

Article

Prediction of Postflotation Tailings Behavior in a Large Storage Facility

Magdalena Wróżyńska 

Department of Construction and Geoengineering, Poznań University of Life Sciences, Wojska Polskiego 28, 60-637 Poznań, Poland; magdalena.wrozynska@up.poznan.pl

Abstract: Extracting and copper production on a large scale generates large volumes of postflotation mine tailings. The scale of operation and development of tailings storage facilities (TSFs) forces the use of innovative solutions enabling safe storage now and in the future. Any changes to the operation require multi-directional monitoring of the impact of these changes on storage safety. The ongoing exploitation will be ensured by expansion of the TSF and a change in tailings storage technology. This approach will preclude the need for changes to the new location, such as changes of land use, and will minimise the volume of mine waste. The paper presents the results of pilot studies carried out to implement the change in postflotation tailings storage technology at Żelazny Most TSF (Poland) in the future. The aim of the paper was settlements prediction of tailings and comparison of deformations with observed settlements. Settlements prediction of tailings was made on the basis of the results of the DMT (Marchetti Dilatometer Test), recommended for the prediction of natural soil settlement. Depending on the analysed zone of the TSF, settlements ranged from a few centimetres to over 1.5 m. Despite the difference shown, the results of DMT and geodetic measurements indicate a convergent trend of settlement.



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1. Introduction

The tailings storage facility (TSF) is one of the key links in the production of copper concentrate, without which manufacturing raw material would be impossible. The issues of the currently exploited TSF are extensive and complicated, from engineering problems and challenges, through economic to environmental and social aspects [1–4]. In Poland, since 1977, there has been only one storage facility for tailings from copper ore flotation for all three active mines of KGHM Polska Miedź SA (Polish Copper). The feature of such a large tailings storage facility, which enables comprehensive waste management, is the low efficiency of utilizing the facility's capacity in relation to the amount of deposited waste, which currently accounts for about 95% of the excavated mining waste. The reason for the unfavourable balance is the low density of the material deposited in the form of sludge, ranging from 1.11 and 1.15 Mg/m³. Further deposition with such large discharges of waste will lead to exhaustion of the operational possibilities of the storage facility. One of the solutions to this problem may be the construction of another tailings storage facility. Another more rational solution seems to be the implementation of a more effective method of depositing waste, e.g., pre-thickened paste. A third approach combining the two previous solutions can also be considered. As far as this solution is concerned, the simultaneous expansion of the existing storage facility and change in the technology used for depositing postflotation tailings would exclude the need to build another facility in a new location. This would also increase the operational capability of the currently used facility and would extend its operation time. However, the implementation of the third solution requires prior assessment of the suitability of the deposited tailings as a subsoil

on which higher density waste (paste) will be stored. Such an analysis is indispensable in predicting the behaviour of the mass of tailings loaded with paste and can be additionally used to assess the overall stability of the entire tailings storage facility.

An experimental embankment was built in order to determine the real reaction of the subsoil made of tailings to the additional load. However, due to the fact that the storage facility is an earth structure, which is diverse and spatially variable in terms of grain size and physical and mechanical properties, the settlement process in these conditions depends on many local factors. In order to learn about the impact of these factors, a number of studies and observations of loaded tailings were carried out as part of a three-year monitoring. Geotechnical monitoring consisted of a series of in situ tests and laboratory tests of extracted tailings samples, among others Marchetti Dilatometer Tests (DMTs), cone penetration tests (CPTUs), and field vane tests (FVTs). Measurements of real displacements covered by geodetic monitoring were also carried out throughout the observation three-year period.

Many researchers and world experts attempted to predict natural soil settlement based on the results of CPTUs and DMTs, indicating both the advantages and disadvantages of these tests [5]. Predicting the settlement of natural soil on the basis of CPTUs is well recognized and widely used [6–16]. In order to estimate the settlement of natural soil based on CPTUs, a constrained modulus M_{CPTU} needs to be determined [11,17–23]. The research conducted by Robertson et al. [24] proves that the estimation of M_{CPTU} only on the basis of the cone resistance value may be inaccurate and even burdened with a large error, especially in the case of pre-consolidated soils. The collapse mechanism under the cone, resulting in large soil deformations during the test, poorly corresponds to M_{CPTU} . According to Jamiolkowski et al. [25], it is impossible to estimate the exact value of M_{CPTU} only on the basis of cone resistance without knowing the stress history. The selection of a reliable empirical factor α , a parameter necessary to calculate M_{CPTU} based on the cone resistance [26], may also pose a difficulty. Due to the abovementioned limitations, CPTU results should be calibrated based on the results of laboratory tests or other in situ tests [27]. Greater accuracy of estimated settlements in relation to the possibilities offered by CPTU can be obtained from the DMT [28,29]. The advantage of the DMT over CPTU that is commonly emphasized in the literature is its advantage in assessing soil deformation parameters [30]. This is due to the test conditions, where in the CPTU the measurement performed with the cone is related to the bearing capacity of the subsoil, while in the DMT, the dilatometer measurement is related to the subsoil deformability. Available research results from many authors clearly indicate that the DMT is meaningful and reliable in estimating natural soil settlement [31–50]. In order to estimate natural soil settlement based on DMT, the constrained modulus M_{DMT} needs to be determined. The authors of [35] recommend the estimation of settlements based on DMT in accordance with the classic uniaxial deformation method, analogously to the CPTU method. According to Marchetti [34], the results of settlements estimated using the 1-D elasticity formula do not significantly differ from the results estimated with the 3-D formula (triaxial deformations) and differences do not exceed 10%. From an engineering point of view, the 1-D model seems less problematic and more practical in this situation (e.g., it does not require the knowledge of Poisson's ratio ν). Determining and comparing settlements predicted with DMT with real observations (geodetic measurements), possibly with the results of tests other than DMT, was implemented by many authors. The high compatibility of the settlements predicted by DMT with the observed settlements for natural soils of different grain sizes was confirmed by [32,51]. The authors of [33,52] also recommend a procedure for estimating settlements based on DMT results. According to Monaco et al. [46], the Marchetti flat dilatometer is currently the most practical device for settlements prediction.

