Tunisian Phosphogypsum Challenges

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ABSTRACT: The accumulation of phosphogypsum (PG) produced till 2015 makes its management a real challenge to the Tunisian authorities and put the Tunisian Chemical Group (TCG) to face a challenge at large scale as the specified storage embankments knew considerable extensions in terms of heights and areas. Several studies were elaborated subsequently in 2007, 2012 and 2013 to focus on the stability of Sfax and Skhira PG embankments' and showed two different chemical and mechanical behaviours according to the experienced deposition process. In 2012, it was revealed that the wet PG embankment of Sfax City with 56m height, 53Ha area and 32° slope can attain 70m maximum height. This embankment can reach 100m in height if a reinforcement technique will be used. This deposition process is well recommended to ensure a better interaction between the embankment and the existing ground surface. Using the dry deposited process, the area of the PG embankment of Skhira City covers 112Ha and presents two elevation levels of 25m and 55m in 2013. However, the dry deposited process results in a damaged embankment profile, significant settlements and lateral displacements. Therefore, a PG embankment of 100m height cannot be targeted. A reinforcement of the embankment by High Density Polyethylene geotextile (HDPE) layers at increments of 4m from 55m elevation allows reaching 130m of height. Comparative study was raised between the wet and the dry process and resulted in favour of the wet process from both industrial and geotechnical perspectives. Thus, the TCG expects turning all its deposition processes to the wet one. A characterization of Tunisian Phosphogypsum was carried out based on the previous studies performed on Phosphogypsum embankments of Sfax and Skhira Cities and on the experimental tests performed on dry deposited Phosphogypsum. A numerical model is built in an attempt to propose an optimized solution to the PG specified storage areas.

KEYWORDS: Embankment, Phosphogypsum, Stability, Environment, Height, Slope.

1. INTRODUCTION

Phosphogypsum ($10(CaSO_4 2H_2O)$) is an industrial residue resulting from the phosphate ore attack by sulfuric acid when producing phosphoric acid (P_2O_5), of which 95% is used for chemical fertilizers and animal feed additives yearly. It is obtained according to the following chemical reaction (Zairi and Rouis, 1999), (Felfoul et al., 2004):

$$[Ca_3(PO_4)_2]3CaF_2 + 10H_2SO_4 + 20H_2O \xrightarrow{70\text{ to }80°C} 6H_3PO_4 + 10(CaSO_4 2H_2O) + 2HF$$

Nevertheless, this leads to many drawbacks. In fact, producing one ton of (P_2O_5) gives 5 tons of Phosphogypsum, leading to excessive quantities of PG which management is an environmental challenge. Indeed, PG used to be deposited into the sea and oceans like in the American United States, Spain and the United Kingdom. However, this was forbidden by the 1990's for environmental concerns while Morocco continued depositing more than 15 million tons of PG annually into the Atlantic Ocean (IAEA, 2013), (International Maritime Organization, 2006). At the same period, a rehabilitation of Sfax City coasts, Tunisia, was occurred to repair the environmental damages caused by the NPK factory (IAEA, 2013).

Several researchers studied the use of PG in many fields, in an attempt to its use in different ways. However, the most successful valorization axis ever found is in fertilizing the saline soils, as experienced in Huelva, Spain (Valverde-Palacios et al., 2011), (Hilton, 2010). Since the valorization possibilities in Tunisia are quite limited, the management of the Phosphogypsum which is rising by 12 million tons yearly is a real challenge to the Tunisian authorities. Except in Gabes City, where it is still deposited into the Mediterranean Sea, the TCG is storing the Phosphogypsum into embankments, known in Tunisia as "TABIAS", in the vicinity of the production units using the wet deposited process in Sfax and Mdhilla Cities and the dry deposited process in the Skhira City site (TCG, 2014).

Nowadays, the TCG faces a challenge of large scale as the specified embankments have known considerable extensions in terms of heights and areas. In fact, Tunisian wet Phosphogypsum embankments heights have reached almost 56m (Bouassida, 2012). For the wet embankment at Sfax site, it was predicted that the maximum height cannot exceed 100m unless a reinforcement technique is used (Bouassida, 2012). Few similar cases are faced by countries involved in phosphate activity around the world as the wet Phosphogypsum embankments heights do not exceed 28m in Huelva, Spain (Valverde-Palacios, 2011), and are almost of 20m in Mianzhu City, Baiyi Village, China (www.greenpeace.org, 2013), while the New Wales facility wet stack at Mulberry, Florida is expected to reach almost 91m in 2023 (www.reuters.com).

Till June 2015, topographic updated land surveys showed that the dry Phosphogypsum embankment of the Skhira City, comprising 112Ha, presented two levels of 25m and 55m successively with 78m in its highest altitude. As the embankments increase in height, stability problems like cracks and slope displacements begin to appear in the dry embankment of Skhira. In 2012, it was proposed to cover the embankment by HDPE layers of 19MN/lm of modulus of rigidity at increments of 4m of height since its top. This reinforcement allows elevating the embankment till 130m of height (Chaari, 2013). Although, according to the TCG this solution not only necessitates the use of important quantities of geotextile layers but also requires excessive energy, developed equipment to flatten the damaged profile resulting from the deposition using dry process.

As phosphoric acid production is progressing, Phosphogypsum embankments are expected to receive important quantities of PG. The establishment of new deposition sites is a possible assumption typically in the Skhira City where it was meant to create a 40Ha surface and 42m height wet deposited embankment. But this site was expected to provide an exploitation period of 7 years only as reported the environmental impact study that launched the TCG in 2012 (FNAC, 2012). Hence, as the PG storage is ground intensive, it is time to optimize the storage sites and to search for another autonomous alternative: the recuperation of the 112Ha existing embankment deposited by dry process and its re-use as a support for a new embankment. No significant similar cases were found in the bibliography concerning dry stacks.

It was also pointed out that the major problems related to the dry process are typically geotechnical and environmental ones such as slope stability, settlements, friction angles and land wastes (TCG, 2014). According to its observations, the TCG mentioned that the PG deposition using wet process seems to be more beneficial than the dry process. Hence, it is particularly interesting to focus on the reliability of both of them via a justified scientific study, allowing this way the

TCG authorities in the Skhira City to take the decision about conserving the actual deposit process or converting it into the wet one.

