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Design and Implementation of Sampling Wells in Phosphate Mine Waste Rock Piles: Towards an Enhanced Composition Understanding and Sustainable Reclamation

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Abstract: Establishing a circular economy in mining begins with a dedicated sampling strategy as its fundamental phase. This specific approach is crucial for enhancing resource retrieval and isolating essential minerals from mining residues. By carefully examining and defining the makeup of waste materials, mining activities can discover overlooked possibilities, promoting sustainability. A thoughtfully planned sampling strategy not only reduces environmental harm but also sets the stage for the effective use of resources. In doing so, the mining industry can shift towards a circular model, adhering to the principles of waste reduction, material reuse, and ultimately promoting a more environmentally conscious and economically viable industry. In the phosphate industry and during the pre-concentration process of phosphate ore through screening, significant amounts of mining waste, consisting of various lithologies including indurated and fine phosphate, coarse-grained silicified phosphate, limestone, and marls, are deposited in waste rock stockpiles. Collecting representative samples from these heterogeneous materials presents challenges in accurately characterizing the entire stockpile. To overcome this issue, circular mining wells were implemented as a novel sampling method in waste rock stockpiles, enabling the collection of intact representative samples. This paper shares a successful experience in constructing three concrete-lined wells within a phosphate mine waste rock stockpile measuring 662 m in length, 240 m in width, and ranging in height from 0 to 65 m. The wells were dug at various depths, ranging from 20 m to 55 m, with a circular section and a diameter of 1.5 m. An integrated method utilizing analytical techniques in conjunction with numerical modeling via Robot Structural Analysis software (version of 2020) was utilized to assess the stress on the well supports and confirm their stability. This methodology serves as a valuable tool for evaluating the stability of similar wells, ensuring the safety of operators. The structural model yielded a stress level of 1 MPa, which aligned with the values obtained from the analytical model. Sensitivity analysis was performed on various parameters (friction angle, Poisson Ratio, and gravity), and the safety factor consistently remained above 1.5 for all scenarios investigated up to a depth of 60 m. Consequently, this study demonstrates that concrete-lined wells can be utilized safely for intact sampling in waste rock stockpiles. This sampling operation will allow the pursuit of optimizing resource utilization and enhancing environmental sustainability, by studying phosphate distribution in the Phosphate Mine Waste Rock (PMWR) for better recovery.

Keywords: waste rock piles recovery; circular mine waste management; mining environmental footprint reduction; circular mining wells for intact sampling strategy

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1. Introduction

In Moroccan context, the discontinuous panel extraction method in open pit is employed to extract sedimentary phosphate. This involves removing intercalation and overburden layers, which are then piled nearby. Bulldozers are used to extract sandy phosphate, transported to treatment plants. However, intercalation layers are sometimes extracted with the phosphate. The mixture is crushed and sized to separate sand-phosphate from waste rocks. Coarse rocks are discarded as waste in PMWR Stockpiles, while fine sandy phosphate is processed further [1].

Effective management of mining waste stockpiles relies on proper sampling techniques, as they provide essential information for waste characterization and decision-making processes. However, sampling within stockpiles poses several key challenges that need to be addressed to ensure the accuracy and representativeness of data collection. The first challenge is spatial variability: waste deposition in stockpiles is not uniform, resulting in spatial variability. Ref. [2] describes the top-down disposal method, which involves releasing the PMWR onto a moving front. Different areas may contain different waste types and characteristics. Sampling methods must consider this spatial variability to ensure that samples are taken from representative locations across the stockpile site. Ignoring spatial variability can lead to biased results and inadequate understanding of the stockpile's overall condition.

The second main challenge is heterogeneity of waste composition: The stockpiles receive a multitude of hazardous waste materials with varying compositions, making it a challenging task to obtain representative samples that reflect the overall characteristics of the stockpiles. Failure to address this heterogeneity can result in misleading findings and ineffective waste management or valorization strategies. Segregation of particles [3] during the stacking or reclaiming processes can also pose challenges in obtaining representative samples. The material may segregate based on size, density, or other properties, leading to an uneven distribution of valuable minerals or contaminants throughout the stockpile.

Phosphate mine waste rocks stockpiles are naturally exposed to the same challenges. The spatial variability of the Ben Guerir's [4] screening PMWR stockpile, as shown at Figure 1, is the best example of visual spatial variation.

Figure 1. Spatial evolution of Ben Guerir's screening PMWR stockpile. ①: July 2004—②: August 2014—③: April 2023 (Google Earths).

In relation to the heterogeneity problem and according to [5], the PMWR piles are exposed to significant heterogeneity as a result of the segregation effect. Furthermore, based on a preliminary characterization of PMWR, ref. [1] reported that it is possible to recover and valorize phosphate, by joining the conventional mineral processing with the fine fraction (<30 mm). This preliminary hypothesis was based on 25 tons samples of destoning and screening PMWR each, subjected to manual sorting. The recovery of residual phosphate from low-grade sources, including phosphate mine waste rock (PMWR), represents a promising solution to the rising demand for phosphate in the food and fertilizer industries. The beneficiation of low-grade phosphate ore offers numerous benefits, such as reclaiming residual phosphate from previously uneconomical resources, decreasing the amount of mine waste that accumulates in PMWR Stockpiles, promoting cleaner production practices, and maximizing production rates [6].

To verify those results, sampling in the body of the PMWR Stockpiles is necessary, for collection of representative samples, in order to determine the mineral content and other elements. Circular mining wells are necessary to retrieve representative and minimally altered samples. The samples are subsequently analyzed to determine their particle size and chemical composition. However, this operation is extremely dangerous, particularly for operational staff [7]. Hence the need to design the well lining to ensure the required stability during excavation operations.

Several authors have treated the design of circular shafts [8–17]. However, their implementation in anthropic materials has posed a challenge for this project, given the heterogeneity of the PMWR piles and the difficulty of carrying out mechanical characterizations that accurately reflect the actual behavior of the deposited materials. [18] have shown that an infrastructure built on a natural slope of only 15° can lead to major instability issues. Therefore, conducting a specialized study that considers both the soil's characteristics at the location and the intended construction is crucial.

The primary aim of this paper is to share a challenging and successful experience in building deep mining exploration wells, within stockpiles, using simple and practical approach. Despite its inherent risks, this approach has enabled the retrieval of undamaged samples that will maintain their composition and particle size distribution. These samples can then be subjected to a targeted characterization campaign.

2. Materials and Methods

2.1. Mine Site Description

At the Benguerir mine site, ore extraction is accomplished via open pit mining, which entails removing overburden and excavating ore from the surface. This intermittent method of ore extraction by trenching usually involves the utilization of heavy machinery like excavators, bulldozers, and trucks to remove rock and soil above the mineralized layers (ore body). After exposing the ore, it is drilled, blasted, and loaded onto trucks to be transported to a processing plant (Figure 2), where it is screened, crushed, and subjected to a series of physical processes to isolate the phosphate from other materials.

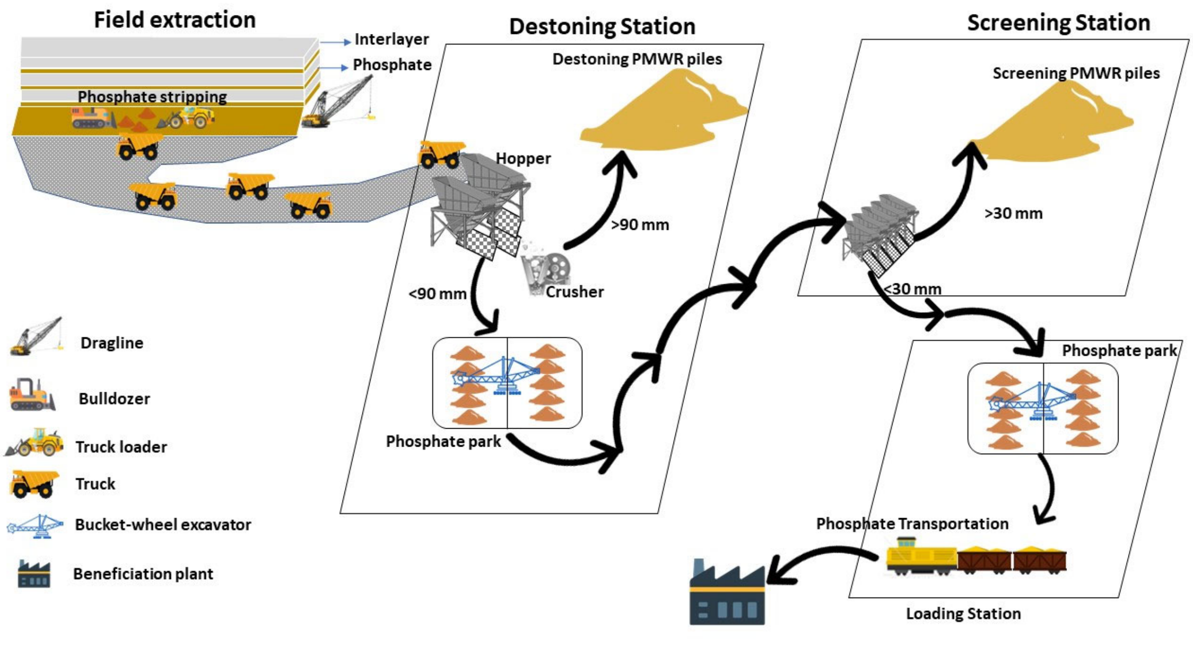

Figure 2. Phosphate extraction and Mining processing protocol in Benguerir prospect.