In terms of the purpose of the work indicating the possibility of continuing to exploit the TSF without having to build a new facility while not making changes to the new location (e.g., land use and land management change), the aims of the present research were settlements prediction (1) of tailings loaded with an experimental embankment using

DMT, used for settlements prediction of natural soils; determination of observed settlements (2) based on the results of geodetic measurements; and, additionally, comparison of (3) predicted and observed settlements of tailings. In addition, the validity of using the DMT recommended for testing natural soils for general trend estimation of tailings settlement was confirmed.

2. Materials and Methods

2.1. Study Site

KGHM Polska Miedź SA is the main domestic copper manufacturer in Poland. During over 50 years of operation, over 18 million tons of copper were produced from extracted rock output, with a mass of 1 billion tons. Based on the estimated recognition of the deposit resources, copper ore can be exploited for the next 30 years. For annual production of approximately 2 million tons of concentrate with an average content of 23% of copper, from 4% to 6% of the extracted mining mass is utilised. The remaining 94–96% are postflotation tailings that require safe management. An important problem arising from such a significant scale of production of the raw materials, whose average content is 1.52% of copper in the deposits exploited in Poland, is the management of huge masses of postflotation tailings. These tailings are generated as a result of the following operations and processes: sifting, grinding, classification, flotation, densification, filtration, and drying. As a result of flotation, about 25 million Mg of waste is transported by the hydraulic method to the storage facility each year and it is rising. At present, the only active receiver of all postflotation tailings from Legnica-Głogów Copper District is Żelazny Most Tailings Storage Facility (Figure 1).

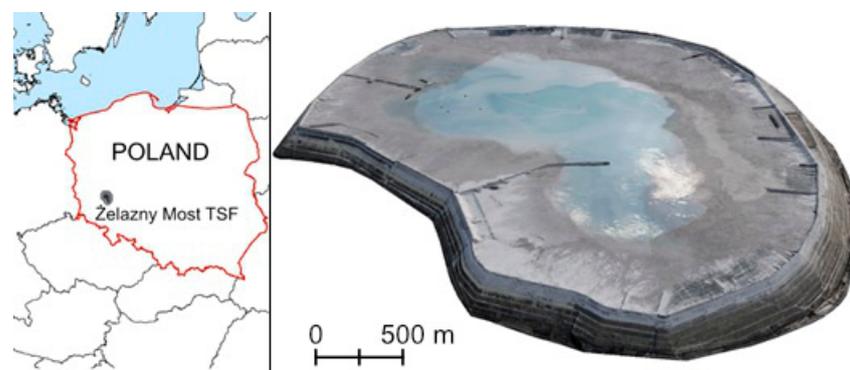


Figure 1. Location (left) and 3-D visualisation (right) of Żelazny Most tailings storage facility (TSF), Poland.

The storage facility is located in the Lower Silesia Voivodeship, the south-western part of Poland; a natural land depression in the south-eastern part of the Dalkowskie Hills, which is part of the Trzebnickie Hills, was used for its positioning. This depression is in the form of a natural kettle hole surrounded by frontal moraine-dammed hills of the Riss glaciation [4]. Żelazny Most TSF is an earth above-ground hydrotechnical construction, currently the largest in Europe and second largest in the world [2,53]. The construction of TSF took place between 1974 and 1977. Since the commissioning on 12 February 1977, the storage facility has been subjected to continuous and simultaneous operation and expansion, because of which it is described as “atypical” [3]. Superstructuring of the facility’s dams is carried out with the upstream method. The facility’s extension module is 2.5 m, which results in an average annual increase in dam height of about 1.3 m [54]. For the continuous superstructuring of dams surrounding the facility, waste of the coarse grains, previously deposited within the so-called beaches, is used. Due to favourable strength and filtration characteristics, meeting the criteria of grain size and ultimately density, sandy postflotation tailings is a full-fledged building material in this place [55,56]. TSF is currently in the process of forming dams up to 190 m above sea level, which results in

the possibility of storing postflotation tailings of a volume of 780 million m^3 . At the current stage of TSF expansion, one of the important factors limiting its further development in the technology implemented so far is the complex geological structure of the natural subsoil of the facility. The superstructure of the existing dams to the crown's ordinate of 195 m above sea level along with the extension of the facility by an additional effective area, the so-called "Southern Section" with an area of over 600 ha, would allow for the deposit of 950 million m^3 of postflotation tailings. In the long run, this provides the possibility of storing tailings until 2037. Operation of the facility after expansion can be continued using the existing deposition method ("wet deposition") or the mixed method. The latter combines the wet deposition method with the method of depositing tailings densified to the consistency of paste. The application of the paste deposition method requires the design and construction of technical infrastructure for densifying tailings. The parallel method may be to collect dehydrated and pre-thickened tailings in a natural way that was previously deposited inside the storage facility. For the first time, an industrial depositing method was used at the Kidd Creek mine in Canada in 1973, although research had already been carried out earlier [57,58]. This method can definitely compete with the currently used method of depositing in Želazny Most TSF. The implementation of a new method of depositing tailings masses of higher density than before on a highly deformable subsoil must be preceded by a series of tests and observations of the behaviour of TSF under the influence of an additional load.

2.2. Experimental Embankment Characteristics

Different conditions for depositing tailings in Želazny Most TSF result in a spatially variable bearing capacity of tailings. The overall prognosis of the subsoil response to the additional load required the construction of a real loading structure. The experimental embankment was formed in the southern part of the Želazny Most TSF (Figure 2). The construction began at the beginning of 2013 and continued with intervals until June 2014.

