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The Application of the Seismic Cone Penetration Test (SCPTU) in Tailings Water Conditions Monitoring

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Abstract: The safe operation of the large, outflow Tailings Storage Facilities (TSF) requires comprehensive and continuous threat monitoring. One of the basic kinds of threat monitoring is to monitor the water conditions in deposited tailings, which is usually carried out using a conventional piezometric observation method from a network of installed piezometers. In complex tailings storage conditions, the reliability of the piezometric method may be questioned. The Seismic Cone Penetration Test (SCPTU) can meet high test standards. The results of the penetration tests closely identify conditions of sediments that determine the tailings water regime verified locally on the basis of pore water pressure dissipation tests. On the other hand, seismic measurements perfectly complement the characteristics of sediments in terms of their saturation. The analysis of the results of SCPTU implemented in the tailings massif also showed that below the phreatic surface, a zone of not fully saturated tailings can be found. Its presence improves the stability conditions of the tailings massif and dams, but also limits the possibility of the static liquefaction of tailings.

Keywords: water conditions monitoring; tailings storage facility; postflotation sediments; SCPTU

1. Introduction

The final link in the technological process of copper production is the tailings storage facility, which receives most of the extracted rock output after processing. The use of the hydrotransport method for depositing tailings in a storage facility means that a significant amount of technological water reaches the storage facility along with tailings [1]. Water, after being drained from outflowed waste, accumulates in the central part of the facility, creating a decant pond [2]. The technological water cycle is monitored and managed both on a global scale related to the entire copper production process, and on a local scale covering the storage facility area. The monitoring of water conditions in an outflow, above–ground facility is an essential element determining the safety of the operated facility [3–6]. While safe accumulation of the controlled volume of technological water in the decant pond is reduced to maintaining a certain distance from the crown of the dams to the shoreline of the pond, a network of piezometers is used to identify the location of the depression line in the tailings massif [7]. Due to the point nature of piezometric observation on the one hand, and non–hydrostatic and often discontinuous distribution of water pressure in sediments on the other, the identification of saturated and unsaturated zones of sediments in the facility's massif based on piezometric measurements is not always completely unambiguous [8]. The correct assessment of water conditions means the realistic parametric identification of sediments, which, in turn, determines the results of the stability analysis of the facility's dams. Finding a rational method of reliable assessment of water conditions is, therefore, of paramount importance for reliable analysis of the stability of the tailings dams [9]. The cone penetration test carried out with the seismic piezocone may be helpful in this matter [10–13]. In this type of test, three independent penetration characteristics are registered continuously, selected profile depths, dissipation tests of pore water pressure excess, and in a cyclical manner, usually with a frequency of 1 m increase in penetration depth, seismic wave velocity measurements. The combination of registered test parameters introduced into advanced interpretation procedures enables precise assessment of the water conditions of sediments in relation to detailed stratigraphic and geotechnical identification of sediments in the profile of the performed research [9,14,15].

The main aim of the work is to demonstrate the qualitative advantage of SCPTU over the conventional piezometric method for the purposes of comprehensive monitoring of water conditions in the spigotted postflotation tailings storage facility. The possibility of separating zones with different saturation in the tailings massif makes the parametric evaluation of sediments more realistic, which translates into the results of the evaluation of stability of the tailings massif and dams.

2. Materials and Methods

2.1. Study Area

The Żelazny Most Tailings Storage Facility (TSF) was put into use in 1977 for the purpose of depositing tailings from a flotation copper ore enrichment. Copper ores extracted from considerable depths by three operating deep mines contain a small percentage of pure metal, while the remainder in the amount of about 94% of extracted ore is tailings in the form of crushed rocks subject to flotation. Annually, about 29 million tons of postflotation tailings are deposited in the storage facility. The process of systematic tailings deposition in the storage facility, uninterrupted for over 40 years, resulted in the fact that Żelazny Most TSF is currently the largest facility of its kind in Europe and the second largest facility in the world. It covers an area of 1400 ha, and along with the so-called Southern Quarter, which is currently being developed, it covers an area of 2000 ha. The height of the dams surrounding the main object reaches 70 m, and the amount of tailings deposited inside is estimated at 640 million m^3 (Figure 1).