To begin mechanical processing phosphate ore, the first step is destoning. This mechanical process involves removing rocks or stones between 90–150 mm in size from the phosphate ore. The extracted materials are then stored in a designated destoning PMWR pile. This step is crucial as the presence of rocks in metric blocks that can damage equipment and reduce the efficiency of subsequent chemical processes. Destoning involves a combination of mechanical methods such as crushing and vibrating screens. Following destoning, the ore is passed through a series of screens with different mesh sizes (30 × 15 mm) in a process called screening. This separates larger rocks and debris (30–90 mm) from the phosphate ore (<30 mm), then stacked in large piles for storage. The waste materials are sent to a separate screening PMWR pile. The PMWR piles are typically arranged in long rows of up to 650 m and have a height of several meters, up to 70 m.

After the destoning and screening process, the phosphate ore is prepared for transportation by train to beneficiation plant for further processing. This involves a variety of chemical treatments, including flotation and calcination, to extract the desired minerals from the ore. The residual materials (<30 mm and >90 mm) resulting from the screening operation are considered waste and are transported via conveyor to the top of the screening PMWR pile, where they are stored. The PMWR pile is constructed using a waste storage method that involves depositing the materials along the slopes from the top of the pile adopting top-down configuration on the plat surface [19]. An excavator (D9 grader) is then used to move the materials from the top of the pile to the base.

2.2. Conceptual Model for Sampling of the Screening (PMWRS) by Mining Wells

Prior to providing a detailed description of the sampling technique utilizing mining wells, it's worth mentioning that the PMWR pile in the Benguerir mine is comprised of diverse elements sourced from geological layers with varying lithological characteristics such as limestone, dolomite, flint, marl, phosphatic sand, and others. These elements have a highly variable work index (26.16 kWh/sh.ton for flint and 9.29 kWh/sh.ton for phosphate rock) and heterogeneous hardness. However, it's important to emphasize that during fieldwork, mapping, and surface sampling, it was observed that the materials exhibit a wide range of particle sizes, ranging from less than one millimeter to more than 90 mm, with the presence of metric blocks and a fine material. The latter is produced by the level of hardness of the mother rocks that created these materials during the mining operations at the Benguerir mine.

Several sampling methods can be deployed to collect samples on the surface, subsurface, and the bottom of the PMWR pile. However, the execution of the core drilling as a sampling method, is possible but will likely result in a low recovery rate due to the alteration of fine particles by water during the core drilling process. Thus, during the execution of destructive reverse circulation drilling (RC) method, the blocks of materials traversed such that particles larger than the diameter of the drill bit will necessarily be pulverized. Moreover, in terms of particle size, the extracted elements and materials will not be representative of the materials in place, so their characterization will certainly present a bias.

After the mapping work and field investigations, a topographical survey was carried out using an airborne drone method. A three-dimensional (3D) modeling of the WRP was carried out to delineate their morphological features and accurately estimate their volume. To accomplish this, a professional drone equipped with GPS-RTK technology was utilized to gather data points with high spatial resolution (2.45 m per pixel), flown at an altitude of 100 m, equipped with a high-resolution 32-megapixel camera, and capturing images with an 80% overlap. Subsequently, the collected data underwent processing using the Lidar module within the Global Mapper software 22.1 to remove any extraneous data and optimize the dataset size. This allowed the collection of a high-precision topographical database, which contains (X, Y, Z) points and geotagged orthophotos. The collected database was analyzed and processed using appropriate software, and a 3D photogrammetric model of the screening PMWR pile was elaborated. This 3D model was used as a basis for the geotechnical simulation and implementation of sampling method using mining wells on the PMWR Stockpile (Figure 3). Therefore, through this document, which describes the technique for the construction of reinforced concrete wells for PMWR piles sampling, consideration was given to the site environment and the protection of personnel and bordering areas.

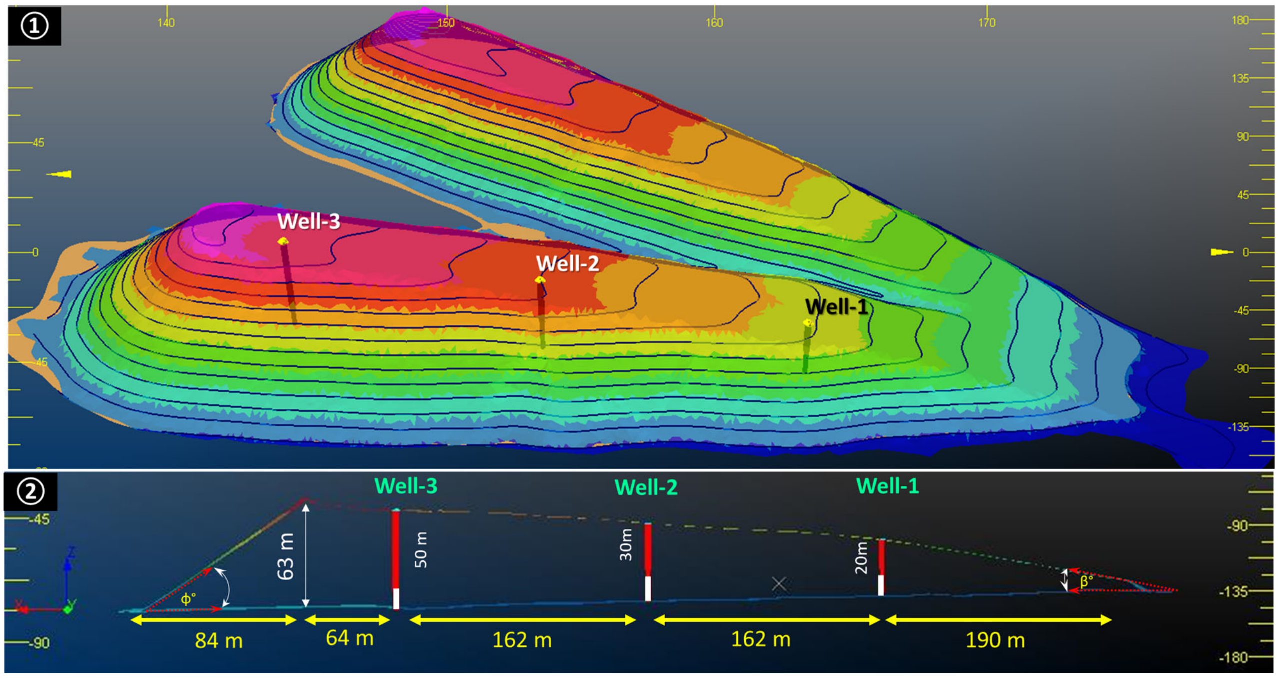

Figure 3. Arrangement of stockpiles and location of sampling wells; Legend: ① Perspective view (3D view) of the left arm of the screening PMWR stockpile; with the location of the three mining wells. It is noted that the well implantation mesh is around 162 m. ② Projection of the three wells on a longitudinal section representing the planned sampling depths by mining wells respectively (Well-1, 20 m, Well-2, 30 m, and Well-3, 50 m).

From the 3D topographic model, the screening PMWR stockpile is made up of two conical-shaped material arms, with a length of approximately 662 m and a width of approximately 240 m. The height varies from 0 to around 65 m at the highest point. The stockpile is characterized by a longitudinal slope of approximately 6° (β = 6°) and a slope gradient around 37° (ϕ = 37°). A perspective view and a longitudinal section along the slope on the access line to the screening stockpile are shown in Figure 3.