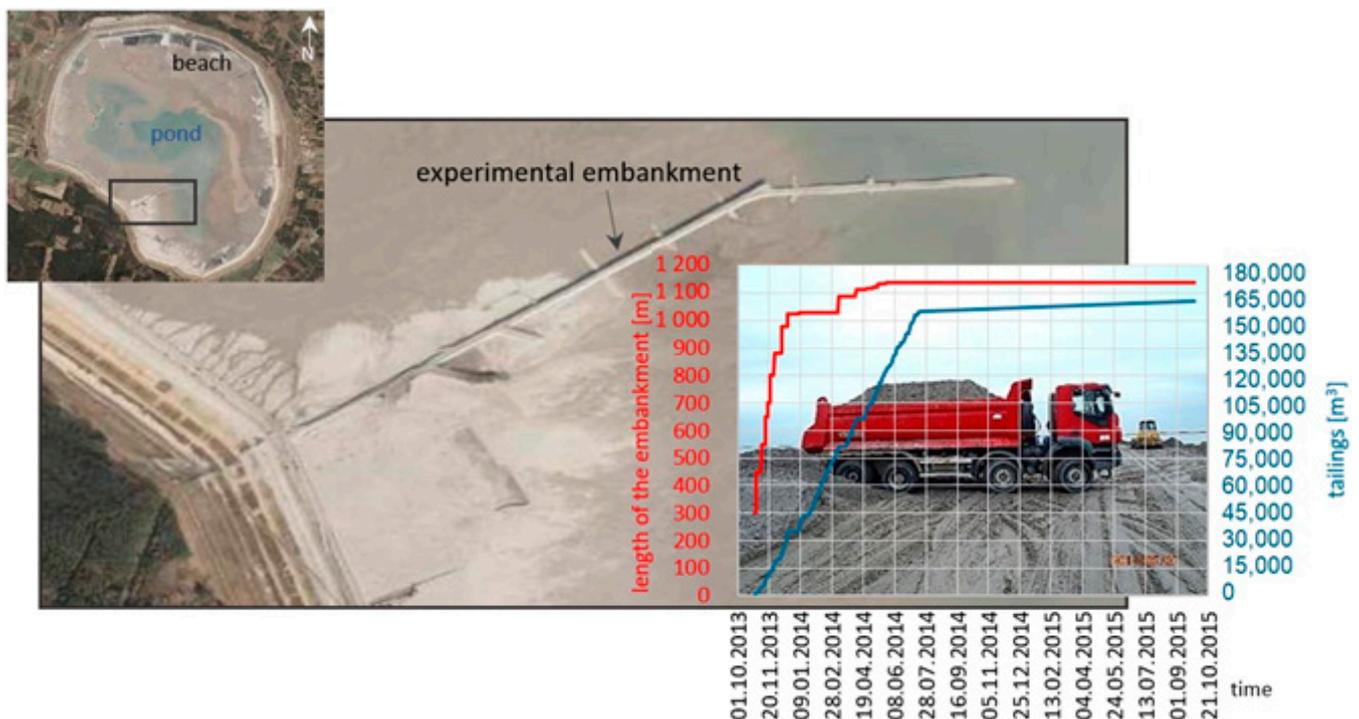


Figure 2. Experimental embankment location within the TSF and distribution of earth masses for embankment construction in time.

About 165,000 m³ of building material were used to build the embankment. This material was selected out of postflotation tailings, generally of sandy grain size, previously deposited on the beach of the storage facility. The tailings were delivered to the construction site by road. The embankment was formed in the direction from its top part forward. The embankment, with a total length of 1140 m and a crest width of 15 m, was formed in a direction perpendicular to the axis of the facility’s dam, which resulted in part of the embankment being constructed on the beach, and part within the pond, which is located in the central part of the facility (Figure 2). Analysis of Figure 2 shows that about 35,000 m³ of waste were used to build a 1000-m-long fragment of the embankment, whereas disproportionately more waste, i.e., c. 130,000 m³, was used to build the final 140-m-long fragment. The result of such a location was extremely variable foundation conditions and the varying bearing capacity of the embankment subsoil. Due to the location, the subsoil of the embankment was divided into 3 zones according to the scheme shown in Table 1 and in Figure 3.

Table 1. Three-zone characteristics of the subsoil of the experimental embankment.

Zone	Location	Characteristics of Embankment Subsoil
I	Beach	<p>Zone with the highest bearing capacity and rigidity:</p> <ul style="list-style-type: none"> – a direct subsoil of the embankment in the area of the dam is built with a layer of sandy tailings and a thickness of 25 m; towards the pond, the layer gets shallower until it completely disappears in the shoreline; sandy grains and the beach drainage system excludes the generation of pore water pressure excess in tailings [59], – below the profile there is a zone with a characteristic, strongly layered sandy-silty structure with varying thickness of interlayers; sandy interlayers are a filtration path that limits the formation of pore water pressure excess in silty tailings.
II	Between the beach and the pond	<p>Transition zone:</p> <ul style="list-style-type: none"> – shallowing of the sandy tailings layer towards the pond, – a visible tendency of increasing of the thickness of silty interlayers; in the area of the shoreline, the zone of strongly layered tailings reaches the highest thickness equal to the entire profile of the deposited tailings.
III	Pond	<p>Most problematic zone:</p> <ul style="list-style-type: none"> – after crossing the shoreline, the top of the silty layer is lowered creating a space that is filled by the accumulation space of tailings with grains corresponding to the finest cohesive sediments; under the bottom of the pond, the layer of the finest (silty) tailings covers the entire recognized profile, i.e., over 35 m, – a zone in a state of full saturation and with the greatest susceptibility to deformation.