This work aims at presenting a synthesis of the different studies investigated to focus on the stability of Sfax and Skhira Phosphogypsum (PG) embankments as well as we introduce the actual challenges of PG storage.

2. PHOSPHOGYPSUM DEPOSIT PROCESSES

The International Atomic Energy Agency (IAEA) estimated the quantity of Phosphogypsum produced worldwide till 2013 to be about 3 billion of tons (IAEA, 2013). Only 15% of this quantity is put into valorization, the other 85% is stored at embankments using either wet or dry process (Moalla et al., 2017).

2.1 Wet process

When deposited using the wet procedure, Phosphogypsum is rejected as slurry composed of almost 30% of solid particles and 70% of water. This sludge is transported to the storage embankment via pipes and is evacuated in the TABIA's top using an evacuator (Figure 1).

The embankment contains two cells separated by an intermediate dike resulting in two sedimentation basins exploited reversely. An exploitation cycle consists in filling in a basin while the other is getting re-managed.

Figure 1 Pipes reversing Phosphogypsum sludge via wet process – Sfax Unit

The gypsum water is discharged in the highest extremity of the sedimentation basin. This way, the sludge is deposited under an area of 0.3 to 0.4% of inclination to the sea. Hence, water moves through gravity, gets evacuated via a valve and reaches a recuperation basin. This drained water is then pumped to the factory for re-use and almost only 20% of the discharged water is wasted by evaporation and infiltration (TCG, 2014).

2.2 Dry process

In the dry process, Phosphogypsum leaves the filter as a powder (solid particles) of 30-35% of humidity. Then, it is transported to the deposit area by belt conveyors and deposited in the top of the TABIA (Figure 2). The PG discharge is processed by progressing over the storage area and adding supplementary belt conveyors. Hence, dry process requests large deposition areas and results in damaged relief, which require important equipment and labor for both of maintenance and management.

Figure 2 Belt conveyors transporting Phosphogypsum to the deposit site via dry process – The Skhira City Unit

3. STUDY OF SFAX PHOSPHOGYPSUM EMBANKMENT DEPOSITED USING WET PROCESS

In 2012, the PG deposit of Sfax which covers 53Ha was almost 56 m of height and 32°of slope. A study carried out by the National Engineering School of Tunis (ENIT) had led to focus on the embankment stability and identify the maximum height that can be reached without getting damaged. The study was based on the geotechnical site investigation consisting in realizing a destructive hole (SD) of 55m of depth, 3 "pressuremeter" holes (SP1, SP2 and SP3) of respective depths: 60m, 42m and 42m, 2 boreholes (SC1 and SC2) of 10m of depth each, Lefranc water test, SPT tests and extraction of intact samples from different depths to be identified in the laboratory (Bouassida, 2012).

3.1 Geotechnical Aspect of Sfax Embankment

The reported investigation permitted to identify the geotechnical profile of both of the embankment and its ground surface. In fact, according to the holes SD and SP1, the embankment presents two different horizons; an upper layer of 8m of thickness, with a cohesion evaluated at 10 kPa and a friction angle of 32°, while the lower layer (relying on land) cohesion is 4 times higher than the upper one. The pressure meter tests carried out as 1 test per 2 meters showed that the pressuremeter modulus of the lower layer is 3 times higher than the upper layer one. The results are illustrated in Table 1.

Table 1 Mechanical characteristics of Sfax Phosphogypsum embankment (Bouassida, 2012)

Layer	**Thickness (m)**	**C (kPa)**	**φ (°)**	**$E_{m\ average}$ (MPa)**	**Pl* $_{average}$ (MPa)**	**N_c**
Upper	8	10	32	49	2.31	15
Lower	48	41.2	32.3	124.2	3.98	21

N_c: Corrected number of blows

Available geotechnical properties of the ground surface of Sfax plant were the averaged Menard's modulus, Em and the limit net pressure Pl* given in Table 2. Pressuremetermodulus ranges from 9.9 MPa in surface to 143.2 MPa in depth. Due to those enhanced characteristics, the ground surface is assumed as a rigid stratum.

Table 2 Pressuremeter characteristics of the ground surface of Sfax Phosphogypsum embankment (Bouassida, 2012).

Layer N°	**Thickness (m)**	**$E_{m\ average}$ (MPa)**	**Pl* $_{average}$ (MPa)**
1	8	9.9	1.17
2	8	24.6	1.89
3	8	16.6	1.55
4	16	143.2	4.04

3.2 Grain Size Analysis and Settlement Estimation

The granulometric analysis showed that Phosphogypsum is a coarse-grained to fine soil with a significant fine percentage when going in depth. Two main reasons are behind this particle size distribution; the first one is the deformation of the grains themselves under the strengths they apply on their contact points, the second is the reduction of the void ratio by re-messes of grains while the embankment elevation is progressing. Terzaghi and Peck correlation (1948) was used to determine the embankment settlement while supposing that it was constructed in four steps: three layers of 8m and last layer of 16m thickness, respectively. After correction, the settlement was approximately equal to 0.86m (Bouassida, 2012).This settlement is almost the double of the Tunisian Ghezala dam settlement (which approximated 0.45m after 26 years of service) founded on a compressible marl formation resting on calcareous stratum that is considered as an impervious and non-compressible layer (Karoui and Bouassida, 2015).

3.3 Estimation of Maximum Embankment Height

The highest elevation of the Phosphogypsum embankment of Sfax was estimated by using Flac 6.0 software; two conclusions were drawn: The mechanical characteristics of the upper layer (φ = 32°, c = 10kPa) allow extending height by 10m yet. A height of 100m can be reached if the embankment gets reinforced by geotextile layers, a technique that was actually the objective of the study carried out in 2013 dealing with the dry deposition process (Bouassida, 2012).

4. STUDIES OF SKHIRA PHOSPHOGYPSUM EMBANKMENT DEPOSITED USING DRY PROCESS

The dry embankment of Skhira knew considerable extensions in terms of area and height. Nowadays, it covers an area of 112Ha on ground surface. Over time, increasingly degradation is yet observed, therefore threatening its stability. Hence, two different studies were carried out to focus on this aspect in 2007 and 2013.

4.1 Geotechnical Aspect of Skhira Embankment

Up to 2007, the PG deposit of Skhira presents two different levels of almost 25m and 55m of height and a slope varying between 1/4 and 2/3. The geotechnical profile of the ground surface reveals 4 horizons which characteristics are shown in Table 3.