To extract the residual phosphate ore from the screening stockpile and given the nature of the target, it was decided to investigate and sampling adopting the excavation of vertical mining wells using manual methods. The conception of the sampling method using mining wells is presented in several steps, which are detailed afterwards.

Based on the 3D model of the screening stockpiles, a geotechnical detailed study was carried out to verify its stability, after which, it was approved that sampling of the stockpile is feasible by digging three mining wells at variable depths from 20 m to 55 m, with a circular section and a diameter of 1.5 m. As for the spacing of the wells, it is about 162 m (Figure 3). The wells were executed by a professional and experienced well digger, with the walls supported by reinforced concrete with a thickness varying between 10 to 15 cm (Figures 7 and 8).

The location points for the wells are identified, and the contour of the wells is marked on the ground while respecting the grid and spacing between the wells. Then, a reinforced concrete slab is installed to secure the extraction winch and protect the walls of the well. After that, the winch equipped with a steel cable is installed. For sample recovery, manual drilling of the well is started at variable depths of 0.50 to 1 m. The manual drilling operation is carried out in such a way that excavating one meter corresponds to collecting a large sample of about 1 m^3 (Figure 7). With this large-section (1.5 m) mining well sampling method, the materials constituting the extracted samples will be more representative of the formations, and their characterization will be more faithful to the reality of the materials of the stockpile, both in terms of lithology, physical and chemical characterization (particle size distribution, porosity, etc.). In fact, after collecting representative samples of the geological material in the field from the WRP. The samples are then preserved to maintain their original state from the field and subsequently analyzed in the laboratory to determine their porosity using the technique of weighing saturated and dry samples, and then confirmed by mercury porosimetry technic.

The sampling of the materials is done during the digging the wells in the stockpile. So, the materials extracted from the wells during the advancement of each meter, are separately ordered in plastic bags and in carefully sealed big bags, including the well number and the sampling level. These samples are transported to the laboratory for physical, chemical, and mineralogical characterization tests (primarily chemical and granulometric analyses by sieving and sedimentometry). However, they are used to determine the lithology with depth and potentially undergo block analysis.

2.3. Theoretical Considerations on Mining Well Stability

To comply with the OCP safety strategy and considering the risks associated with the activity of wells digging, a detailed technical study of the stability of the wells is necessary. Two methods were adopted for the estimation of applied thrust pressure on the support. Which allowed to calculate the safety factor on the support.

For wells digging, it was planned to construct a reinforced concrete retaining wall with a thickness of 0.15 m to confine the soil and ensure stability of the walls of the shaft during excavation operations. It has been considered that the concrete will reach a strength of 2.5 MPa at a minimum age of two days. This value is considered safe according to several research studies that have dealt with the early age compression strength of concrete [20–22]. The strength of the concrete will then naturally increase over time, which implies that the safety factor will also increase over time.

The thrust on the retaining wall increases as the excavation progresses: closest to the excavation face, the three-dimensional distribution of stresses makes the thrust lower than that corresponding to plane deformations (an "infinite" shaft). As one moves away from the excavation face, the thrust increases until it reaches a state of equilibrium with the retaining wall. Given the excavation speed and waiting time for setting, the concrete will develop a strength greater than 2.5 MPa in the area away from the excavation face.

On the other hand, stockpiles are anthropic materials deposited above the natural terrain. In this context, due to the gravelly-sandy to gravelly-silty nature of the stockpiles, the lack of rigorous compaction (materials dumped) and the absence of the water table, a unit weight of 17 KN/m^3 has been considered. In addition, a Mohr-Coulomb type failure criterion [23] has been considered with zero cohesion and an internal friction angle of 33°. Due to the heterogeneity of the materials that make up the slag MWRS and the difficulty of obtaining representative measurements in the laboratory on these materials, the angle of friction was estimated as a first approach, based on the measurement of the minimum stockpiles slope, which are currently stable. The Poisson's ratio [24,25] of the mine waste piles has been considered to be 0.3.

Table 1 summarizes the main parameters used in the design of the wells concrete support.

For calculation of applied thrust pressure on the support, using the analytical method, the calculation was carried out by considering an elastoplastic model [26] of the stockpiles with a Mohr-Coulomb type plasticity criterion, without hardening. It was considered that a plastic zone with a thickness of "Rs" develops in the massif around the well, as shown in Figure 4.

Table 1. Data and parameters for calculating the wells support.

Data	Value
Geometry of the well section	Circular
Well radius (a)	a = 0.75 m
Depth	Variable (25 m, 40 m and 60 m)
Nature of the supporting structure	Reinforced concrete wall
Minimum thickness of support	0.15 m
Compressive strength of concrete	*R*c = 2.5 MPa
Water table	Lack
Type of land	PMWR piles
Particle size	Gravel-sandstone to Gravel-siltstone
bulk density	$\gamma = 17\ kN/m^3$
Poisson's ratio	$\nu = 0.3$
Cohesion	C = 0 kPa
Internal friction angle	$\varphi = 33^\circ$

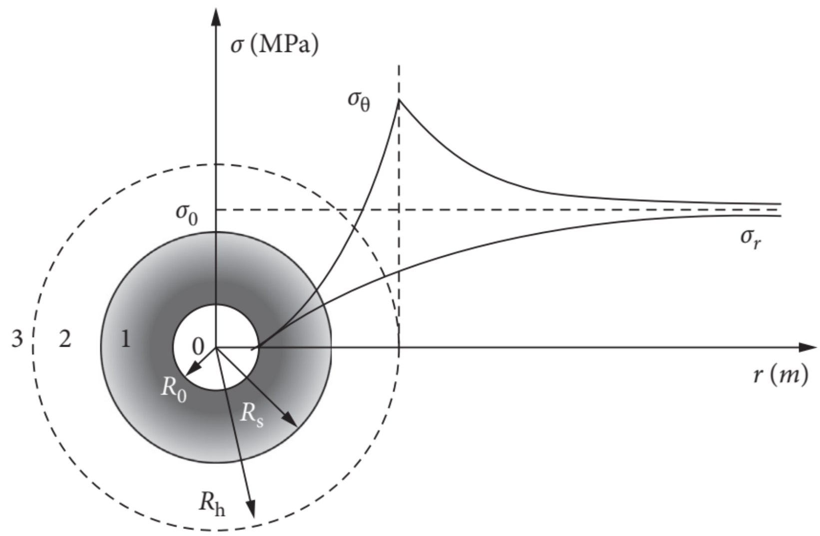

Figure 4. Stress distribution diagram of elastic-plastic zones of a well [27]; Legend: R_0: Radius of the well; R_s: Radius of plastic softening zone; R_h: Radius of the hardening zone, 1: Plastic softening zone; 2: Plastic hardening zone; 3: The elastic zone.

The convergence of deposits results in a pressure applied by the rock mass on the concrete support. Thus, by the law of action/reaction, the confinement will apply pressure on the rock mass as shown in the Figure 4. Before excavation, it is assumed that the vertical stress σz in the PMWS is:

$$\sigma z = \gamma \cdot z \quad (1)$$

where γ is the bulk density and z the depth.

The vertical constraints are equal to:

$$\sigma x = \sigma y = K0 \cdot \sigma z = \frac{\nu}{1-\nu} \cdot \gamma \cdot z \quad (2)$$

where ν is the Poisson's ratio of the stockpile material and $K0$ represents the coefficient of lateral earth pressure at the initial state.

After excavation, calculations are carried out for stresses in cylindrical coordinates, given the geometry of the problem. The local equilibrium equation (neglecting the terms of second order) is the following:

$$(\sigma\theta - \sigma r) \cdot dr = r \cdot dr \quad (3)$$

The stresses σr and $\sigma\theta$ are principal.