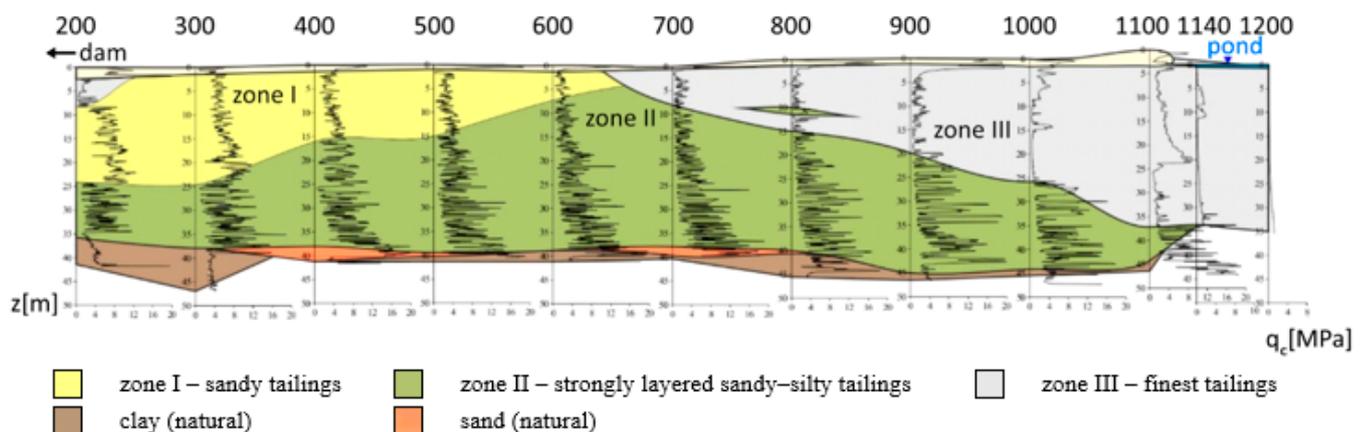


Figure 3. The embankment’s subsoil (cross-section obtained on the basis of cone penetration test (CPTU) results and laboratory analysis of tailings grain size; zones as indicated in Table 1).

2.3. Data Collection

Research and observations carried out as part of the monitoring were divided into two groups (Figure 4). In situ tests included in the geotechnical monitoring (I) and geodetic monitoring (II) of real displacements of the subsoil loaded with an embankment were carried out at selected test points. Simultaneously, samples of tailings were taken for laboratory testing.

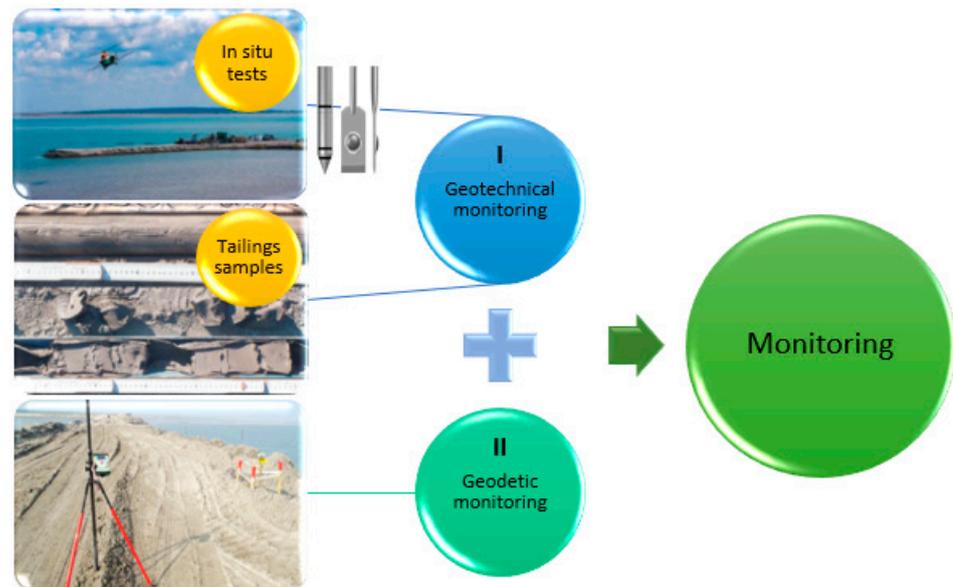


Figure 4. Monitoring components of the embankment and its subsoil.

I Geotechnical monitoring—DMT

The DMTs [60] included in the first group of tests were carried out both at the embankment crest and at a floating platform. Depending on the location of the test point, the penetration depth ranged between 12 and 42 m. DMT tests were carried out in accordance with the test standard in which two characteristic pressures, ΔA and ΔB , are determined with a frequency of 20 cm every 20-cm increase in the penetration depth. According to Marchetti [36], external pressure ΔA and internal pressure ΔB are used to correct the A and B readings (positions of the dilatometer membrane) into corrected readings, the corrected first reading p_0 and corrected second reading p_1 . In the next step, intermediate parameters are determined, the material index I_D , horizontal stress index K_D , and Dilatometer modulus E_D . Then, intermediate parameters are converted by means of commonly used correlations to geotechnical parameters, e.g., constrained modulus M_{DMT} , cohesion c_u , and friction angle φ (Figure 5). M and c_u are generally the most useful and accurate parameters by DMT [61,62]. According to Marchetti [36], predicting settlements of shallow foundations is probably the number one application of the DMT. This statement applies in particular to sands where undisturbed samples cannot be retrieved. Based on M_{DMT} , settlements of the tailings loaded with an embankment were estimated. Settlements were calculated by means of the one-dimensional formula ($s_{1,DMT}$) according to the diagram shown in Figure 5. Settlements of postflotation tailings were calculated using DMT Settlements Software (v 1.0.1.16, Studio Prof. Marchetti, Rome, Italy). According to the description, the DMT Settlements Software computes the one-dimensional conventional settlements calculation below uniformly loaded surface areas of flexible loads using the DMT results. The software is designed to import from .uni files the constrained modulus of the soil and the vertical effective stress from the DMT. To perform a settlements calculation, the following input must be given: loaded area (defines the load in terms of weight and geometry), soil parameters (define the soil in terms of modulus and vertical effective stress), and calculation options (define specific parameters and criteria used in the calculation).

Vertical stress increments are evaluated according to the Boussinesq theory of elasticity for homogeneous elastic half space.