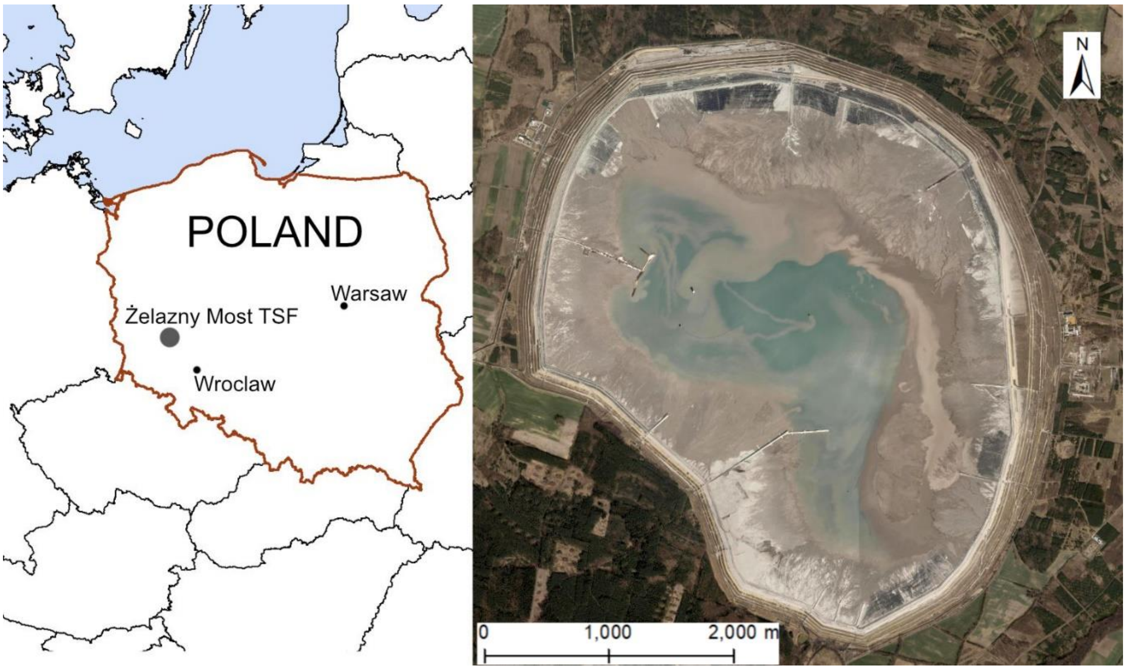

Figure 1. Location and aerial view of the Żelazny Most Tailings Storage Facility (TSF).

Postflotation tailings in the form of a mixture of mine–technological waters and finely ground rocks are led to the storage facility by a pipeline system using the hydrotransport method. From the pipeline installed on the crown of the dam, which surrounds the entire facility, tailings are outflowed into the interior of the storage facility's area (Figures 2 and 3).

Figure 2. Waste spigotted onto the facility's beach [13].

Figure 3. The view of the beach with spigotted waste [13].

The spigotted postflotation tailings are subjected to the process of segregation sedimentation, which is a result of the material of the coarsest particles of the sediments in the area of the discharge site, and the finer material is a little farther, while technological water flows together with the finest waste to the central part of the storage facility. The decand pond acts as a water clarifier where the intake towers are used to recycle it for secondary use in the flotation process. From the pond, where the volume changes periodically from 5 million m^3 to 8 million m^3, about 0.5 million m^3 of accumulated waters are recovered daily for the flotation process. The permissible capacity of the pond is limited by safety considerations that require maintaining the shoreline of the pond at a distance of not less than 200 m from the external dams' crowns surrounding the storage facility. Due to the fact that the dams of the facility are earth dams of the filtration type that enables the flow of waters through the tailings massif, an extensive drainage system is an important element that is supporting the facility's safety system [1,16,17]. The main task of the drainage system is to maintain the lowest possible location of the phreatic surface in the tailings massif and in the dam bodies and to take over a part of the technological waters migrating to the subsoil of the storage facility. The second postulate results from limiting the degrading effect of saline technological waters on groundwater. The basic elements that make up the drainage system are: circumferential drains of the beach, a girdling ditch, and drainage of the starter dam, as well as vertical drainage in the form of a deep well barrier (Figure 4).