The Mohr-Coulomb criterion is written:

$$\frac{\sigma\theta + C\cdot\ cotan\ \varphi}{\sigma r + C\cdot\ cotan\ \varphi} = \frac{1 + Sin\ \varphi}{1 - Sin\ \varphi} \tag{4}$$

The combination of the previous equation, valid in the plastic zone, and the previous equilibrium equation gives the expressions of stresses $\sigma\theta$ and σr at the level of the plastic zone, that is for r between a and R:

$$\sigma\theta = (p + C\cdot\ cotan\ \varphi)\cdot\ \frac{r^{(2\cdot sin\varphi)/(1-sin\varphi)}}{a} \cdot \frac{1 + Sin\ \varphi}{1 - Sin\ \varphi} - C\cdot\ Cotan\ \varphi \tag{5}$$

$$\sigma r = (p + C\cdot\ cotan\ \varphi)\cdot\ \frac{r^{(2\cdot sin\varphi)/(1-sin\varphi)}}{a} - C\cdot\ Cotan\ \varphi \tag{6}$$

Beyond the plasticized zone (r > b), the problem corresponds to that of a circular gallery in a linear elastic medium. The continuity condition for r = b in plane deformation is:

$$\sigma\theta + \sigma r = 2\cdot \frac{\nu}{1-\nu}\cdot\gamma\cdot z \tag{7}$$

The combination of Equations (5)–(7) allows for the calculation of p, the applied thrust pressure on the support:

$$p = (1 - sin\varphi)\cdot\left(\frac{\nu}{1-\nu}\cdot\gamma\cdot z + C\cdot Cotan\varphi\right)\left(\frac{a}{b}\right)^{(2\cdot sin\varphi)/(1-sin\varphi)} - C\cdot Cotan\varphi \tag{8}$$

This relationship is maximum for b = a, that is when the stresses have not had time to be transmitted inside the massif, in which case:

$$pmax = (1 - sin\varphi)\cdot\ \left(\frac{\nu}{1-\nu}\cdot\gamma\cdot z + C\cdot\ Cotan\ \varphi\right) - C\cdot\ Cotan\ \varphi \tag{9}$$

Furthermore, in the case of a soil without cohesion (as in the case of the stockpiles), the previous relationship becomes:

$$pmax = (1 - sin\varphi)\cdot\ \left(\frac{\nu}{1-\nu}\cdot\gamma\cdot z\right) \tag{10}$$

2.4. Numerical Modeling

For calculation of applied thrust pressure on the support by numerical modeling, Robot Structural Analysis [28,29] has been used. The software enables the simulation of various structures, such as buildings, bridges, and other structures, under diverse load conditions. It provides a broad spectrum of tools for structural analysis and design, including finite element analysis, code-based design, and dynamic analysis. The software also permits the modeling of different types of materials, such as concrete, steel, and timber. Robot Structural Analysis works by using a finite element analysis (FEA) method [30–33], which entails breaking down a complicated structure into smaller, more manageable components known as finite elements. These elements are governed by a set of mathematical equations that dictate their behavior, and when assembled, they form a comprehensive model of the structure. Subsequently, the modeled structure is subjected to various types of loads, including gravity, wind and other forces, to simulate its response. The software calculates the stresses, strains, and displacements across the structure and evaluates whether it satisfies the necessary safety standards and code regulations.

Once the applied thrust pressure on the support has been defined, the compression in concrete should be estimated. Considering that the reinforced concrete support is cylindrical with $a1$ and $a2$ being respectively the outer and inner radius (a1 > a2), it will be subjected to an external pressure corresponding to pmax. The radial stresses σr and ortho-radial stresses $\sigma\theta$ in the support will be:

$$\sigma r = \frac{p \cdot a1^2}{a1^2 - a2^2} \cdot \left(1 - \frac{a2^2}{r^2}\right) \tag{11}$$

$$\sigma\theta = \frac{p \cdot a1^2}{a1^2 - a2^2} \cdot \left(1 + \frac{a2^2}{r^2}\right) \tag{12}$$

The stresses in the concrete are all in compression. The ortho-radial stress $\sigma\theta$ is always greater than the radial stress σr. It is also maximum for r = a2, i.e., at the level of the inner wall of the support. It is then equal to:

$$\sigma\theta = \frac{2 \cdot p \cdot a1^2}{a1^2 - a2^2} \tag{13}$$

The support has a thickness of e = 0.15 m, which is much smaller than the radius of the well (equal to 0.75 m). Therefore, we can reasonably assume that a1 $\approx$ a2 $\approx$ a and a1 $-$ a2 = e. Thus:

$$\sigma\theta = \frac{p \cdot a}{e} \tag{14}$$

This compressive stress must remain lower than the compressive strength of the concrete, since it is located at the lower face of the support, where the minor principal stress is zero.

3. Results and Discussion

3.1. Assessment of Support Stability

Based on the data provided in Table 1, Equation (10) gives the maximum pressure applied to the concrete support (pmax) valid for a cohesionless environment. Equation (14) provides the maximum stress generated in the concrete. The maximum pressure calculated by the analytical method is equal to 200 KPa and compression stress σ0 in the support is equal to 1 MPa, as shown at Table 2.

Table 2. Maximum pressure and stress applied in the support.

Depth (m)	Maximum Pressure Pmax without Cohesion (in KPa)	Compression Stress σ0 without Cohesion (in KPa)
5	17	83
10	33	166
20	66	332
30	100	498
40	133	664
50	166	829
60	199	995

Moreover, the use of Robot Structural Analysis software for numerical modeling results in stresses of 1.05 MPa, outside of the edge effect zones, as shown in Figure 5. The stress attained from the structural model is consistent with the values obtained from the analytical model, with stress levels around 1 MPa.

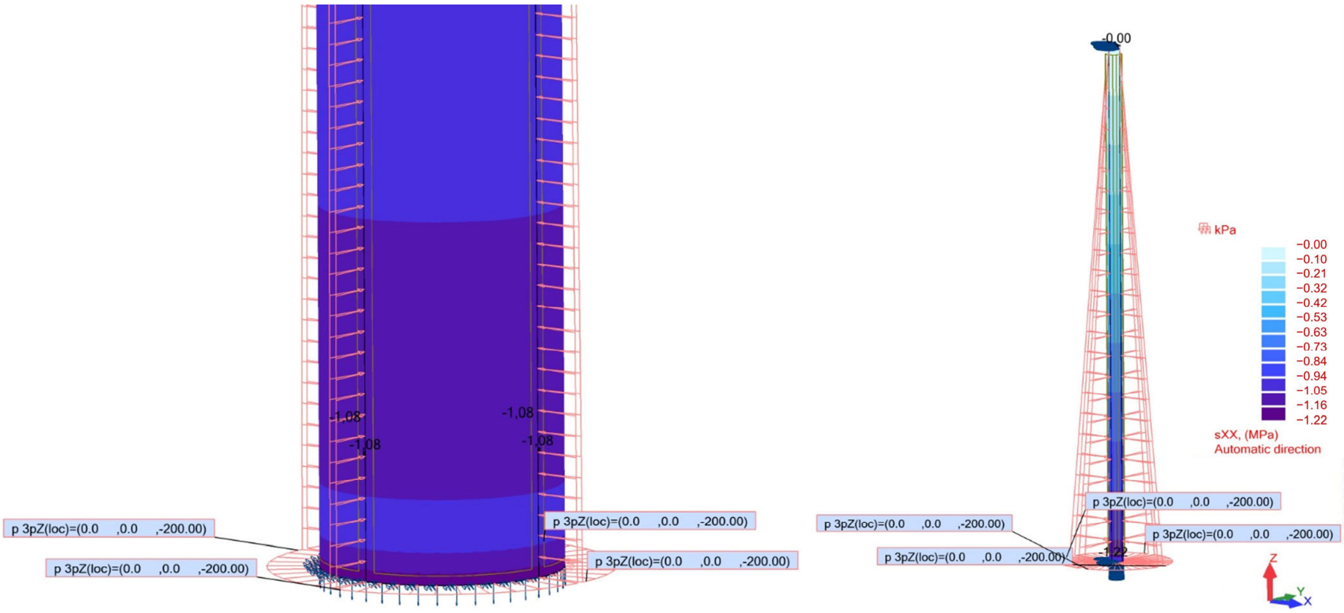

Figure 5. Results of the numerical modeling of the stress applied on the well.

Table 3 presents the calculation of the compression stress in the support structure and safety factor FS $\left(FS = \frac{Rc}{\sigma 0}\right)\cdot$ Where RC is the compressive strength of concrete and $\sigma 0$ the compression stress applied on the support. It follows that for the parameters of the study, as shown at Table 1, all safety factors are greater than 1.5 up to a depth of 60 m (results given in Table 3). Therefore, the thrust of the stockpile on the concrete support does not induce a compression greater than its compressive strength, which is 2.5 MPa.

Table 3. Maximum pressure, compression stress in the support structure, and safety factor.

Depth (in m)	Compressible Stress σ0 without Cohesion (in KPa)	RC Concrete (in KPa)	FS
5	83	2500	30.1
10	166	2500	15.1
20	332	2500	7.5
30	498	2500	5.0
40	664	2500	3.8
50	829	2500	3.0
60	995	2500	2.5

Additionally, to confirm this outcome, a sensitivity test was carried out, based on the scenarios outlined in Table 4. This test involves varying each parameter by ±25%.