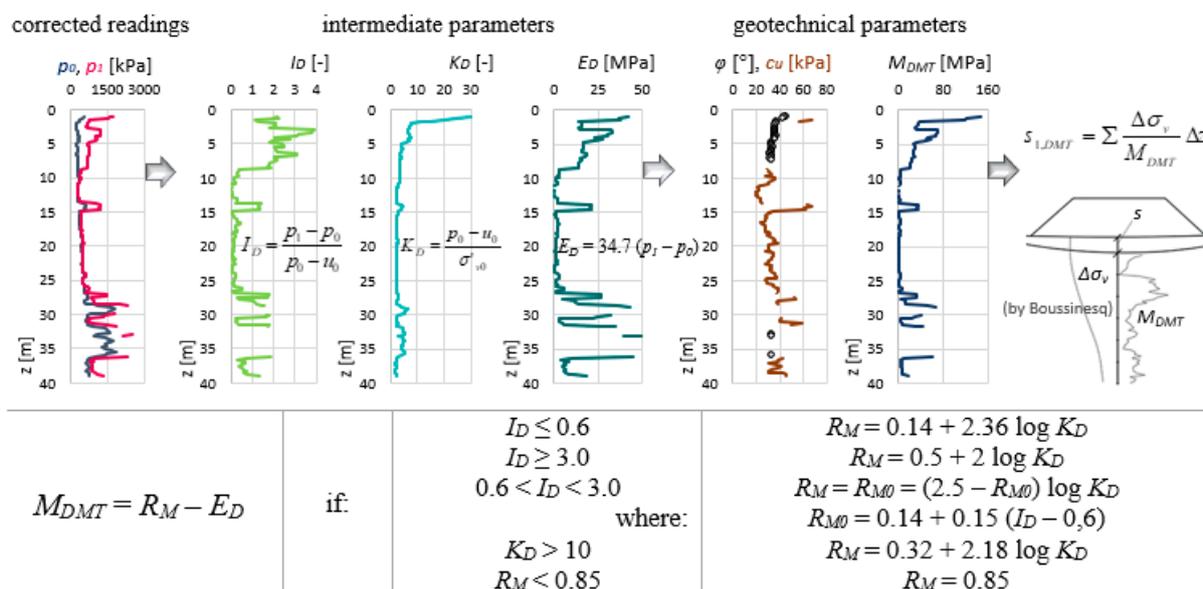


Figure 5. Scheme for settlement prediction by DMT (where: p_0 and p_1 —corrected first and corrected second reading, I_D —material index, K_D —horizontal stress index, E_D —dilatometer modulus, φ —friction angle, u_0 —equilibrium pore pressure, M_{DMT} —constrained modulus, σ_v —vertical stress, σ'_{v0} —effective overburden stress, z —depth, R_M —correction factor, s —settlements; data comes from the DMT performed on the embankment axis at a distance of 1 km from the TSF dam).

II Geodetic monitoring

Observed settlements were determined on the basis of data obtained from geodetic monitoring (Figure 4). In order to carry out displacement measurements, a geodetic network was established. It consists of 62 control points installed both at the top and in the immediate vicinity of the embankment. Measurements were made using Global Navigation Satellite System (GNSS), in Real Time Kinematic (RTK) and Real Time Network (RTN) measurement modes using the ASG-EUPOS system. Control measurements were carried out every two weeks throughout the entire embankment construction period and for one year after its completion. In total, 1382 geodetic measurements were carried out.

3. Results

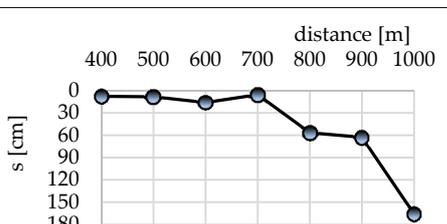
The results of the conducted DMT and geodetic measurements enabled assessment of the settlement of tailings. Two limitations were applied while selecting test points at which the settlements were examined. First, the analysis was restricted to the results of a section of 600 m, at which test points were located every 100 m. The analysis was performed for an embankment section from the point located 400 m away from the TSF dam to the point located 1000 m from the dam. Because of minor settlement values for the stiff sandy beach of the facility, the fragment located between the dam of the TSF, and a point located 400 m away from the dam were excluded. The second limitation applied to the selection of test points which would provide credible DMT results and geodetic measurements.

3.1. Predicted Tailings Settlements—DMT

The calculated settlements are obtained using the interpretation formulae and the calculation method recommended in [45]. Cumulative settlement results are summarized in Table 2. The analysis of settlements calculation indicates that the smallest settlements are found in zone I (Table 1), where the embankment was placed on the sandy TSF beach. The settlement values in zone I are between 7.69 cm at 0+400 and 8.13 cm at point 0+500 (Table 2). At the point located 100 m away (0+600), the settlement values are already twice

as large and exceed 16 cm (zone II in Tables 1 and 2). At the next point from zone II (0+700), the settlement values are reduced, reaching 5.54 cm. Lower settlement values can be explained by the fact that the embankment height at point 0+700 was lower, which resulted in lower subsoil load than in adjacent points (Table 2). At three consecutive points (zone III), settlement values increased from 56.54 cm (0+800), through 62.81 cm (0+900), reaching the highest value of 165.78 cm at point 1000 m from the TSF dam (zone III in Tables 1 and 2). At point 1+000, the largest settlement was to be expected due to the identification of a layer of very weak silty deposits, which build an unstable subsoil of the embankment at the bottom of the pond. Figure 6 shows the result sheet from the program DMT Settlements Software for the test point where the largest settlements were determined.

Table 2. Summary of results of settlements calculation, below the centre of embankment.

Zone	Location ¹ (km)	Layers ² (-)	σ_v (kPa)	s_{DMT} (cm)	Settlements Below the Centre 
I	0+400 0+500	183 190	70 75	7.69 8.13	
II	0+600 0+700	184 193	80 75	16.06 5.54	
III	0+800 0+900 1+000	160 169 171	80 85 93	56.54 62.81 165.78	

¹ Location (km) = km from the TSF dam. ² Number of layers, where thickness of one calculation layer = 0.20 m.