Table 3 Geotechnical profile of the ground surface under the Skhira Phosphogypsum embankment (Bouassida, 2007)

Layer	Th* (m)	ω (%)	γ (kN/m³)	C_u (kPa)	C_c	e_0	$φ_u$
Gypsums silt	18	20	19.7	345	0.07	0.62	34°
Clay loam	2	20	19.6	345	0.07	0.62	34°
Sand	5	-	-	-	-	-	-
Clay loam	5	23	19.6	90	0.21	0.66	35°
Th*:Thickness							

There is no problem in relation with the ground surface bearing capacity as a Factor of Safety of 2 is obtained for an elevation of 100m of height, a unit weight γ of 19.7kN/m^3, an undrained cohesion and friction angle of c_u = 85 kPa and $φ_u$ = 31°.

The embankment slope stability was verified by TALREN software (version 4 v 3.1) using Bishop's Theory. This allowed following the Factor of Safety while varying the embankment height and slope and revealed that the embankment can reach 60m of height with a slope of 2/3 and a Factor of Safety F = 1.3. The estimated maximum height was 70m with a slope of 1/2 (Bouassida, 2007).

4.2 Settlement Estimation

The ground surface and the embankment settlements were estimated using consolidation Terzaghi's equation and linear elastic formula, total settlement varies from 4.72 m to 4.91m (Table 4).

Table 4 Settlement estimation of the Skhira embankment and ground surface (Bouassida, 2007)

Height (m)			10	20	30	40	50
Settlement (m)	Embankment		0.56	1.12	1.68	2.24	2.8
	Ground surface	SCT2	1.12	1.42	1.63	1.79	1.92
		SCT3	1.19	1.53	1.77	1.95	2.11

Hence, important settlements are predicted, caused essentially by the embankment's weight. Nevertheless, this settlement can be reduced when the embankment is reinforced by geotextile layers. This option was studied in 2013 for embankments deposited using dry process.

4.3 Estimation of Maximum Embankment Height

A study was carried out in 2013 using Plaxis numerical modeling to determine the maximum height that can reach the Skhira dry Phosphogypsum embankment when being reinforced by HDPE layers from different elevations (Chaari, 2013). Mohr-Coulomb's failure criterion was adopted for the numerical modeling. No available justifications of the methodology for slope stability analysis, parameters chosen and the sensitivity of the parameters are available. This part is missing in the reported study (Chaari, 2013).

It supposes that the Phosphogypsum embankment is resting on a ground surface composed of 4 layers and that the embankment has 140m height. The deposit is modelled as a superposition of 3 respective layers from the top-down: PG(1), PG(2) and PG(3) in such a way that each one presents different mechanical characteristics inspired from previous studies (Figure 3).

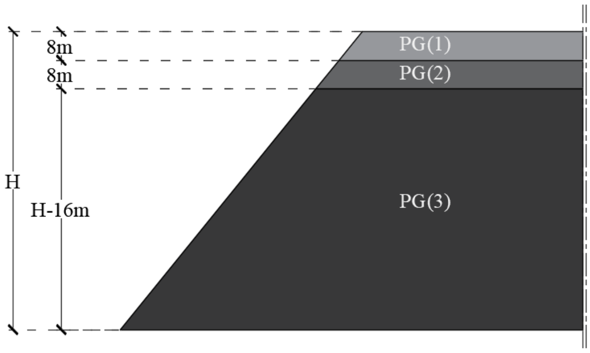
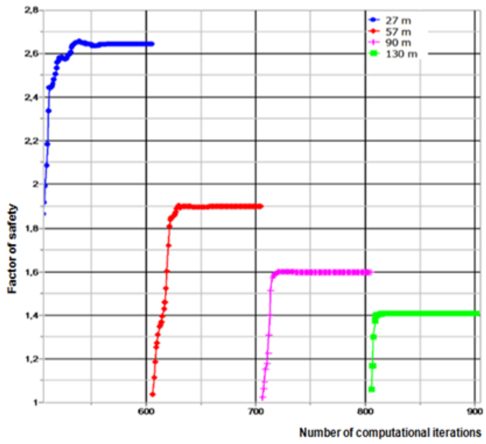


Figure 3 The three layers PG(i) of the dry deposited embankment at Skhira City (Chaari, 2013)

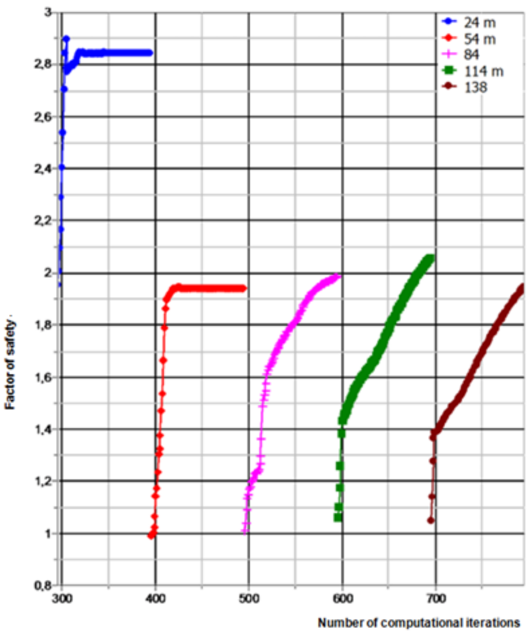
The TCG experience showed that each year, the Phosphogypsum embankment height increases by 4m. From a loading stage (n) to another (n+1), an amelioration of the mechanical characteristics of the layer (n) happens. From (n+1) to (n+2), the mechanical characteristics of the layer (n+1) get improved, those of the layer (n) also increase and over time, the layer (n) get integrated into the layer (n-1) (Chaari, 2013). In what follows, the study assumes a fixed height of 8m for each of the layers PG(1) and PG(2) and a variable height increasing at increments of 8m from a design sequence to another where a design sequence corresponds to a loading phase. Three cases were investigated: the first one refers to unreinforced embankment. The second case corresponds to reinforced embankment from 55m height. The third case refers to reinforced embankment from its basis.