Table 4. Definition of the scenarios undertaken for the sensitivity analysis of the calculation parameters.

Scenarios of Calculation	f (°)	*n*	g (KN/m^2)
S1	33	0.3	17
S2	33 + 25%	0.3	17
S3	33 − 25%	0.3	17
S4	33	0.3 + 25%	17
S5	33	0.3 − 25%	17
S6	33	0.3	17 + 25%
S7	33	0.3	17 − 25%

Figure 6 displays the variation of the safety factor in relation to the depth. This variation corresponds to an exponential decay curve, meaning that the safety factor decreases exponentially between the surface and a depth of 25 m. Beyond that, the variation of the safety factor, by varying the analyzed parameters, is also sensitive to the depth. However, the safety factor remains consistently above 1.5 across all scenarios studied, as indicated by this figure.

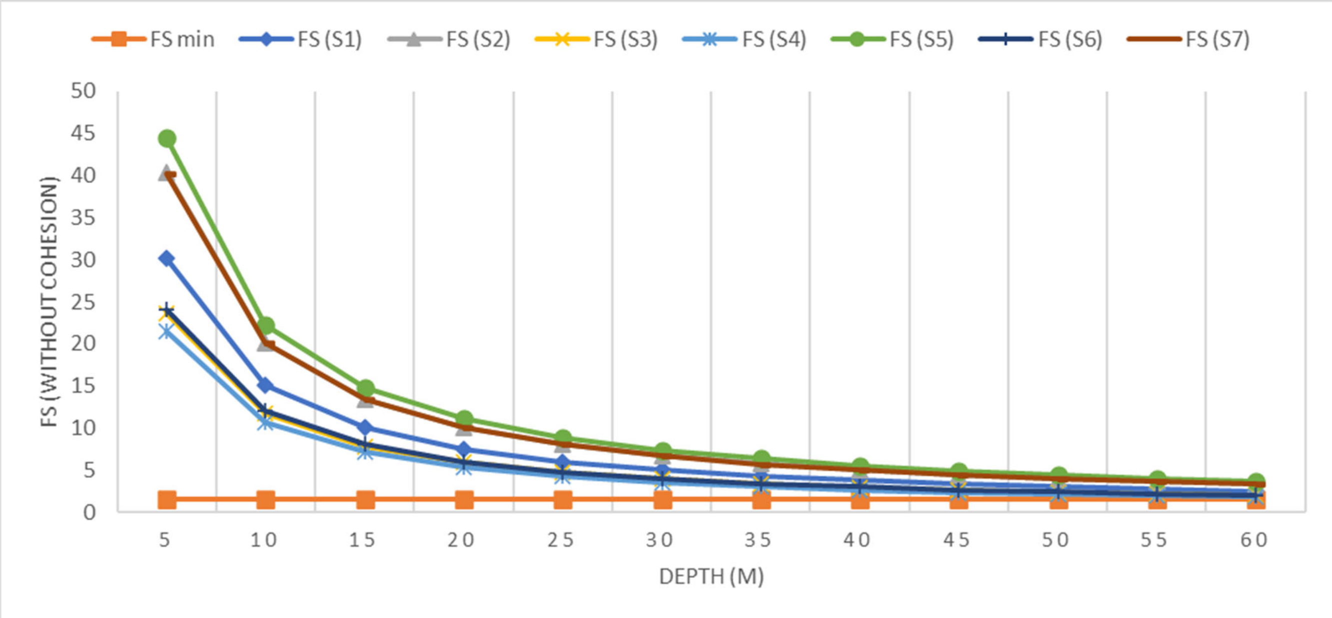

Figure 6. Variation of the safety coefficient according to the depth.

3.2. Conceptual Model for Sampling in the Body of the Stockpile

Personnel safety is of paramount importance during the construction of a mining well. The risks associated with this activity are numerous and can be very serious in case of accidents. To comply with the OCP safety strategy and considering the mentioned risks, a construction phasing has been carried out. It involved the following steps, as illustrated in Figure 7.

The workers were trained in safety protocols and equipped with appropriate personal protective equipment (PPE), such as helmets, gloves, boots, and safety harnesses. Regular equipment inspections, constant monitoring of the atmosphere in the well, and the establishment of emergency and evacuation procedures in case of danger have been implemented to ensure personnel safety.

3.3. Results of the Sampling Using the Mining Well Method

The digging wells works were carried out while respecting the specifications set at the outset following the conceptual model presented in detail in Figure 7. Therefore, the sampling procedure in a mining well has been established in accordance with the safety requirements on industrial production sites. It considered the measures to be put in situ to control the risks and situations arising from activities on the screening stockpiles site at the Benguerir mine.

As the work progressed, the sampling operation were carried out by collecting a sample every one-meter interval within the well's depth. In total, 93 samples were collected, with 21 samples from well-1, 34 samples from well-2, and 38 samples from well-3 (Figures 7–9).

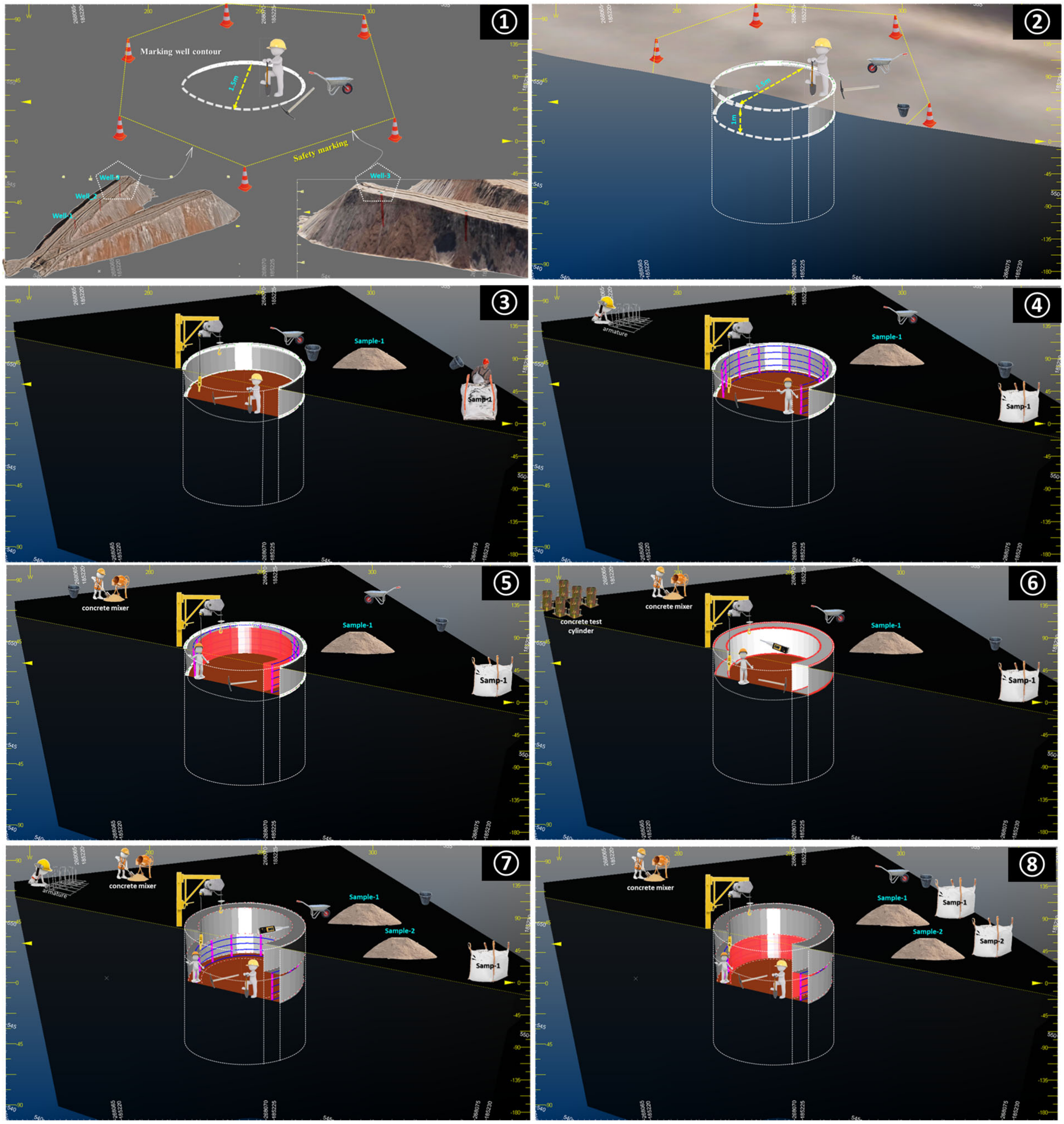

Figure 7. Conceptual model for sampling the screening pile by mining wells: ① Setting up safety marking for the concerned area and marking the well contour; ② Starting excavation of the first meter; ③ Recovering the 1st sample; ④ Placing the reinforcement grid; ⑤ Installing the metal formwork; ⑥ Pouring concrete; ⑦ Walling the well, recovering the 2nd sample, and placing the 2nd reinforcement grid; ⑧ Installing the formwork and pouring concrete, then recovering the 3rd sample and continuing the excavation of the well.

