e_0 from Foti et al (2002) formula in a complex geological settings such as ZM copper tailings depository. With the aim to assess the influence of the initial anisotropy (fabric and stress-induced) on the V_s, Figs.28 and 29 show the profiles of the horizontally polarised shear waves V_s (hh) compared with the vertically polarised ones V_s (vh) as measured in the CH 4E-5E and CH 7E-8E during the 2014 cross-hole series.

Depth 9.5m; Silty sand: γ = 19.6 kN/m^3; e_0 = 0.821; FC = 81%; V_s = 242 m/s
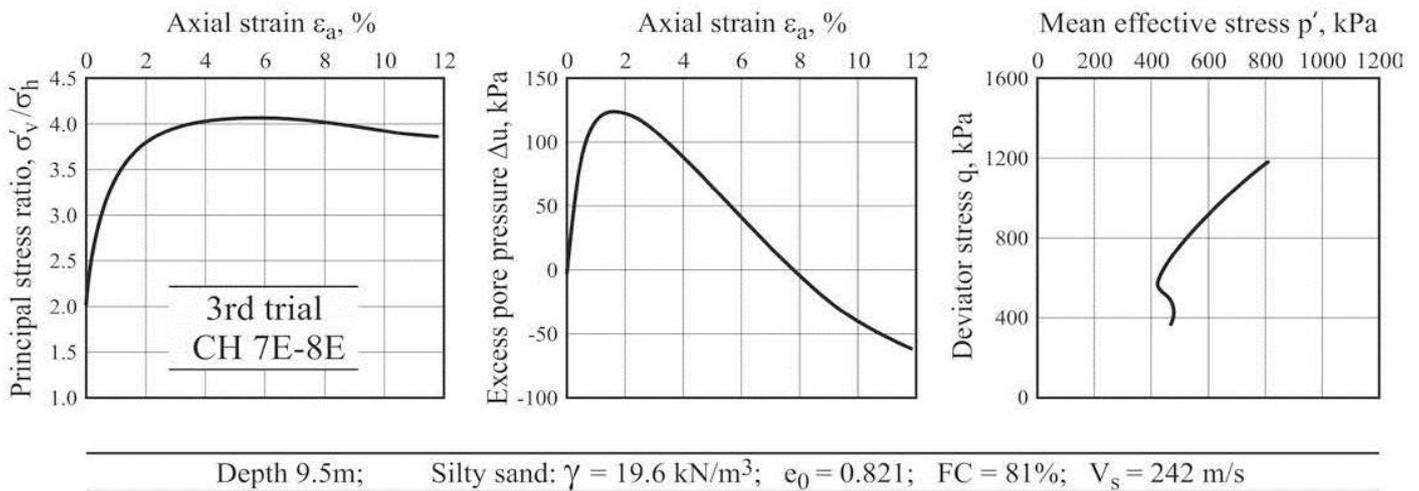
Fig. 26. TX-CK$_0$U-C tests on undisturbed Gel-Push specimen, Geoteko (2014)
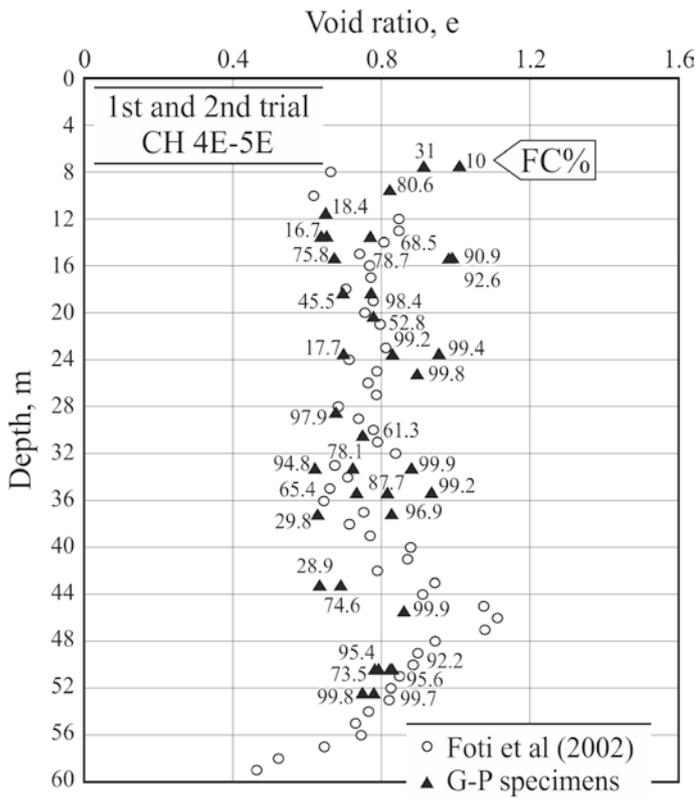
Fig. 27. Void ratio of Gel-Push samples and computed from CHT