4.3.1 Unreinforced Embankment (case 1)

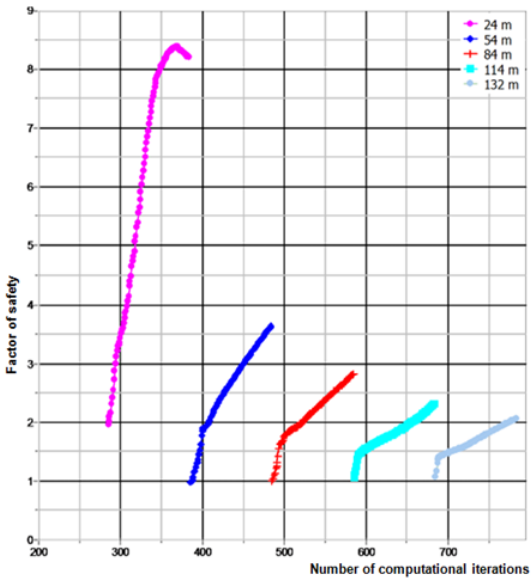
For this case, four embankment heights were considered: 27m, 57m, 90m and 130m. Plaxis simulation showed that an embankment of 130m height with a slope of 2/3 can be built without risk instability with a Factor of Safety F1 = 1.4 (Figure 4a).The resulting settlement approximating 2.6m was predicted with a maximum horizontal displacement at the embankment basis with a rate of 0.37m (Figure 5a).



Case 1. Unreinforced embankment

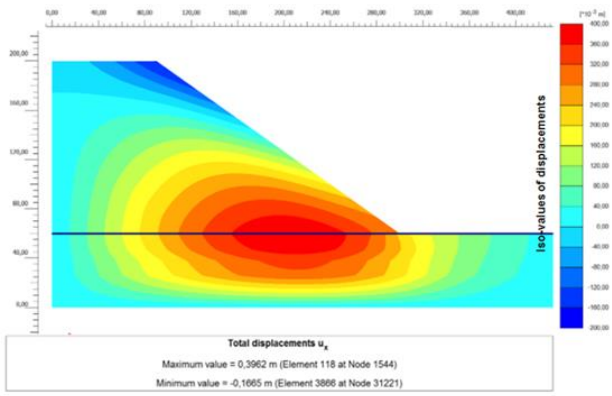


Case 2. Embankment reinforced by HDPE layers from 55m of height

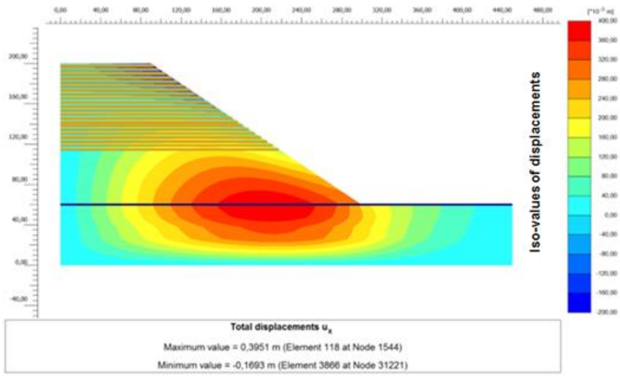


Case 3. Embankment reinforced by HDPE layers from its basis

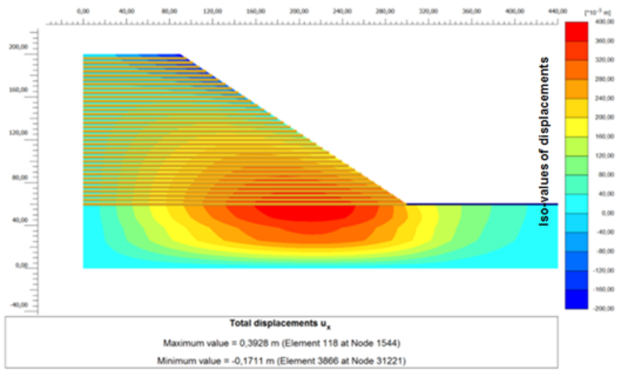
Figure 4 Factor of Safety vs. computational iterations for varied embankment height, cases 1, 2 and 3, (Chaari, 2013)



Case 1. Unreinforced embankment



Case 2. Embankment reinforced by HDPE layers from 55m elevation



Case 3. Embankment reinforced by HDPE layers from its basis

Figure 5 Iso-values of horizontal displacements within PG embankment of 140m height: Cases 1, 2 and 3, (Chaari, 2013)

Compared to the 2007 study, it is clear that due to the increase in the Factor of Safety by 0.1, the embankment height got almost doubled. This gap was explained by the manual design cumulated errors and the high Factor of Safety demanded by Plaxis software, although similar results were obtained when the GeoStudio Slope software was used (Chaari, 2013).

4.3.2 Reinforced Embankment From 55m Height (case 2)

For this case, five embankment heights were considered: 24m, 54m, 84m, 114m and 130m. The incorporation of High-Density Poly Ethylene (HDPE) layers of stiffness modulus equals 19MN/lm at increments of 4m from 55m of height was expected to ameliorate the reported Factor of Safety by 35% (F2 = 1.9) (Figure 4b). It is noted that such reinforcement has no significant effect neither on the settlements nor on the horizontal displacement compared to the unreinforced embankment case (Figures 5a and 5b).

4.3.3 Full height Reinforced Embankment (case 3)

In order to characterize the layers behavior as well as their eventual contribution to the settlement and horizontal displacements reduction, a third case was mentioned. The studied model was identical to the second case with reinforcement by HDPE layers of identical characteristics from the embankment basis by 4m increments. Five heights of embankment were considered. The results obtained by Plaxis software provided quite higher Factor of Safety F3 = 2.06 compared to F2 = 1.9 (Figures 4b and c).

However, this confirms the hypothesis that Phosphogypsum mechanical characteristics increase by time and that the PG(3) layer's Young module which is of 194 MPa is reliable to ensure the embankment stability. Failure risks are rather probable in the superior 16m of the deposit (PG (1)), in whatever construction level of the embankment (Figure 3).

From a mechanical concern, this simulation proved an excellent adhesion at the embankment-HDPE layer interface characterized by equal displacement components.

4.4 Study Main Outcomes' and Limits'

It could be concluded that the embankment reinforcement using HDPE layers has not any effects on the settlement and the lateral displacement and remains insignificant at the bottom of the deposit where Phosphogypsum already acquired the mechanical characteristics of a stratum. The incorporation of HDPE layers from 55m in height provides higher Factor of Safety which allows very high embankment.