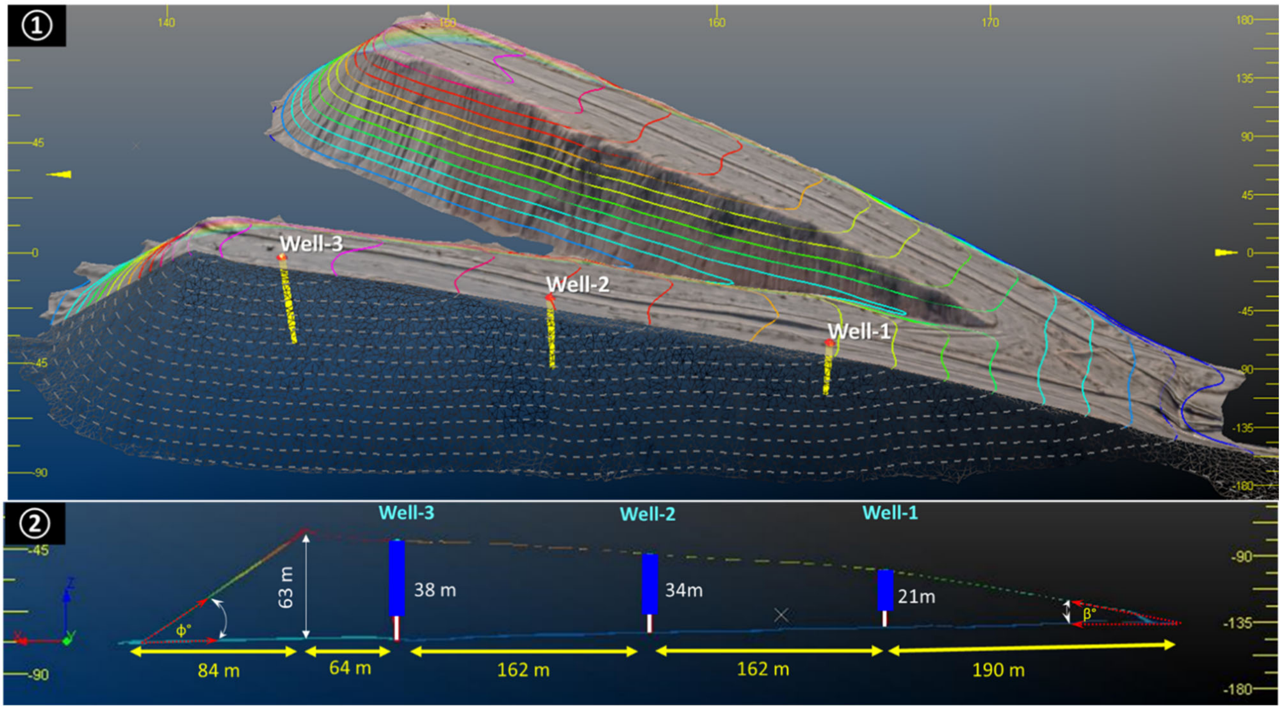

Figure 8. Detailed Three wells localization in the PMWR: ① Perspective representation (3D view) of the left arm of the screening PMWRS; showing the location of the three wells (Well-1, Well-2, and Well-3) that are executed for deep samples collection, the spacing between the wells is approximately 162 m. ② Projection of the three wells on a longitudinal section representing the status of the depth excavation in each well; respectively well-1 is 21 m; well-2 has 34 m and well-3 has 38 m completed.

In addition, two further samples were taken in sub-surface: the first from the top of the screening stockpile at the conveyor dumping area. This sample represents the initial reference of the residue before any evolution. The second sample was collected at the bottom of the stockpile to assess the impact on the material caused by its tilting from the top of the pile. These two samples constitute two reference states of the screening stockpile materials.

Despite the use of casing during well excavation, a stringent safety monitoring program was implemented under the supervision of GSMI/UM6P and L3E laboratory project teams. This program ensures quality control and safety during the sampling of concrete specimens for testing the concrete used to support the mining shaft walls.

Regarding the operation of supporting the wells with reinforced concrete, and after the excavation of each meter of the well, the support of the wells begins by placing welded mesh reinforcements on the walls (circular reinforcement grid), then a moldable metal formwork is installed, and the concrete is prepared and placed to a thickness of 10 to 15 cm, which will serve to support the walls of the well (pouring of concrete).

After the concrete has set for a minimum of 48 h of cure, the next section of the well is drilled in the same manner to recover the next sample. It is important to note that before each concrete pouring, samples for lab testing are prepared for each meter of excavation. These specimens are taken and conditioned for 7 and 28 days. A total of 10 concrete tests were performed, with six (6) specimens per test, for a total of 60 tests. The crushing test results of the 28-day cured specimens are very satisfactory and show variable results from 8.8 to 11.8 MPa. The 7-day cured specimens, after testing, recorded a variable strength of 4.9 to 8.3 MPa. These values exceed the considered compressive strength of the concrete, which is equal to 2.5 MPA.