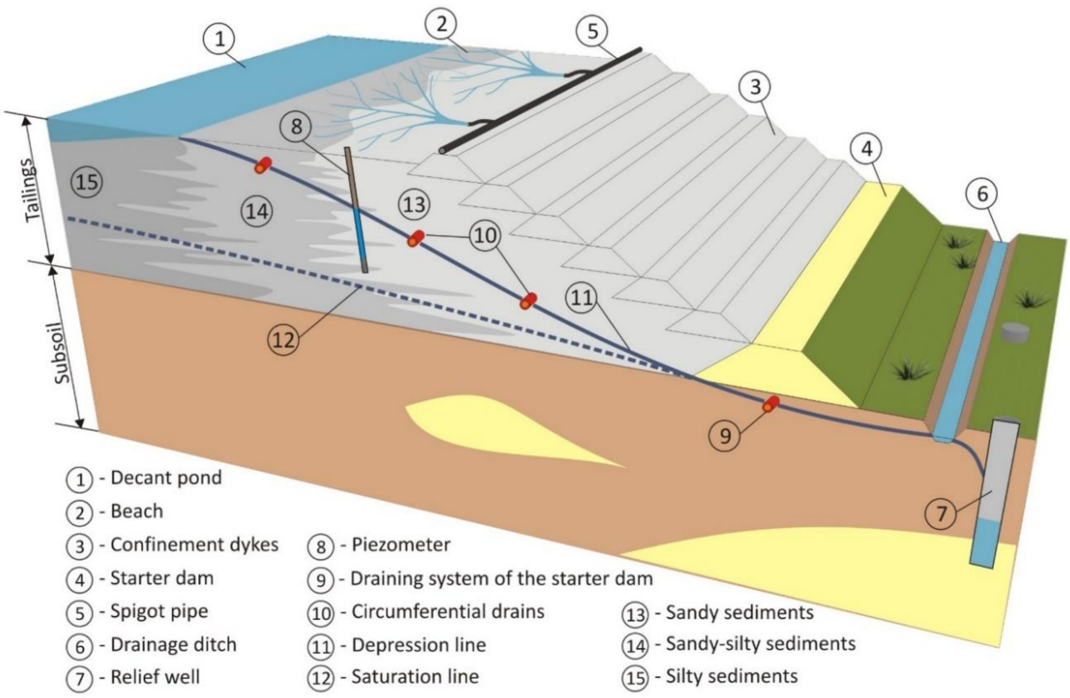

Figure 4. Schematic cross–section of ring dam and drainage system.

The structural elements of the facility are external dams surrounding the storage facility. At the initial stage of the facility construction, the starter dams founded on subsoil were constructed in the form of a limiting earth embankment made of sand and gravel. The higher embankments forming the dykes that are supported on the starter embankment were built with the upstream method of the coarsest waste that was deposited on the beach inside of the facility [13]. 5 m high superstructure moduli separate 10 m wide shelves formed on the outside of the dam slope (Figure 4). With an average annual volume of deposited waste of about 18 million m^3, the average annual growth rate of waste in the facility equals 1.3 m.

2.2. Research Material

The method of depositing mine waste in a storage facility using the spigotting method presents serious risks. The mining output in the form of solid rock, which was originally lying in the subsoil, is transformed in the technological process into a grain structure dominated by sandy and silty fractions.

The discharge of tailings into the interior of a storage facility and using the spigotting method onto the beaches as a result of the sedimentation process causes their natural segregation in terms of grain size. The consequence of this process is that the sandy fractions are deposited on the beach in the vicinity of the dam, the sandy–silty material is in the more distant parts of the beach, while the finest silty fraction together with the technological water flow into the central part of the facility. Numerous studies [2,18–20] documenting the spatial distribution of sediment grain size in a facility point to a clear trend of an increase in the average content of silt in the beach profile as it moves away from the discharge site and, conversely, an increase in the average content of the sand as the beach profile approaches the discharge site. In addition, in the more distant beach profiles, the amount and thickness of silty layers formed in the sandy sediment zone increases [13]. The central massif of the facility is formed by sedimenting waste in salty water with a grain size dominated by the silt and with a small admixture of a clay. The grain size distribution of postflotation tailings in the context of natural soil classification ranges from fine sands, such as silty sands, sandy silts, and silts, to silty clays. Such a large variability of tailings in terms of grain size distributions means that their physical, mechanical, and filtration properties must differ significantly. This issue is well illustrated by the assessment of tailings filtration capacity, which, expressed by the water permeability coefficient, indicates the variability of this parameter value in the range between 10^{-4} m/s and 10^{-9} m/s [21]. Due to the technology used to deposit waste in the facility, the state of the sediments also shows a strong diversity. Sediments used for the construction of dams collected from the beach in the process of forming and rolling are deprived of the original structure in the embankment, while the embankment material requires compliance with density criteria [18]. Sediments that retain the natural structure resulting from the sedimentation process deposited on the beach are distinguished by their loose and medium density. Fresh sediments filling the pond are characterized by a liquid state, while older sediments subjected to the process of consolidation are soft to stiff state [13]. The occurrence of loose sandy sediments in a state of full saturation with an adverse change in the load conditions caused by a raising level of waste storage is a model condition for their liquefaction. Another type of unfavorable load conditions may be cyclic loads caused by the impact of a paraseismic wave induced by a mining shock. Both of these cases can occur at Żelazny Most TSF [1,22].

2.3. Methods

In the opinion of many researchers [8–12,23,24], the cone penetration test with the measurement of pore water pressure and seismic wave velocity (SCPTU) is currently perceived as the most comprehensive, and also extremely reliable, in situ subsoil test (Figure 5).

According to the standard of this test, an electric piezocone is pressed into the subsoil at a constant speed of 2 cm/s, which continuously, with a frequency of every 2 cm increase in penetration depth, allows the recording of test parameters, which are:

- measured cone resistance q_c,
- sleeve friction resistance f_s, and
- dynamic pore water pressure u_c.

If the filter for measuring pore water pressure is located directly behind the tip of the cone, then the general designation u_c corresponds to the index u_2. Stopping of cone penetration starts the dissipation process of the measured dynamic pore water pressure, which is reduced to in situ pore water pressure at the level of cone penetration—u_0. Another regular measurement carried out after stopping cone penetration, usually with an interval of 1 m increase in penetration depth, is the measurement of seismic signals, including the recording of:

- shear wave velocity v_s, and
- compression wave velocity v_p.