Nevertheless, this reinforcement using HDPE layers is limited by three main factors: First, the Tunisian Phosphogypsum pH is found to be of 2.9 (Ajam et al., 2009) and about 3 (Felfoul et al., 2002a). This high acidity of Phosphogypsum affects the integrity of HDPE layers. Although, it was proved that it increases by time as it is of 2.63 outlet filter, 2.96 when Phosphogypsum is aged 10 years and 3.24 when has been stored for 50 years (Felfoul et al., 2003). Second, because of the accumulation of Phosphogypsum by storing, the thickness of layer PG(3) is in a continuous increase.

Each Phosphogypsum discharging cycle defines a new thickness of this layer and the layers PG(1) and PG(2) (the upper 16m of the embankment) are always active. Over time, there will be an accumulation of HDPE layers partially included into the layer PG(3) which is assimilated to a stratum and does not require any reinforcement (Figure 3). Third, the study did not take into consideration the observed cracks within the embankment as reported by TCG engineers. So, these results cannot be achieved in reality unless the deposit procedure might be improved.

5. PERFORMANCE OF EMBANKMENT MONITORING

The variation range of Tunisian Phosphogypsum chemical composition as presented by the TCG in 1995 is shown in Table 5 (Belaiba et al., 2004). In 2017, The Skhira plant laboratory provided a recent chemical analysis of the dry deposited Phosphogypsum composition that showed slightly different results, compared to the previous ones (Table 5). In fact, the chemical composition of Phosphogypsum depends on the origin of the phosphate or the manufacturing process, the efficiency of the plant and the age of the deposit (Choura et al., 2015). These characteristics evolve over time like the soluble P_2O_5 which content increases as the PG gets older due to rain wash for example (Felfoul et al., 2003).

Table 5 Tunisian Phosphogypsum chemical composition

Element	Content (1995) - Tunisian PG	Content (2017) – Tunisian dry deposited PG
P_2O_5	0.063 – 0.197%	1.5 %
CaO	31.9 – 32.14 %	32 %
SO_3	44.58 – 44.75 %	44 %
SiO_2	1.73 – 2.27 %	1.8 %
Al_2O_3	0.13 – 0.16 %	0.1 %
Fe_2O_3	0.09 – 0.10 %	0.05 %
MgO	0.01 – 0.02 %	0.01 %
Na_2O	0.12 – 0.16 %	
K_2O	0 - 0.01 %	
F	0.6 – 1.2 %	1.5 %
Cd	23 – 35 ppm	
Organic C	0.33 – 0.64 %	0.8 %
Water content	20 - 35 %	32 %
%: Percentage by weight		

The nature and characteristics of the resulting Phosphogypsum are strongly influenced by the phosphate ore composition and quality (Sahu et al., 2014). Hence, Phosphogypsum is considered to be radioactive as it derives from the naturally radioactive phosphate ore. This radioactivity is due to the radium content coming from the natural decomposition of uranium. The USEPA has classified Phosphogypsum and rock phosphate as ''Technologically Enhanced Naturally Occurring Radioactive Materials'' (TESTANDARD) and Phosphogypsum exceeding 370 Bq/kg of radioactivity has been banned from all uses by the EPA since 1992 (Sahu et al., 2014). For the Tunisian Phosphogypsum, The238U and 232Th activities (47 Bq/kg and 15 Bq/kg) areas low as the average concentrations of these radioelements found in Tunisian soil sand thus do not present any risk for the environment. The activity of the 226Ra found in Tunisian PG (215 Bq/kg) remains lower than those found for the majority of PGs (Ajam et al., 2009).

The color of Phosphogypsum is dark at recent age. Its unit weight evolves as it gets drained and self-weight compacted and its specific unit weight is of 23.1kN/m^3. Its specific color and odor as well as its low specific unit weight reveal the presence of organic matter. These properties are comparable to those of the Tunisian marine Sediments of Gabes harbor (Υ =15.2 kN/m^3, Υ_s=22.5 to 24.6 kN/m^3) and Rades harbor Sediments (Υ =17.7 kN/m^3, Υ_s=25.5 to 25.7 kN/m^3), BelHadj Ali et al. (2014).

The mechanical characteristics of the wet deposited Phosphogypsum over time were studied basing on three specimens: SP1: outlet filter, SP2: aged 10 years and SP3:aged 50 years (Felfoul et al., 2003). The specimens SP2 and SP3 are superficial. The study proved that the best bearing capacity was obtained for SP2 (CBR=51% compared to 49% and 5% for SP3 and SP1 respectively) as well as for the best shear strength(c=73kPa and φ=37°). The greatest part of the compressive and the tensile strengths were developed by the 15 first days of Phosphogypsum deposition with a better mechanical performance and behavior to water for the specimen SP2. The study was based on the strength's ratio defined as the ratio of the strength (compressive or tensile) after immersion to the strength without immersion. This ratio was null immediately after immersion and stills so for SP1 even 120 days after immersion. This indicates a very bad behavior to water of the fresh Phosphogypsum. For SP2, the strengths ratio got improved for 1.13 to 1.36 times 24 hours after immersion and doubled after 5 days. This indicates that as a result to the bad weather, the strengths fall but can get improved by time. This good behavior to water is explained by the high cohesion of the Phosphogypsum at a young age (SP2: c=73kPa, SP1: c=53kPa and SP3: c=50kPa) (Felfoul et al., 2003). For the specimen SP3, the strengths got through an optimum at 28days of the sample's preparation. However, the strengths ratio decreased with the age. The fresh Phosphogypsum wash allowed improving the compressive strength which reveals that the decrease in acid and organic contents enhances the compressive strength of Phosphogypsum. Hence, the chemical evolution of Phosphogypsum is behind the variation of its mechanical characteristics rather than its age (Felfoul et al., 2003).

Performance monitoring of the dry embankment is not mentioned in the bibliography, there are only observations deduced from field visits carried out in March 2017. In fact, when deposited under the conventional water content (30-32%), a clear heap form is obtained. The Phosphogypsum starts to dry and local subsidence are observed at the foot of the heap (Chaari, 2013). The deposition of Phosphogypsum with a water content ω> 30-32 % results in slides at the top of the deposit assimilated to mud-flows. The material behaves like a liquid and the flows increase as the deposited quantity of Phosphogypsum increases. Undulations reaching the foot of the embankment are observed instead of the heaps. One day later, water seepage and horizontal cracks appeared (Figure 6).