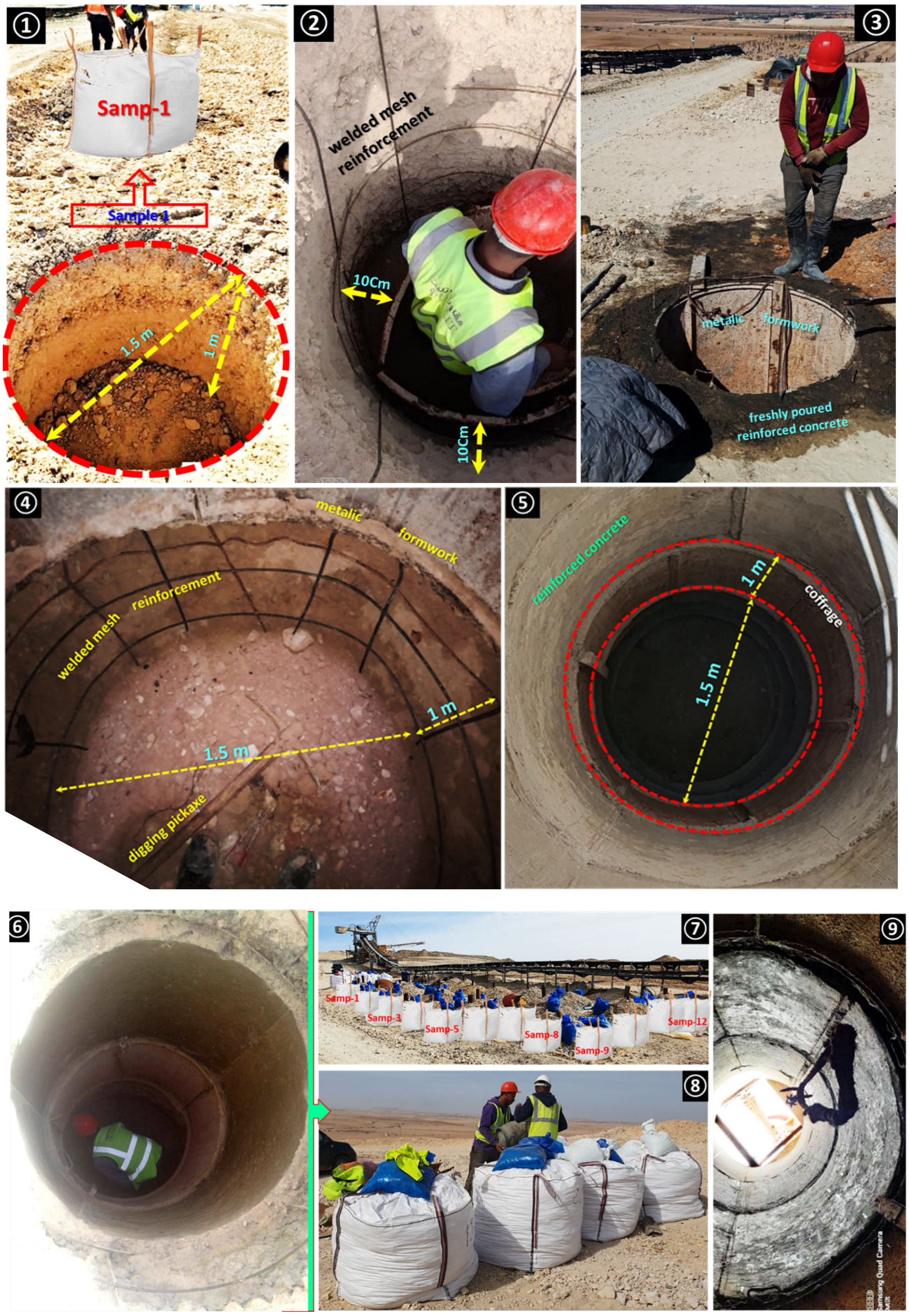

Figure 9. Illustration of the different operations of wells digging and samples recovering: ① After the GPS implantation and identification of the well's points on the field, we proceed with the initiation of well-1 excavation according to a circular section with a diameter of 1.5 m. The excavation of materials for a depth of one meter constitutes the first sample (sample 1). ② Installation of the metallic formwork and placement of the reinforcement mesh, with a spacing of about 5 to 10 cm between the shaft walls and the formwork (the thickness of the supporting concrete). ③ Pouring of the concrete. After drying for 2 to 3 days, the excavation of the next meter begins. ④ Progress of the excavation of well-1 for the collection of sample 2, noting the details of the installation of the reinforcement mesh. ⑤ Placement of the metallic formwork and pouring of the concrete to support the next excavated meter. ⑥ Progress of excavation and sampling of the fourth meter in well-3. ⑦ Sorting of the samples On-site. ⑧ Placement of the samples in big bags. ⑨ View from the bottom of well-2.

Based on these results, it is worth noting that the concrete strength values used for the support of the wells are significantly higher than the requirement for the stability of the constructed structures (2.5 MPa) as shown at assessment of support stability section. These results have been confirmed by field inspections and controls, and no signs of failure or cracking have been observed on the wells. Figure 10 shows different views from the surface and the bottom of the wells, as well as the actual state of the wells. Therefore, measurements using a sclerometer are planned to further reinforce the control and monitoring of the stability of the wells.

Figure 10. Result of excavation and final status of the three mining wells (well-1, well-2, and well-3) with different views from the bottom and from surface of the wells: ⑩ Reinforced concrete support of the wells is stable, and no signs of failure or cracking have been reported.

3.4. Analysis and Discussion of the Process of Material Storage of the PMWRS

Conducting mapping operations and field observations of the accessible surface area, using the topographic and morphological model generated by Datamine RM software (as shown in Figure 2), and further supplemented by information collected from the screening stockpile's construction history were key operations. They allowed to demonstrate that the initial batches of residues were stored in bulk on the flat ground, and without an active slope, they did not undergo grain size stratification. As the stockpile grew due to the reception of more materials, the height of the material drops also increased. However, it was shown that the effect of grain size became noticeable only when the drop height reached the "floor" level of 5 m and the "threshold" section (which corresponds to a base length of 50 m, as seen in Figure 11).

The sorting and grouping of materials that vary in lithology and density are determined by their diameter and weight, which both increase with depth. Consequently, the smallest particles are situated at the surface and occupy the uppermost layer of the deposited materials, whereas the larger particles with greater weight are located at the bottom. As the landfill develops, the height of the tipping point of the materials changes, resulting in horizontal sorting by size. At the base of the landfill, the materials have larger diameters, which progressively decrease as the landfill is constructed. This process leads to a vertical particle size classification of the materials from top to bottom, with smaller elements being found closer to the top. The degree of particle size classification is determined by the slope of the φ angle line in relation to the horizontal plane. The parallel lines of the same slope (blue lines) in Figure 12 represent the isochrones of the different deposits, which are the historical sequences of the deposits.

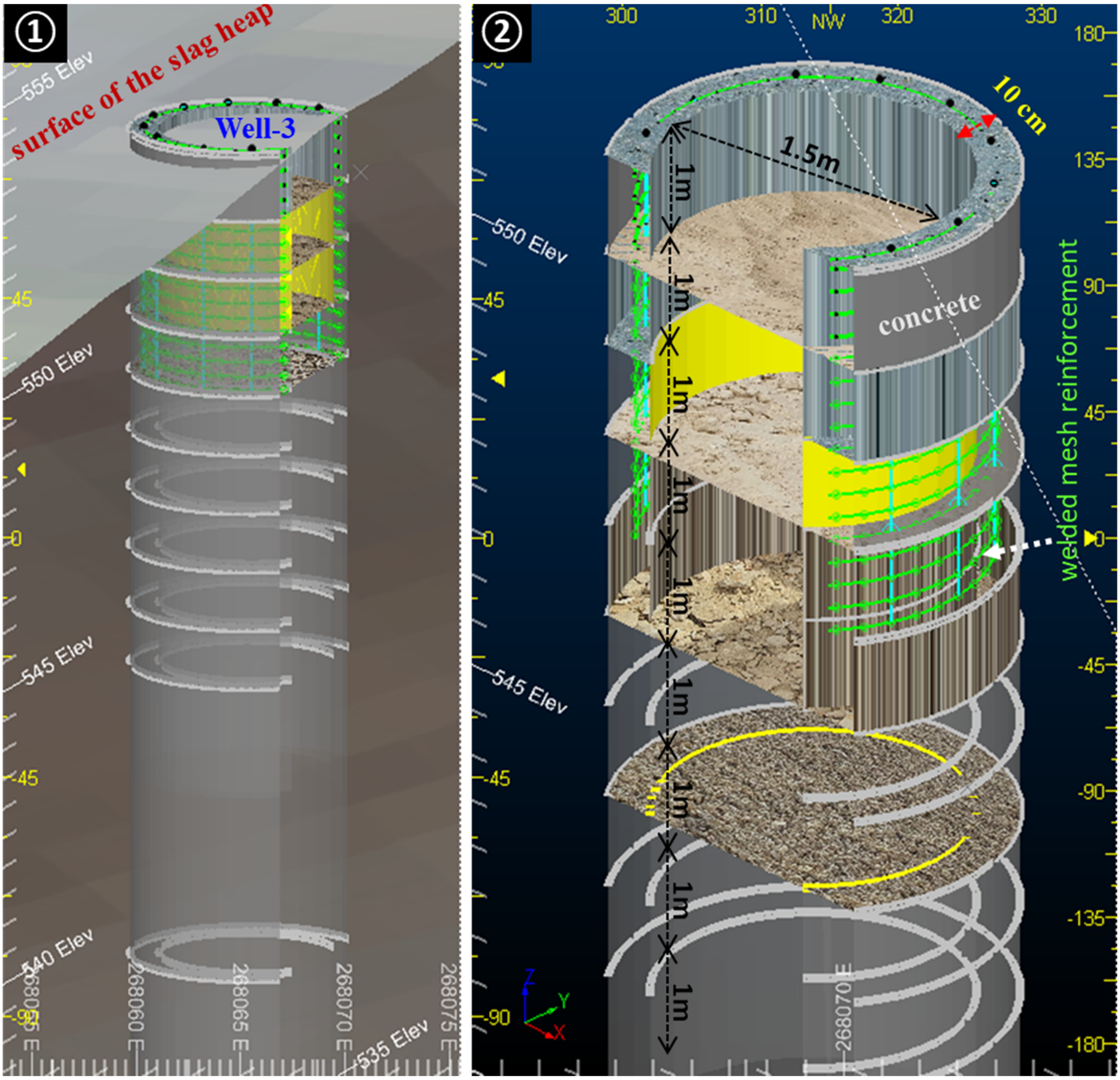

Figure 11. Representation of the design for mining wells: ① Localization of well-3 on the left arm of the screening PMWRS. ② Perspective view with a cross section (3D) of well-3 indicating the depth and walls supported by reinforced concrete, the diameter (1.5 m), and the thickness of the well support with concrete walls reinforced with welded mesh reinforcement.

The findings highlighted during the analysis of the construction processes of the screening stockpile mentioned above are well recorded on the walls of the wells (Figure 13). During the excavation of the wells, a daily follow-up was carried out, focusing on the lithological survey of the shaft walls and the stripping of the excavated materials. It should be noted that in the sampling wells, it was noticed that the particle size classification is spectacularly expressed. As the excavation works progress deeper, the grain size increases due to the litho-stratigraphic weight and fluid circulation. It is important to note that the indured phosphate lithology have become slightly friable and can be partially attributed to the production of phosphate fines.