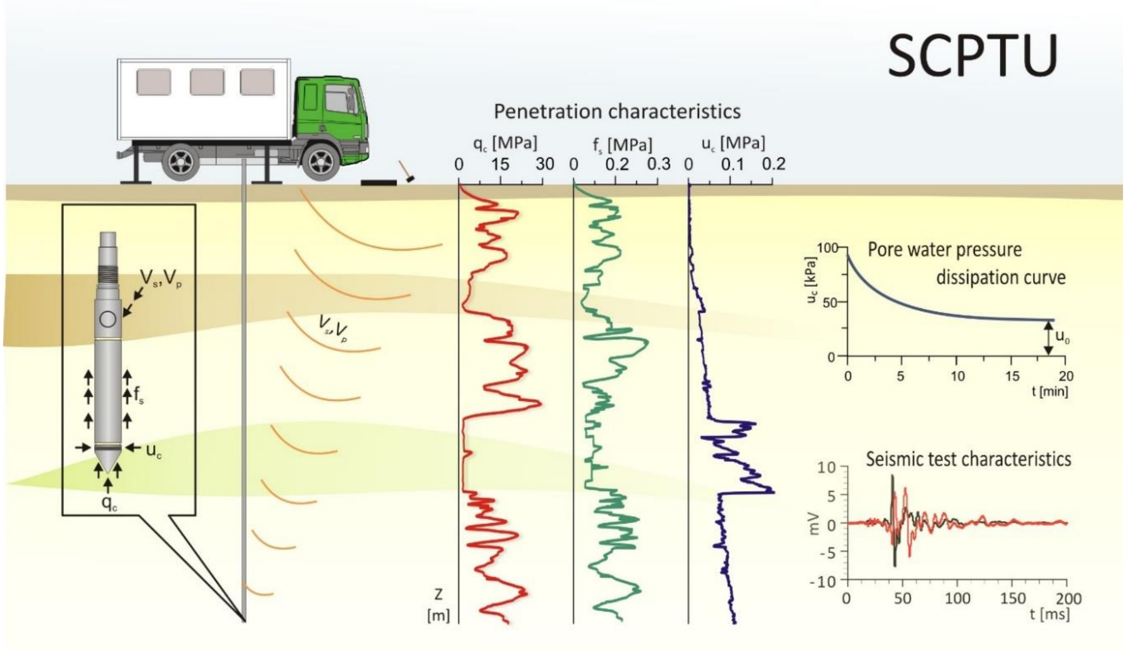

Figure 5. Principles of seismic piezocone testing.

In order to identify soil and water conditions based on the CPTU results, classification systems and interpretation procedures verified against local conditions are used [13,15,24]. In the interpretation proceedings, intermediate stages in which the registered test parameters are subject to standardization and normalization are used. The basic test parameters in this group are:

- corrected cone resistance $$q_t = q_c + u_c\,(1 - a) \quad (1)$$
- net cone resistance $$q_n = q_t - \sigma_{v0} \quad (2)$$
- friction ratio $$R_f = (f_s/q_t) \times 100\% \quad (3)$$
- pore pressure parameter $$B_q = (u_2 - u_0)/(q_t - \sigma_{v0}) \quad (4)$$
- normalized shear wave velocity $$v_{s1} = v_s(p_a/\sigma'_{v0})^{0.25} \quad (5)$$

where: a—net area ratio of the cone, σ_{v0}—total overburden stress, u_2—pore pressure measured behind cone, u_0—in situ pore pressure, v_s—shear wave velocity, p_a—reference stress (= 100 kPa), and σ'_{v0}—effective overburden stress.

The first two of the parameters presented above are the basic parameters for assessing the physical and mechanical properties of soils, the next two are commonly used in classification systems to identify the type of soil and drainage conditions, and the last one may be an indicator of the soil susceptibility to liquefaction.

3. Results and Discussion

The upstream extension of the facility results in the fact that the confinement dykes, which close the waste storage area, are founded on previously deposited waste. Depositing waste in a facility using the hydrotransport method requires maintaining a pond of technological water in the central part of the facility. Both of these elements have a significant impact on the stability of dams [2]. Therefore, maintaining the lowest possible location of the phreatic surface in the tailings' massif and dam bodies is one of those aims that can improve the conditions of dam stability. The developed beach drainage system and the starter dam are subject to this goal. The correct operation of the drainage system is monitored by a network of 1200 piezometers. It is on the basis of the piezometers readings analysis that the shape and location of the depression line are determined in a control cross-sections. Obtaining the most convergent to the real course of the depression line in cross-section is, therefore, of paramount importance for the final results of calculations of dam stability. This line implicitly separates the unsaturated medium from the full saturation sediments, which in the adopted calculation model differentiates the sediments in terms of strength assessment (Figure 4). For sandy sediments deposited on the beach in the area of discharge points, regardless of the saturation state, favorable values of the shear strength parameters expressed in the effective friction angle $\varphi' = 34°$ are assumed for calculations. In parts of the beach located farther away from the place of waste discharge, in the area of sandy-silty sediments, which are above the depression line, favorable strength assessment characterizing the sandy sediments is maintained, while below the depression line in the description of sediments, the effective friction angle is replaced by undrained shear strength. It is recommended to assume the value of this parameter at the level of 0.4 of the effective overburden stress ($s_u = 0.4\ \sigma'_{v0}$).