The deposition of Phosphogypsum at a high-water content (ω>>> 35%) resulted in a big puddle of water at the top of the embankment (deposition line C) where the Phosphogypsum particles got settled. Important clear water seepage was observed by this deposition line.

Figure 6 Phosphogypsum deposited with a water content ω > 30-32 %

A similar phenomenon occurred in the deposition line B where there was deposition of Phosphogypsum with very high-water content according to the TCG. The water was so abundant that it was impossible to install a belt conveyer there as it did sink into the ground. Hence, the deposition line was redirected and a drainage ditch of 1m of depth was digged among the area. The water seepage has been observed for more than 4 months which proves the presence of water retained into the embankment body. Ata larger scale, experience with dry storing indicates that the lower layer of the embankment will be saturated even in desert, in arid climate and without rain infiltration due to gypsum self-weight consolidation and settlement (Fuleihan, 2012).This occurs to some extent in all dry stacks even when Phosphogypsum is well filtered (ω << 25%).

6. COMPARATIVE STUDY BETWEEN THE WET PROCESS AND THE DRY PROCESS DEPOSITION

A comparative study is launched to focus on the reliability of the wet and the dry deposition processes. The study concerns 6 successive years of phosphoric acid (P_2O_5) production ranging from 2005 to 2010 and focuses on the parameters affecting the cost of PG storage.

6.1 Parameters and Data Used

The existing embankments in Sfax and the Skhira Cities areas and contents are shown in Table 6. In what follows, "X" designs the dry discharge of the Skhira City and "Y" the quantity of stored Phosphogypsum in the same area till 2010. The TCG experience shows that an area of X Ha can receive 1.76Y Tons of PG if proceeding using the wet deposit process, which means a win of 76% on the stored quantity.

Table 5 Stored Phosphogypsum tonnage and discharge areas for Sfax and Skhira embankments till 2010

		Wet process	Dry process
		SFAX	SKHIRA
Discharge area	Ha	53	112
Stored PG quantity till 2010	T	36 798 300	42 021 000
Stored PG quantity by m²	T/m²	69,431	37,519

Wet process has always been known less safe to land and ground water as almost 64% of dumped water is either evaporated or infiltrated in the soil underneath (TCG, 2014). However, due to the use of geomembrane, an important portion of the evacuated water can be drained and reused in the industrial process. Like so, even if the water consumption in the wet process is almost 6 times the dry one (Table 7), this seems to be less dangerous than the dust emission which is inevitable in the dry process and which causes air pollution and disturbs habitations near the production site. The water recovery does not only save the environment, but also has an effect on the industrial efficiency: According to the last statistics given by the TCG's phosphoric acid production units, this effect in the wet process ranges from 0.5% to 1% while it is of0.42% only in dry process. This makes clear that the water losses are quite high for the dry process, it reduces the industrial efficiency, and the recuperate water quantity for reuse in the factory as well.

Table 7 Water balance for the wet and the dry depositing processes (TCG, 2014)

	Water consumption	Recovered water percentage
	$m^3/T(P_2O_5)_{produced}$	%
Wet process	13.5	31-36
Dry process	2.4	25

The previous studies focusing on the stability of the embankment of the Skhira City show some limits of the dry process of a geotechnical concern (Table 8). In fact, according to the 2007' study, the embankment settlements due to its own weight were estimated about 2.8 m, resulting in a total settlement varying between 4.72m and 4.91m in the tested points against a maximum of 0.86m only in the wet embankment of Sfax (Bouassida, 2012).

Table 8 The dry and the wet embankments properties

Embankment deposited by	Dry process (Bouassida, 2007) and (Chaari, 2013)			Wet process (Bouassida, 2012)		
Area (Ha)	112			53		
Height (m)	2 levels: 25 and 55			56		
Mechanical characteristics	Height (m)	c (kPa)	φ (°)	Height (m)	c (kPa)	φ (°)
Layer 1 (upper)	8	90	30	8	10	32
Layer 2	8	97.2	30	48	41.2	32.3
Layer 3	H (*)-16	104.4	30			
	(Chaari, 2013)					
The whole embankment	H	85	31°			
	(Bouassida, 2007)					
Total settlements (m)	4.72 – 4.91			0.86		
Horizontal displacement (m)	≈ 0.4			insignificant		
General aspect	• More damaging settlements and displacements apart from the cracks and the slope instability			• Regular top and slope • Better mechanical behavior of the embankment and the ground surface		

H (*): height of embankment at arbitrary elevation of its deposition

The Tunisian Phosphogypsum embankments are not instrumented. Hence, no actual measurements are available to follow up the settlement measurements. The settlement of an instrumented experimental Belgium Phosphogypsum embankment was followed-up during 30 months (Gorlé and Reichert, 1985). The embankment is 5.2m of height and 50000m^3 of volume and is executed by compaction of consecutive layers of Phosphogypsum of 0.2m of thickness. After two years follow-up, the embankment settlement is still progressing while the settlement of the ground surface and the sand layer underlying the embankment is maximal after 6months. The extrapolation of the results over a ten-year period at linear and logarithmic scales gives 0.2m and 0.06m respectively (Gorlé and Reichert,1985) and1.17m over 61 years. Predictions using Terzaghi et Peck correlation (1948) indicate the wet deposited embankment of Sfax City should settle by 0.86m since its construction to current time (1952 – 2012) (Bouassida, 2012). Differences between experimental and numerical results are argued as follows:

- The instrumented embankment is executed through Phosphogypsum compaction; it does not result from the conventional Phosphogypsum deposit processes.
- The results extrapolation does not take into consideration that over time, the settlement slows down.

Besides, both of the two studies do not take into consideration the deposit cycles.

A better stability was obtained for the wet embankment with a slope of 2/3 and with a Factor of Safety of 1.02 in opposition to 1/4 in some sensible parts of the dry one under a factor of 1.3 (Bouassida, 2012).

Hence, the mechanical characteristics of Phosphogypsum are best performing in the wet process than the dry one, it gives better results with regular top and slopes and provides better mechanical behavior of the embankment and the foundation than the dry one. The settlements and displacements are much more significant in the dry process, apart from the cracks and the slopes instability problems.