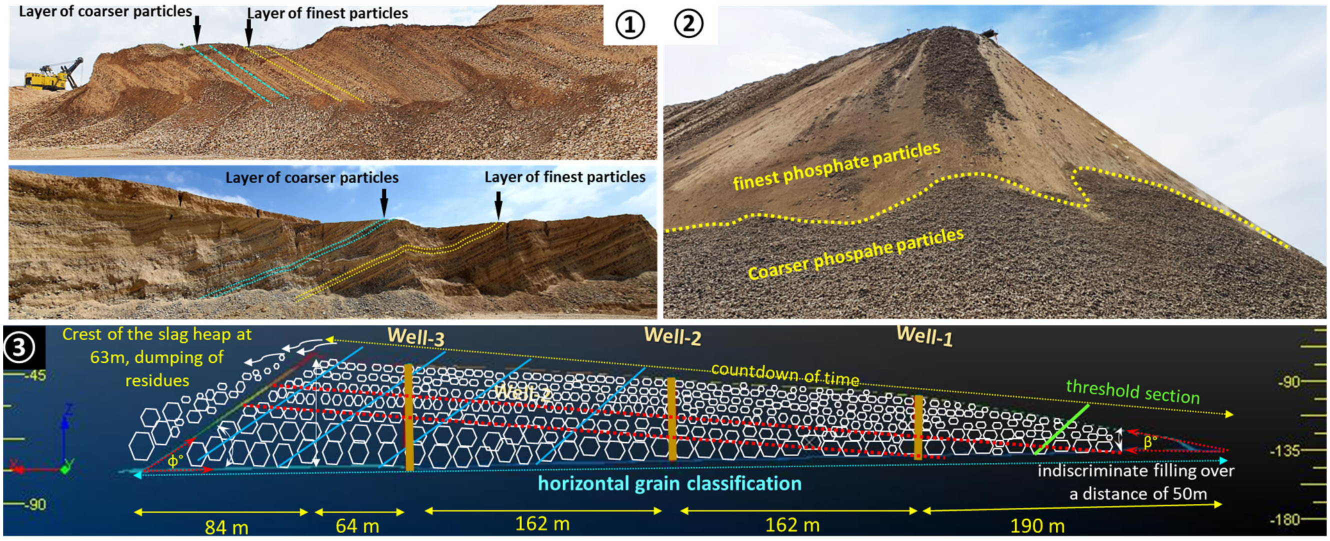

Figure 12. Illustration of the stockpile construction process and its evolution. ①—Artificial stratification resulting from a grain-size classification with fine particles at the top and coarse particles at the base of the screening PMWRS in ②. ③—longitudinal section showing the stockpile process construction and its evolution.

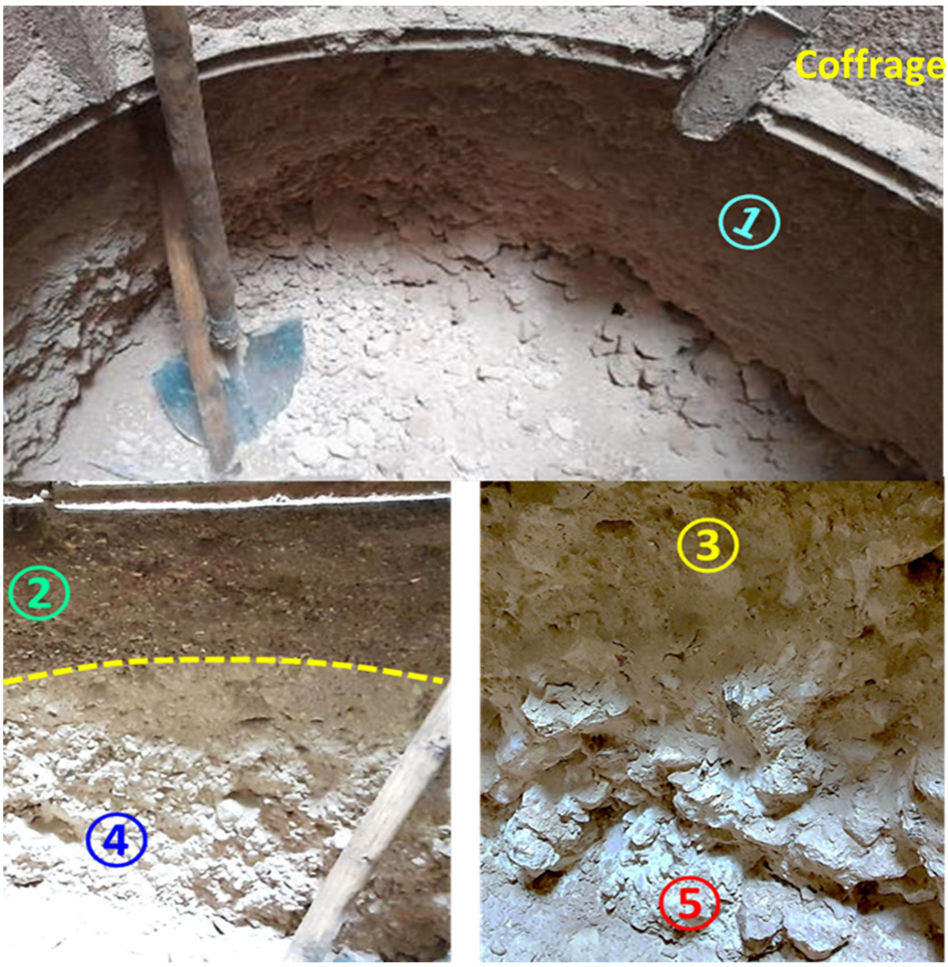

Figure 13. Lithological survey of the walls of well-1; Legend: ① Fine phosphate, ② Sandy, calcified and calcareous phosphate, ③ Calcified indurated phosphate, ④ Altered and calcified phosphate, ⑤ Fragments of indurated phosphate that have become friable, generating a sandy phosphate.

On the other hand, the gravelly part decreases in diameter due to intergranular friction wear and fragmentation due to shocks during the stockpile storage operation. Thus, the fines settle at the place of their production due to lack of inertia and braking due to friction, while the pebbles continue to fall along the 37° slope (Figure 12) while decreasing in diameter.

Finally, in the context of this work and, the ratio of times required to build a certain length of the stockpile (e.g., 1 m) corresponds to the ratio of volumes of deposited waste. A calculation with simplifying assumptions shows that this ratio is on the order of 35 between the threshold section and the summit section of the dump (Figures 12 and 13). This means that building one meter of the dump starting from the summit section will require thirty-five times the time it takes to build the same meter of the dump starting from the threshold section.

4. Conclusions, Recommendations and Perspectives

The sampling method utilizing mining wells has proven to be effective in recovering a representative sample for every meter of depth progressed. To ensure the safety of the operation, the stability analysis of the wells was thoroughly studied to validate the design and progress of the well. The methodology and design of the well digging followed safety standards to minimize risks.

This paper presents a successful experience involving the construction of three concrete-lined wells within a large phosphate mine waste rock stockpile. The stockpile measures 662 m in length, 240 m in width, and varies in height from 0 to 65 m. The wells were strategically excavated at different depths ranging from 20 m to 55 m, featuring a circular section with a diameter of 1.5 m. To ensure their stability, a geotechnical study was conducted. Analytical and numerical modeling techniques, utilizing Robot Structural Analysis software, were employed to calculate the stress exerted on the well supports. The structural model produced a stress level of 1 MPa, which aligned with the values derived from the analytical model. Sensitivity analysis was carried out on various parameters such as friction angle, Poisson Ratio, and gravity. The safety factor consistently remained above 1.5 for all scenarios investigated up to a depth of 60 m.

As a result, this study demonstrates that concrete-lined wells can be employed safely for intact sampling purposes within waste rock stockpiles. The samples obtained from these wells will undergo chemical and geotechnical analysis to provide valuable insights into the subsurface characteristics of the area.

Moreover, these wells will serve as calibration products for the boreholes conducted as part of the project. By comparing the physical, chemical, and geotechnical data from both the wells and boreholes, a comprehensive database will be constructed to develop a 3D block model. This model will provide a better understanding of the stockpiles and help in making informed decisions regarding the project. Overall, the sampling method using mining wells has proven to be a valuable tool in obtaining crucial data for the project.

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