The location of the pond in the central part of the facility is elevated, as opposed to the original terrain structure, in which the facility is located at a height of about 70 m, which causes the water from the pond to migrate to the subsoil supplying groundwater. The process of filtration of water from the pond to the subsoil is slowed down by sediments and layers of the subsoil. The heterogeneous structure and the nature of the sediments layered as a result of the sedimentation process makes filtration a complex process, and the distribution of water pressure in the profile can be discontinuous and usually different from hydrostatic distribution [8]. Identification under such conditions of the real distribution of pore water pressure, an indication of the extent of the zone of fully saturated sediments and unsaturated sediments and, as a consequence, the prediction of the phreatic surface in the calculation cross-section for the analysis of the stability of dams of the facility, requires proven and reliable methods of monitoring of water regime. The most commonly used method of this type of monitoring is the method based on piezometers readings. However, in the case of a hydrotechnical object depositing postflotation tailings, the assessment of water conditions in the tailings massif based on the analysis of the indications of a single piezometer cannot be reliable. This type of measurement indicates only the water pressure measured in the tailings at the depth of the piezometer filter installation. Without additional information about the shape of this water pressure distribution in the analyzed profile, it is difficult to clearly determine the depth at which the free water table stabilizes (Figure 6a) [8].

A much more realistic assessment of the water conditions in the analyzed profile of the tailings can be obtained when a single piezometer is replaced with a piezometer bundle consisting of several independent devices whose filters have been installed at different profile depths (Figure 6b). Based on the analysis of the results of such observations, an approximate to real distribution of water pressure in the profile is obtained, from which the depth of stabilization of the free water table in sediments can be determined. Due to the point nature of the measurements in the sediment profile and the influence of the piezometer bundle installation, as well as the construction of the device itself, it is difficult to identify isolated, not fully saturated sediment zones within the fully saturated sediment complex [8].

In the context of the above limitations, the cone penetration test is much more precise than the piezometric method in deposited waste conditions for the method of identifying water regime. In this test, one of the continuously recorded penetration characteristics is measured by cone penetration dynamic pore water pressure, which, from a physical point of view, is the sum of the piezometric pressure and excess pore water pressure generated in the soil around the cone as a result of the penetration process. Stopping cone penetration naturally triggers the mechanism of dissipation of excess pore water pressure to a set water pressure, which corresponds to piezometric pressure. The graphic picture of this process is the curve of pore water pressure dissipation [11,15]. A complete dissipation of water pressure to a value of zero indicates no water present at the cone's stopping depth. A similar result of the dissipation process in tailings below the phreatic surface indicates the identification within the complex of saturated tailings, isolated by the strength of the various filtration properties of the nearly saturated zone. Such a situation is favored by the strongly horizontally layered profile of the storage facility's massif, which is a direct consequence of sedimentation processes in various spigotting conditions. With the dominant vertical direction of filtration of water through the tailings massif, it is slowed down on the top of silty sediment layers with limited filtration capacity and vice versa in sandy sediment layers. In such a situation, the infiltrating water is accumulated on the top with a layer of silty sediments, and with an intensive outflow from the lower layers of sandy sediment.

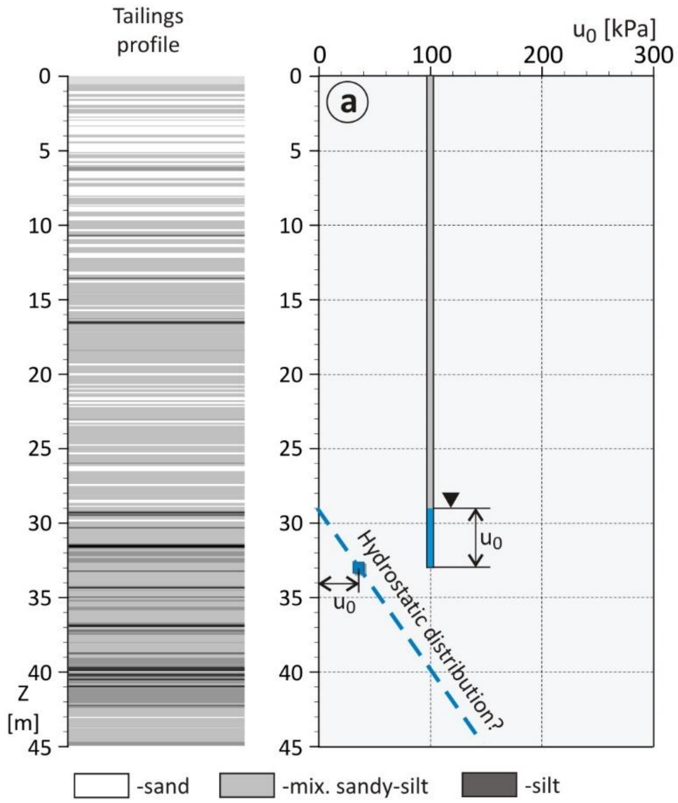

Figure 6. The comparison of the assessment of water conditions in sediments based on (**a**) single and (**b**) multiple piezometers readings.