The TCG experience shows that the stops rate by breakdowns is of just 0.01% for the wet process while it is of 3.83 % for the dry one. Therefore, the Phosphogypsum embankment of the Skhira City needs a lot of care and reparation, its maintenance cost is higher than the wet deposited embankment case (TCG, 2014).

6.2 Main Results

Based on the reported reasons and on the TCG staff's know-how and experience, it is clear that the wet process is more advantageous than the dry one. In fact, depositing Phosphogypsum using wet process allows stacking almost 76% of PG more than when using dry method. In addition, although the wet process is 6 times more water consumer, it allows a better recuperation of soluble P_2O_5, which is translated by an effect on the industrial efficiency ranging from 0.5% to 1%. Besides, there is almost no shutdowns caused by the circuit breakdowns in wet process, the production is only stopped for the planned maintenance periods and it mobilizes a fewer staff. By consequence, the maintenance cost in wet process is around 20% of the cost in dry process.

For the geotechnical behavior, one obtains an enhanced stability for the embankments deposited by the wet process with better strength characteristics (cohesion and friction angle), less settlements and horizontal displacements as well as uniform slopes and top.

For all these reasons, the TCG is oriented to adopt from now on the wet process to stack its residues and is planning to modify its equipment in the Skhira factory and replace it by a wet process circuit.

7. CHALLENGES AND PERSPECTIVES

This paper highlighted the problematic challenges faced by Phosphogypsum Tunisian authorities. The wet and dry embankments show two different mechanical behaviors.

The previous studies make clear a better slope stability and fewer settlements and displacements for PG deposited via wet process where the embankment can be elevated to almost 70m and can reach 100m once reinforced by geotextile layers. In contrast, dry process results in a damaged embankment profile, important settlements and horizontal displacements, and cannot exceed 100m in height without reinforcement by HDPE layers. Hence, wet process is well recommended to ensure better interaction between the embankment and the ground surface and to allow stocking almost 76% over of PG without the risk of getting damaged once important heights are reached.

Added to the industrial benefits of the wet process, this indicates that the TCG factory of the Skhira City would rather convert its deposition process into the wet one. This means that the existing embankment of the Skhira City is expected to receive at its top a new stack deposited using the wet process such as slurry.

Land optimization is essential and the deposition of PG slurry under the existing dry embankment is an eventual solution unless no new deposition site could be provided in very brief delays. It must therefore be recognized that the mechanical behavior of the dry embankment of the Skhira City should be characterized once it is a support for the new stack deposited using wet process.

Based on the previous studies, nothing guarantees that the dry embankment can really support this slurry without getting destroyed as until now there is no idea about neither the deep of the cracks covering its top nor if they are connected to each other. The drillings occurred in the study of 2007 show the presence of some water horizons in the middle of the dry embankment. Field persons from the TCG reported that cavities full of water were observed in the embankment body and that the water content there was superior to the content at the moment of rejecting Phosphogypsum which makes one wonders if the water infiltration in the existing embankment could make worse the situation.

Furthermore, when dealing with the wet process, there must be at least two decantation basins essential for the wet method functioning. In dry process, experience shows that a bulldozer cannot move above Phosphogypsum just rejected from the filter, it has to wait for 2 or 3 days till the PG hardens and during this period it becomes yet resistant to be flattened. Even if, it is not evident that the deposited water will follow the gravity and escape from the drainage point, knowing that the support is dry and porous compared to a wet process deposited basis.

The simulation of the mechanical behavior of the complex dry embankment–slurry as support–deposit is required to characterize the problem and judge if any reinforcements are required before applying this solution to overcome this challenge unless no new deposition site could be provided. For this purpose, an experimental study was carried out to characterize the studied Phosphogypsum.

7.1 Specimens Extraction

Two specimens (S1) and (S2) were extracted in 2017 from the existing dry embankment of Skhira City at 1.2m of deep from two different sites (Figure 7): (S1) is located in the South-East part of the embankment at almost 35m of height. It was deposited since 2013; the site presents cracks of variable sizes. (S2) is located in the center of the embankment at almost 60m of height, and has been deposited since 2012. It has a similar aspect to the first site (S1).

a. (S1)

b. (S2)

Figure 7 On site extraction of PG specimens a. (S1) and b. (S2)

The Specimens were stored in closed plastic bags to conserve their hydraulic properties (Figure 8).

Figure 8 Specimens (S1) and (S2)

7.2 Geotechnical Characterization

Geotechnical characterization of Tunisian Phosphogypsum includes the determination of classical soil properties as water content, grain size distribution, Atterberg limits, Methylene Blue Value and unit weight.

As Phosphogypsum contains organic matter (Table 5) which gets deteriorated from 50°C (XP P 94-047), and as gypsum desydratation can start from 40°C, gets accelerated at 60°C and it starts to waste from its constitution water at 105°C (Vieillefon, 1978), water content was determined by the desiccation of samples at 50 °C till weight stabilization, obtained after 8 days (XP P 94-047). Grain size distribution was carried out by the dry sieve method followed by the hydrometer method (Analyse granulométrique par sédimentométrie., Février, 1987). Atterberg limits were performed on the fraction ≤ 400µm by the Cone penetrometer (NF P 94-052-1) and the rolled thread method (NF P 94–051). Methylene Blue Value (MBV) was determined according to the NF P 94–068 standard.

7.3 Experimental Results

Water content of the specimens (S1) and (S2) are respectively 20.88% and 21.84% while Phosphogypsum was initially deposited at a water content of 30%. The reduction of water content is due to Phosphogypsum age, as it was abandoned and was subject to weathering effects. The little difference between the water content of (S1) and (S2) is explained by the fact that the first site (S1) is older than second one (S2).

The solid unit weight of Phosphogypsum is of 2.31 g/ cm^3, which is close to the natural gypsum specific unit weight (2,3 g/ cm^3).

According to the TCG-Skhira factory, the maximum grain size of Phosphogypsum outlet filter is of 2mm. Obtained sieve residue on a 2mm sieve even in little quantities (1% for (S1) and 2.2% for (S2)) can be argued as follows: either there was a grinding defect before starting the test, or Phosphogypsum got self-compacted due to its self-weight and weathering effects. However, the second explanation is more realistic as it confirms that Phosphogypsum tends to acquire enhanced characteristics over time (Chaari, 2013).

Grain size distribution showed that Phosphogypsum is slightly clayey sandy Silt for (S1) and is silt sand for (S2) (Figure 9).