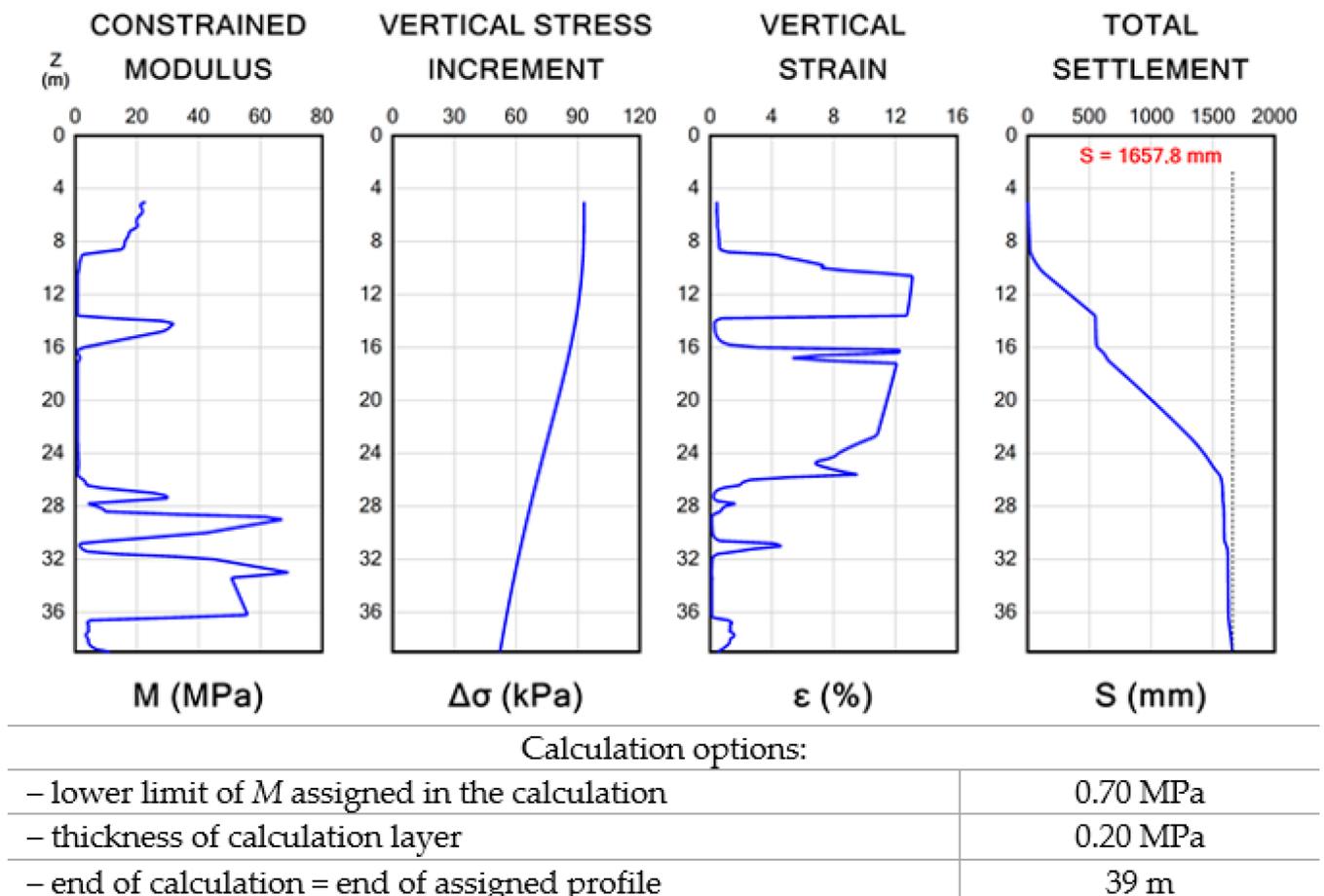


Figure 6. Results sheet of settlements calculation, below the centre (test point 1+000).

3.2. Observed Tailings Settlements—Geodetic Measurements

The results of the geodetic measurements enabled the determination of the actual settlement values of the loaded subsoil. The measurements at points analogous to the DMT were performed at the control points located in the embankment's axis at its top. The same part of the 600-m-long embankment was analysed starting from a point located 400 m from the TSF dam. Cumulative settlement results are summarized in Table 3. Observed settlements in zone I (Table 3) reach values from 21.60 cm (0+500) to 30.03 cm (0+400). At the first point of zone II (0+600), the settlement value is exactly the same as in the first test point in zone I (0+400). At the second point (0+700), a decrease in the settlement value to 19.70 cm is noted. At subsequent research points (zone III), settlement values regularly increase with the distance from the TSF dam towards the pond. At a point 800 m away from the TSF dam, the settlements reach a value almost double that of the previous point, amounting to 37.51 cm, while at 0+900 they exceed 0.5 m. The highest settlement values were observed at the last analysed point: the measurement value was almost twice as high as at the previous point and equalled 92.25 cm (Table 3).

Table 3. Summary of the results of the observed settlements.

Zone	Location ¹ (km)	$s_{observed}$ (cm)	Settlements Below the Centre
I	0+400	30.03	
	0+500	21.60	
II	0+600	30.03	
	0+700	19.70	
III	0+800	37.51	
	0+900	50.09	
	1+000	92.25	

¹ Location (km) = km from the TSF dam.

3.3. The Comparison of the Predicted and Observed Settlements of Tailings

Based on the analysis of the results, it was found that settlements, both predicted by DMT and observed (geodetic measurements), in overall terms, progressively increase as they move away from the beach towards the centre of the storage facility where the pond is located. Because of the central location of the pond, which is in the zone more susceptible to deformation of the subsoil (zone III), settlements in this place reach the highest values, which are several times higher than in zone I and II (Table 4).