An excellent complement to the assessment of water conditions based on the analysis of the dissipation curves of pore water pressure excess of tailings from the CPTU is the inclusion in this assessment the other two penetration characteristics, i.e., cone resistance and sleeve friction to this analysis [13]. Distributions of these parameters with depth allow for the determination of friction ratio characteristics (Equation (3)), a parameter identifying the sediments profile including the location in the profile of layers of different grain size, and also different water permeability. Strong zig–zag effects on the friction ratio diagram show the layered nature of sediments deposited on the path of cone penetration. High values of the ratio R_f identify silty layers, while lower values R_f indicate sandy sediments. A good example of the considered case of the possibility of the occurrence of isolated zones of not fully saturated sediments within the sediments of full saturation is a layer of sandy sediments, in which the absence of water was demonstrated, closed with silty layers located at depths of 33.5 m and 34.3 m in the profile (Figure 7). Figure 8 depicts differences in the assessment of water pressure distribution in sediments that is determined based on a single piezometer reading, an observation from a piezometric bundle, and on a pore water pressure dissipation test from the CPTU.

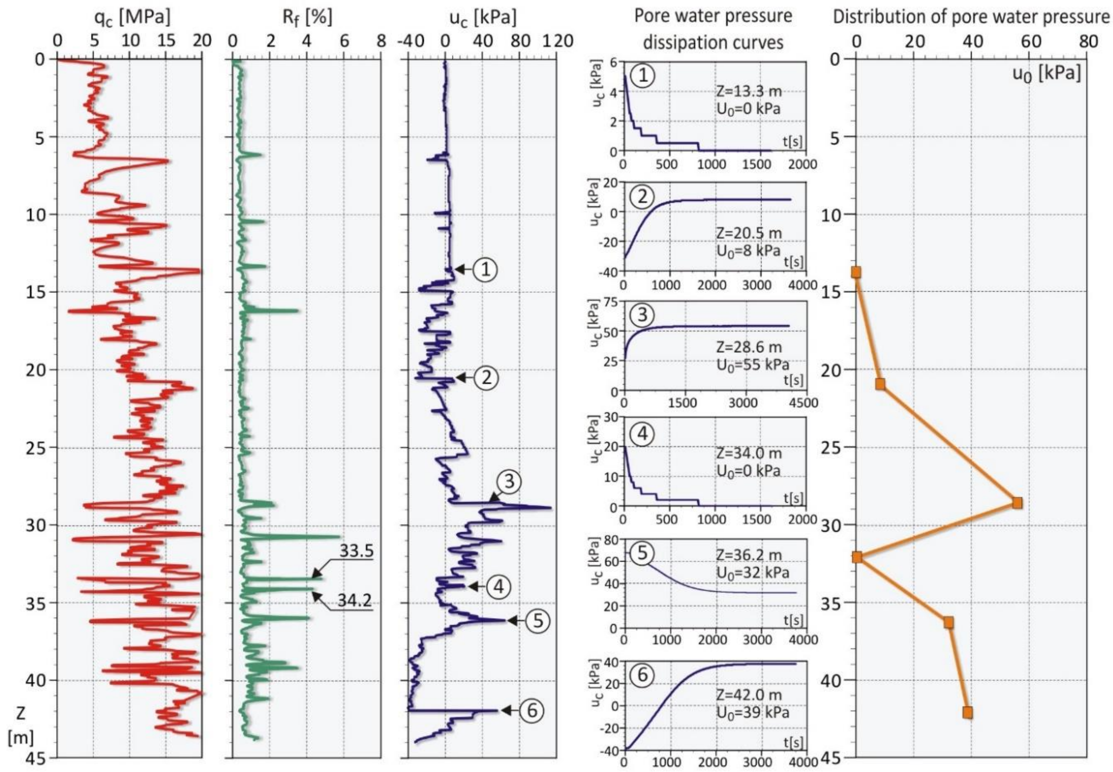

Figure 7. Identification of water conditions of sediments based on cone penetration test (CPTU) results.