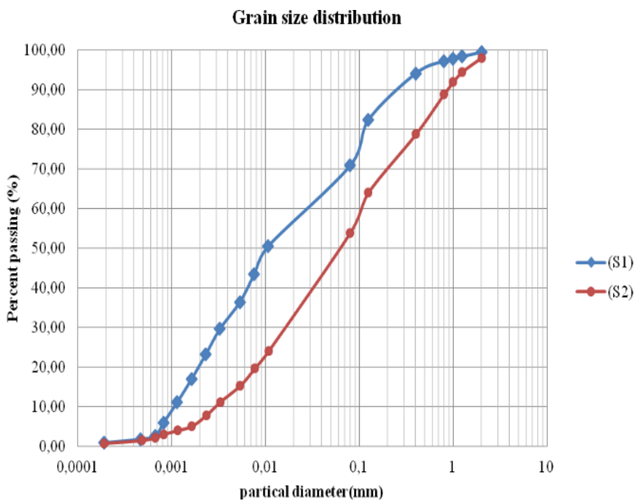


Figure 9 Grain size distributions of specimens (S1) and (S2)

According to literature, Tunisian Phosphogypsum, generally deposited using wet process, alternates between sand and silt. In fact, its grain size distribution is similar to silt (Moussa, 1982), it is classified as fine sand on surface and silty sand in deep (Bouassida, 2012). Although, it should be noticed that the hydrometer method showed Phosphogypsum coagulation at the bottom of the test tube (Figure 10).

Figure 10 Phosphogypsum coagulation at the hydrometer tube

Similar observations were obtained when studying gypsum effect on laboratory tests and foundations (Salhi et al., 2013). The same problem was faced when carrying out Atterberg Limits which were not practical and lead to interrupted tests (Figure 11). The non-feasibility of Atterberg Limits is explained by the high content of sand and gypsum in the considered soil (CaO: 32%; SO_3: 44%) (Table 5).

Figure 11 Non-feasibility of Atterberg Limits

The MBV values are respectively of 0.075 and 0.02 for (S1) and (S2), which are very low. However, according to the GTR 92 (LCPC –SETRA., 1992) and the French Standard NF P 11 300, as the fine percentages are widely greater than 12%, Phosphogypsum is not classified as water non-sensitive soil.

7.4 Characteristics of Phosphogypsum Adopted for the Numerical Study

A numerical study is currying out using both of Plaxis and Midas software to focus on the mechanical behavior of Phosphogypsum once it is deposited using wet process at the top of the existing dry embankment. Mohr-Coulomb Criterion is adopted in this study and the deposit process is simulated while considering the construction stages of the conventional Phosphogypsum wet deposit processes. It supposes that the wet deposited embankment presents 3 decantation basins such as each exploitation cycle lasts for 4 months (corresponding to one cycle/ basin/ year).

Based on the previous studies and the reported experimental tests, it is concluded that Phosphogypsum presents evolving characteristics depending on its deposit process, age, chemical composition, physical and mechanical characteristics. Hence, the numerical modeling assumes that from a deposition stage to another, the wet deposited Phosphogypsum expected to relay on the existing dry embankment of Skhira City goes over time through evolving characteristics PG I, PG II and PG III as shown in Tables 9 and 10.

Table 9 Physical properties of Phosphogypsum adopted for the numerical study

	γ_h (kN/m^3)	γ_{sat} (kN/m^3)	ω %	ω_{sat} %	S_r	e
PG I	13	15.7	$= \omega_{sat}$	57	1	1.33
PG II	15	17.13	20	37	0.54	1.02
PG III	17	18.03	20	28	0.72	0.65

The study considers that Phosphogypsum is initially deposited at a very low unit weight. PG I presents a loose state of Phosphogypsum (e = 1.33) with ω_{sat}=57%. The friction angle is negligible (ϕ=5°) and cohesion is c=25 kPa (Table 10). Four months later, it gets drained, Phosphogypsum is denser (PG II) (e=1.02), the friction angle gets higher (ϕ=15°) and the cohesion decreases to 20kPa (PG II) before it becomes 25 kPa (PG III) at a late time. Water content decreases to 20% and gets stabilized at this content while Phosphogypsum void index decreases to 0.65 for PG III. Young Modulus evolves from 2MPa to 3MPa than 8MPa for PG I, PG II and PG III respectively and Poisson ratio is of 0.3 at an advanced stage of Phosphogypsum deposit.

Table 10 Adopted mechanical characteristics of Phosphogypsum for the numerical study

	c (kPa)	**φ (°)**	**E (MPa)**	**ν**
PG I	25	5	2	0.35
PG II	20	15	3	0.33
PG III	15	20	8	0.3

8. CONCLUSIONS

In this paper it was shown that Tunisian Phosphogypsum embankments notably in Sfax City with 56m height, 53Ha area and 32° slope and in Skhira City with area of 112Ha and two elevations of 25m and 55m, respectively, present challenging structures in terms of critical heights and areas.

Comparative study between the wet and the dry processes of deposited PG can lead to 76% of additional stored quantity, a better effect on industrial efficiency, less circuit breakdowns and maintenance cost when depositing PG using the wet process. Based on maximum embankments heights, settlements, horizontal displacements, slope stability and environmental effects, the wet deposit process revealed more beneficial than the dry one. Hence, the conversion of the dry deposit process to the wet one in Skhira City is highly recommended and expected.

Taking into consideration the new projected deposit process, the deposition of PG slurry under the existing dry embankment of Skhira City is an eventual solution to optimize the specified storage areas.

A characterization of Tunisian Phosphogypsum was carried out based on the previous studies performed on the Tunisian Phosphogypsum embankments of Sfax and Skhira Cities as well as on the experimental tests focusing on physical characteristics of dry Phosphogypsum. It resulted that superficial PG is silty sand to clayey sandy Silt with a water content of almost 20% against 30% when initially deposited. Contrarily to the wet deposited Phosphogypsum as reported in the previous studies, Atterberg Limits tests were non-feasible because of the high content of sand and gypsum in the tested PG specimens.

In light of all findings, a recent numerical model permitted to study the mechanical behavior of the embankment while considering the construction stages of the conventional Phosphogypsum wet deposit processes. The numerical results for the prediction of the behavior of PG embankment are detailed in Karoui et al (2020).

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