Fig. 28. CH 4E-5E - Measured shear wave anisotropy.
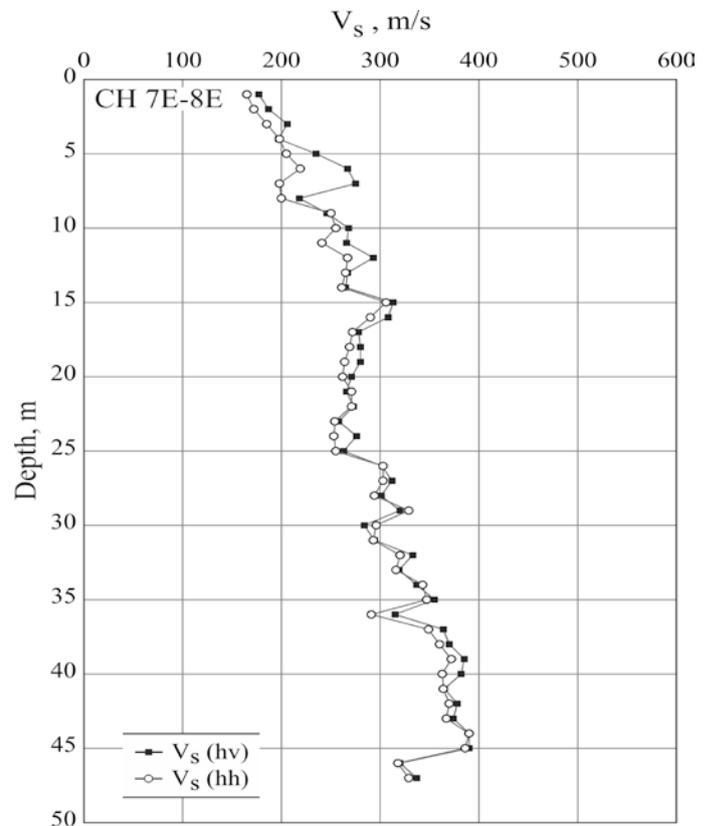
Fig. 29. CH 7E-8E - Measured shear wave anisotropy.

As it can be inferred from the above figures, the initial anisotropy of V_s, in the examined case, is quite small excepting a few localized spots, as shown in Figs 28 and 29.

Nevertheless, because the values of V_s (vh) and V_s (hh) were measured in the cross-holes 7E-8E and 4E-5E, the writers could investigate how the initial anisotropy (Figs.28 and 29) affects the e_0 computed by Foti et al (2002) formula.

With this aim in mind, for a given value of V_p, the void ratio of tailings were computed twofold, introducing, alternatively, the values of V_s (hv) and V_s (hh). The obtained results are shown in Fig.30, suggesting that in the examined case the uncertainty due to the V_s anisotropy on computed e_0 is in the range of 1.5% to 2.9%.

For more information concerning how the uncertainty of the measured V_p and V_s influence the yielded values of the void ratio refer to Foti (2004).

Overall, taking into account that equation ..2) refers to the theory of poroelasticity of the fully saturated isotropic medium [Biot (1956)], the issue of how the initial anisotropy of both V_p and V_s affects the computed void ratio deserves further validation.

Fig. 30. Tailings void ratio computed after Foti et al. (2002).

3   CLOSING REMARKS

The paper summarizes the results of in situ and laboratory tests carried out in more than two decades to characterize the copper tailings stored at ZM depository.

Considering the geotechnical hazard involved in this project and the ore extraction planned for at least the next thirty years, the characterization of tailings will continue using different methods and aware of any innovative in situ and laboratory techniques that might improve the methods used so far.

Based on the data here reported the following conclusions can be drawn.

In terms of in situ tests, attention has been paid to the in-hole geophysical methods which play a crucial role in assessing the susceptibility of tailings to static liquefaction. The measurements of the compression wave velocity (V_p) allow making a reliable distinction between fully and near to saturated state of tailings which issue is affecting significantly their undrained shear strength.

Moreover, the normalized shear wave velocity (V_{s1}) provides, for sands and silty sands, a useful empirical index of the promptitude to suffer cyclic or static liquefaction.

Within this frame three different kinds of tests (CH, S-DMT, S-CPTU) yielded very consistent V_{s1} profiles with depth.

As to laboratory tests, the use of Gel-Push Tr sampler has allowed retrieving good quality undisturbed samples of tailings at depth.

The TX-CK$_0$U-C tests have indicated that in view of the dilative and dilative-contractive behavior of tailings during undrained shearing, even in fully saturated state, they are hardly prone to be subject to flow failure.

Furthermore, using the seismic waves velocities (V_p and V_s) measured in cross-holes an attempt was made to compare the void ratio measured in laboratory on the Gel-Push samples with that computed according to Foti et al (2002) using equation 2).

In spite of the pronounced spatial variability of tailings, the computed values of e_0 match reasonably well with those measured on Gel-Push samples.

Moreover, having measured in cross-holes 7-8 and 4-5 both horizontally [V_s (hh)] and vertically [V_s (hv)] shear wave velocity, ratio of which reflects the initial deposit's anisotropy, an essay was undertaken to compute e_0, introducing Foti et al (2002) formula, V_s (hh) and V_s (hv) respectively. The results of this exercise have shown that in the case of ZM tailings, the V_s initial anisotropy affects the computed e_0 in range between 1,5% to 2.9%.

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