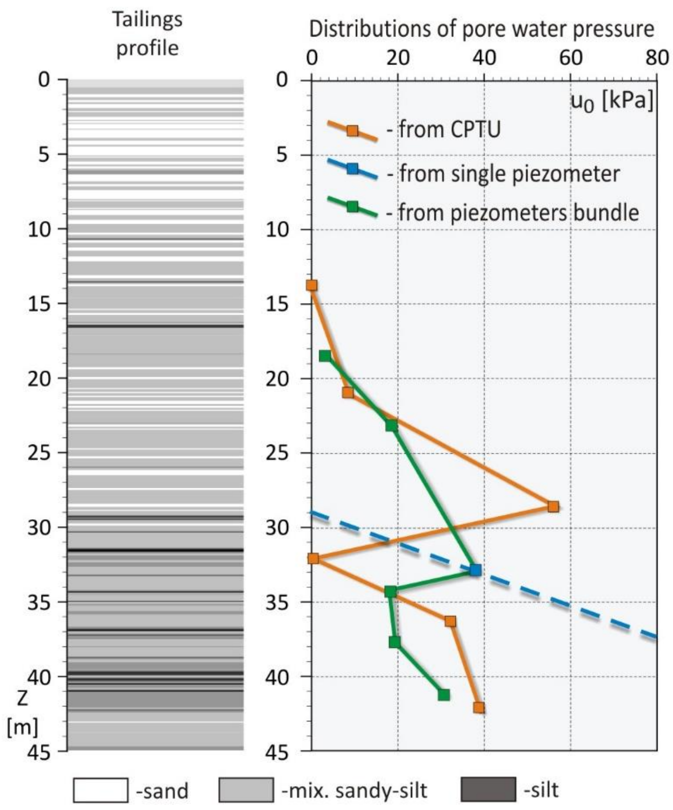

Figure 8. The comparison of water conditions in sediments with the piezometric methods and based on CPTU.

Determining the water conditions of the subsoil based on the CPTU results is a point assessment as it relates to those profile depths at which the pore water pressure dissipation test was carried out. This issue is particularly important in the zones of not fully saturated sediment, where due to the local variability of sediment deposition conditions in the profile, the result of point measurement at a selected depth may affect the assessment of water conditions in the entire zone. The proper solution to this problem is the transition from point identification to zone identification. This type of solution is ensured by the SCPTU, in which the down-hole seismic wave velocity measurement will be included in the cone penetration test. In this method, the seismic signal is generated from the terrain surface, and then recorded with a geophone mounted in the seismic cone at the depth at which the cone is currently positioned. With such a measurement technique, the recorded seismic signal covers the profile zone limited by successive depths at which the seismic measurement was performed. Using the basics of the theory of elasticity, the full and not full soil saturation zones can be determined on the basis of the compression wave velocity [25]. The velocity of the compression wave in the subsoil with a value above 1600 m/s indicates a two-phase medium, and the solid particles and the liquid phase indicate ground water. The presence of the third phase that indicates air significantly limits the velocity of the compression wave. Determining the distribution of the wave velocity as a function of profile depth allows for the identification of soil zones with different saturation. Figure 9 presents the SCPTU results obtained in the profile of the tailings massif and water conditions identified based on these results. The distribution of water pressure determined on the basis of the results of pore water pressure dissipation tests as a function of the profile depth coincides with the water conditions determined on the basis of the compression wave velocity distribution. In the context of the results of such analysis, three main zones can be distinguished in the sediment profile. The first zone, located above the depression line, in the upper part of the profile from the surface of the facility to a depth of about 15 m (Figure 9), includes unsaturated sediments characterized by a degree of saturation $S_r < 1$, within which the free water table does not stabilize and the possible local perched water table has a source of insulated layers sediments accumulating water.