Table 4. Comparison of settlements.

Zone	Location ¹ (km)	Settlements (cm)			Settlement Ratio $s_{DMT}/s_{observed}$
		DMT _{predict.}	Avg. DMT _{predict.}	Observed	
I	0+400	7.69	7.91	30.03	0.26
	0+500	8.13		21.60	0.38
II	0+600	16.06	10.80	30.03	0.53
	0+700	5.54		19.70	0.28
III	0+800	56.54	95.04	37.51	1.51
	0+900	62.81		50.09	1.25
	1+000	165.78		92.25	1.80

¹ Location (km) = km from the TSF dam.

When analysing settlements divided into individual zones, it should be stated that predicted and observed settlements differ in each of these zones. With definitely different means of the predicted and observed settlements in zone I, respectively 7.91 cm and 25.82 cm, settlement ratios ($s_{DMT}/s_{observed}$) equalled 0.26 and 0.38 (Table 4). A slightly greater settlement compliance was demonstrated in zone II, as the average settlements predicted

by DMT are 10.80 cm, while the average observed settlements is 24.87 cm, while at 0+600 predicted settlements were twice smaller than the observed settlements, $s_{DMT}/s_{observed} = 0.53$ (Table 4). In the next point in zone II (0+700), predicted settlements were 5.54 cm with four times the observed settlements, $s_{DMT}/s_{observed} = 0.28$. The lower settlement value at test point 0+700, which was explained in 3.1, locally contradicts the overall trend of an increase in the settlement value towards the pond. Although the settlements determined using both methods differ significantly, it can be seen that the lower settlement values at a point 700 m away from the TSF dam were obtained both on the basis of the results of DMT and geodetic measurements. This fact confirms that a lower load (smaller embankment height) had a direct impact on the lower settlement value at point 0+700. At the next three test points (zone III), both predicted and observed settlements increase in line with the overall trend (Table 4, Figure 7a). At point 0+800, the settlement ratio is 1.5, which is also the average value of this ratio for the entire zone III. The settlement ratio at the 0+900 test point equals 1.25. This value indicates the highest convergence in the value of settlements obtained by the two methods considered. At the last test point (1+000) $s_{DMT}/s_{observed}$ is already 1.80. The main impact on the average settlements in zone III of 95.04 cm (predicted) and 59.95 cm (observed) was due to the large discrepancy of results at the last analysed point 1+000, where predicted settlements amounted to 165.78 cm, while observed equalled 92.25 cm. At this point, tailings are characterized by the largest anisotropy resulting from the cyclic spigotting of postflotation sediments migrating to the pond, where the accumulation of postflotation sediments of the finest grain structure is increased. In addition, it should be noted that 30 m further from the last analysed test point, the observed settlements were already 156.63 cm, i.e., comparable to the predicted settlements (165.78 cm) at 1+000 ($s_{DMT(1+030)}/s_{observed(1+1000)} = 1.06$). However, there is no direct possibility to compare the results due to the fact that the 1+030 point is an intermediate point where the DMT test was not performed. A comparison of the predicted and observed settlements and settlements agreement is shown in Figure 7.

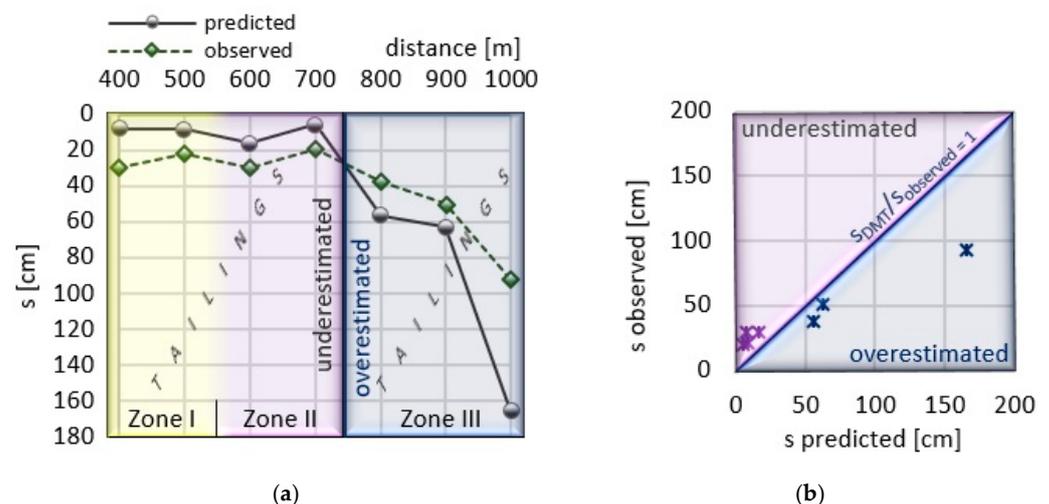


Figure 7. (a) Predicted and observed settlements comparison; (b) settlements agreement of tailings.

4. Discussion

Unstructured postflotation tailings, after entering the facility, are subject to the deposition process. By analogy to the natural deposition process that occurs as a result of energy being lost by the stream carrying the hydrated material, postflotation sediments begin to freely sediment inside the storage facility. As a result of tailings particle sedimentation, postflotation sediments are formed. Close to the outlets of the spigotting pipes (beach = zone I) are the thickest particles, most often of sandy grain size, which potentially exhibit the properties of fine-grained non-cohesive soil. The further from the place of waste dumping, the more layered the sediment is, and individual layers are characterized

by a smaller thickness. The volume of waste of finer grain size dominated by the silty fraction also increases. Particles with the finest grain size (silt and clay) migrate to the pond. Postflotation sediments, which freely sediment in the salty water environment, combine into porous aggregates with a strongly layered structure. The effects of natural sedimentation segregation are changes in the physical and mechanical properties of the waste as a function of the distance from the place of discharge. These changes directly affect the response of tailings to additional load in individual zones (Table 1).