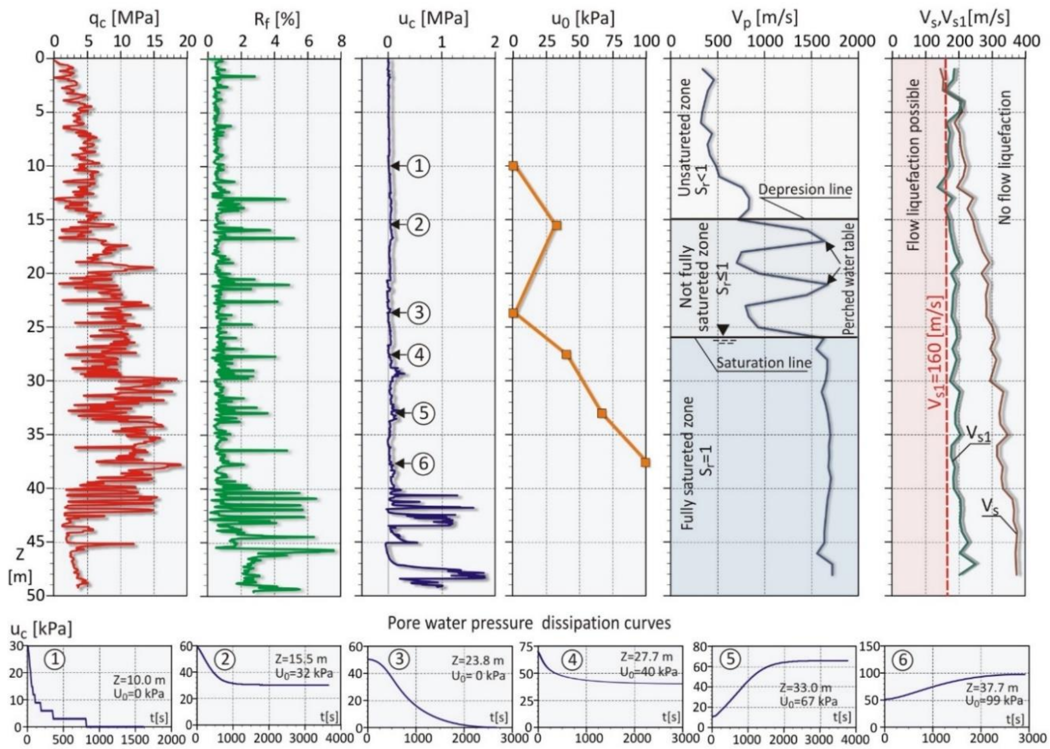

Figure 9. The complete assessment of water conditions in sediments with the seismic cone penetration test (SCPTU).

The second, intermediate zone, between the depression and saturation lines, within the profile depth range from 15 m to 26 m (Figure 9), collects sediments in the state of full and not full saturation ($S_r \leq 1$). In the second zone, the distribution of pore water pressure is in the form of a non-hydrostatic distribution, which, depending on the local filtration capacity of the sediments, may exhibit discontinuity features. The third zone, located below the saturation line, in the bottom part of the sediment profile below the depth of 26 m (Figure 9), collects fully saturated sediments ($S_r = 1$), within which the distribution of pore water pressure corresponds nearly to the hydrostatic distribution.

The analysis of the distribution with the depth of velocity of the second recorded seismic wave (shear wave) in combination with the identification of different zones of sediment saturation allows for the assessment of the threat of static liquefaction of the sediments [26]. Based on the results of Vidic et al. [27], it can be assumed that in the zone of saturated postflotation tailings of copper ores, such a limit is the velocity of a normalized shear wave with a value of 160 m/s (Equation (5), Figure 9).

Performing a qualitative assessment of the water conditions of postflotation tailings deposited within the TSF by the SCPTU compared to the conventional piezometric method brings many additional benefits expressed by a more precise and detailed identification of these conditions, as a result of which a new idea to the parametric assessment of sediments is possible. The distinction in the profile of the intermediate facility zone of nearly to saturated sediments raises the question of whether the same sediments strength parameters adopted in this zone as in the area of fully saturated sediments is not a too conservative approach. This is indicated by the results of the interpretation of penetration characteristics from the CPTU, which document the intermediate shear strength of sediments in the intermediate zone. This view can be confirmed by the results of strength tests of natural soils documenting the increase in shear strength of these soils in the nearly to saturated state [28,29]. Taking this fact into account when calculating the stability of the storage facility's dams leads to the determination of a more favorable stability factor.

4. Conclusions

Monitoring of water conditions in hydrotechnical facilities, which includes the outflowed postflotation tailings storage facility, is one of the basic operations to ensure the safe exploitation of such facilities. The literature on this issue indicates inadequate water conditions as the main cause of failures of TSF [3–5,7,30,31]. Hence, the problem of proper recognition and reliable monitoring of water conditions is of particular importance. In this regard, the conventional monitoring technique used in postflotation TSF is a method based on piezometers readings, which, due to the nature of the object and the specificity of the stored material, may face some limitations that affect the reliability of this method. A good solution in this situation is to use the cone penetration test with the measurement of pore water pressure dissipation and the measurement of the velocity of seismic waves (SCPTU). The purpose of using SCPTU is to increase the safety of dams, especially for upstream structures. Based on the results of this test, continuous stratigraphic and parametric sediments characteristics in the penetrated profile, real piezometric distribution of pore water pressure, and zonal sediments saturation characteristics are obtained.

Because the observed anomalies of water conditions in the facility massif can be explained and verified as a result of detailed analysis of sediments conditions, the profile image of the subsoil obtained from the SCPTU is complete from the point of view of geotechnical recognition. An important advantage of SCPTU, and especially the part of the test that concerns geophysical measurements, is the possibility of finding zones in the massif profile of sediments because of their state of saturation. An intermediate zone of not full saturation of sediments below the depression line and above the saturation line can be isolated due to the analysis of the distribution with the depth of the compression wave velocity in the tailings profile. Its presence improves the stability conditions of the object and reduces the risk of static liquefaction of the sediments.

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draft preparation, W.T.; writing—review and editing, M.W., W.T.; visualization, S.G., M.W.; supervision, W.T.; project administration, P.S. All authors have read and agreed to the published version of the manuscript.

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