The most reliable way to assess the actual response seems to be geodetic measurements of settlements. However, these are long-term measurements on the basis of which total settlements cannot be estimated as a result of a single measurement. Geotechnical in situ tests, such as DMTs, are successfully used to predict the settlement of natural soils [36,40,43,49]. In the case under consideration, the values of tailings settlements predicted by DMTs differ from the observed settlements. Some results are overestimated, while some are underestimated. A clear underestimation of settlements takes place in zone I, where the subsoil is built of sandy layers (beach) characterized by a higher value of constrained moduli. Settlements calculated based on overestimated constrained moduli should be underestimated [63]. A slightly better fit is observed in zone II, separating the sandy beach from the pond. In zone III, on the other hand, where the embankment subsoil, which is also the bottom of the pond, is built of low-bearing postflotation sediments, predicted settlements are overestimated. A similar problem is very common. Settlement values of natural soils for the Barcelona airport terminal determined based on CPTU and DMT results showed an overestimation of settlements by 28% compared to measured settlements [29]. However, the authors argued that the method used supplemented by a local correlation (M_{CPTU} and M_{DMT}) can be successfully used to estimate settlements. According to Schmertmann [32], the average ratio of natural soils settlement predicted by DMT to actual observations was 1.18, ranging from 0.7 to 1.3. [38], also obtained high agreement between settlements predicted by DMT and measured settlements. The average ratio of settlement results determined from DMT tests to actual observations equalled 1.87, ranging from about 1.0 to 2.5. In the case of an embankment built within the Želazny Most TSF, the settlement ratio is in the range of 0.26 to 1.8, with an average value of 0.86. However, using the average settlement ratio is not justified in this case. Consequently, this leads to far-reaching average values. The use of average settlement values predicted by DMT and observed (46.08 cm and 40.17 cm, respectively) looks similar. It should be remembered that the loaded subsoil is built of postflotation tailings, not natural soil. Characteristics of the latter are much better recognized, and in addition, they do not have such specific zoning, unlike tailings. Therefore, it will be more appropriate, if at all, to use average values within separate zones (Table 1), where the average settlement ratio is 0.31 in zone I, 0.43 in zone II, and 1.59 in zone III. This approach clearly indicates underestimation of settlements in the first two zones and overestimation in the last zone (Figure 7). The discrepancy of results can be explained in two ways: first of all, paying attention to the DMT test interval, which may result in an increased frequency of random soil parameters registration, with higher stiffness (heavily layered sand and silt tailings of zones I and II, underestimated settlements) and weak zone III waste (overestimated settlements). Despite this, the literature emphasizes that the measurement interval along with the speed of the DMT test results in the fact that, in addition to determining soil parameters, predicting settlements is the number one application of the DMT, as mentioned earlier [41,47]. The results of other geotechnical tests at a larger interval, performed to assess settlements (e.g., SPT, standard penetration test, generally performed at 1.5-m intervals), are considered to be unreliable and not credible [37,42]. Settlements predicted by SPT can be overestimated against settlements predicted by DMT [64,65]. Other tests, such as PMT (pressuremeter test) and SBPM (self-boring pressuremeter), are time-consuming and less economical [43,46]; secondly, the results of the DMT do not include immediate and secondary settlements, which could partly be included in the results of geodetic measurements (zone I and II). It should be noted that the predicted settlements are meant to be “the settlement in working

conditions". According to Monaco et al. [46], the DMT-calculated settlement is the primary settlement. A similar situation occurred in the case of the experimental embankment at Treporti (Venice, Italy) [41,46,47,66]. According to Marchetti et al. [41], measured settlements amounted to 360 mm (including secondary), while settlements predicted by DMT reached 290 mm (net of secondary). The discrepancy of the results was explained by not including part of the secondary settlements (70 mm, which is less than 20%). The adulators of [30,35,38,42,44,49,67] also indicate high agreement of values predicted by DMT and observed settlements. In Želazny Most TSF, more similar results of settlement tailings predicted by DMT in relation to the results determined on the basis of geodetic measurements may be obtained in the future by introducing local correlations to determine the constrained modulus M (e.g., correlations based on the results of DMT and CPTU).

5. Conclusions

Considering the results of the conducted research and the results available in the literature, it can be stated that the DMT test, widely recommended for determining settlement of natural soils, can also be used to estimate the settlement trend of tailings. The results of the DMT tests allow the determination of approximate tailings settlement values. In addition, they allow determination of the overall trend of settlement of weak tailings in line with the trend determined on the basis of geodetic observations. The conducted analyses led to the following general conclusions being drawn:

- Settlement of the postflotation tailings, depending on the facility zone, range from a few cm within the beach of the facility to over 1.5 m within the supernatant pond;
- Based on linear elasticity, DMT tests provide a settlement proportional to the load (Table 2); the results of the DMT test obtained after applying the load allow an approximate determination of the actual response of the tailings to the additional load; they indicate the trend of settlement consistent with the trend determined on the basis of geodetic measurements (Figure 7a);
- The results of DMT and geodetic measurements document the general correctness of the increase in the value of tailings settlement as they move away from the facility's dam towards the pond; predicted and observed settlements in zone I and II < predicted and observed settlements in zone III (Table 4, Figure 7a);
- The DMT in relation to geodetic measurements clearly underestimates (zone I and II in Table 1) settlements of a more rigid subsoil and vice versa; overestimates (zone III in Table 1) settlements after crossing the pond line (Table 4, Figure 7b); and
- The weakness of DMT in the context of strongly layered tailings may be the aspect of discontinuous measurement, which in turn may lead to random measurements; the choice of a dilatometer membrane with appropriate stiffness, tailored to the tailings characteristics, may also affect the recorded test parameters. Omission of this element may directly affect the credibility of results obtained from the DMT test. The weakness of geodetic measurements is the time in which measurements are made and their cyclicity, which is next to the unification of methodology and interpretation of results, one of the three principles of monitoring.

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