RESEARCH ARTICLE OPEN ACCESS

Numerical Simulations of Residues Areas in different phases: Filling and Upstream Stacking

Sieira, A. C. C. F.*
**(Structures and Foundations Department, Rio de Janeiro State University, Brasil)*

ABSTRACT
Currently in Brazil, the deposition technique of bauxite residues provides an initial operation to discharge waste within artificial lakes, in a slurry form (wet disposal). After achieving the storage capacity of the reservoir and drying the waste, the embankment is raised by the upstream method. So, the slurry is discharged on top of a material which is undergoing a consolidation process. The prediction of bauxite wastes behavior is a challenge for geotechnical engineers, since these materials show a distinct response of the materials usually found in natural deposits. The present work aims at simulation of a bauxite residue area in different stages of operation: wet disposal and upstream, using a finite element program. The geotechnical parameters were defined according field and laboratory tests executed in the area. The numerical prediction was compared with the instrumentation field, located in different phases of operation. The results show the applicability of the numerical program in predicting the behavior of waste areas.

***Keywords* -** numerical prediction, residue areas, wet disposal, upstream.

I. INTRODUCTION

The deposition of industrial waste is a major challenge in geotechnical engineering, since these materials exhibit a distinct behavior of materials usually found in natural deposits.

The overall decrease in the number of waste disposal areas and the implementation of strict environmental legislation has created the need for maximum utilization of the existing deposition areas. The objective is to operate and handle the reservoirs so as to maximize the volume stored and, consequently, the useful life of these deposits.

Generally, the technique of waste processing bauxite operation deposition provides an initial operation of release waste (wet disposal), in artificial reservoirs (Figure 1). The reservoir life depends fundamentally on the geotechnical behavior of the residues, whose properties vary over time and depth in the light of simultaneous processes of consolidation and sedimentation [1].

After the exhaustion of the reservoir and drying the residue, the upstream method starts, increasing the useful life of reservoirs. In this method, the pulp is thrown on the waste pre-existing, which is in the process of consolidation, resulting in significant settlements in the residue foundation. The analysis of the settlements is complex, considering that the waste consolidation requires large strains. So, the use of classic theories of consolidation is not applicable.

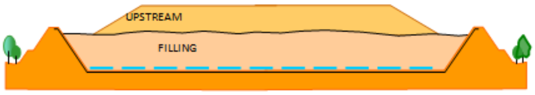


Figure 1. Waste Disposal Technique

II. RESIDUE AREA

The waste area has a storage capacity of approximately 4,000,000 m3. Initially, this area received the conventional technique wet waste disposal. After filling the reservoir, the area began to receive waste by the upstream technique. Among the filling phase and upstream phase, there is a period when the area does not receive waste. This period is important for the occurrence of drying and densification of the residue with subsequent resistance increase.

Figure 2 shows the typical cross section of the residue area at the end of the upstream operation. The area is composed of three distinct materials:

- Material 1: original dike of compacted soil;
- Material 2: 15.00 m layer of waste released by wet disposal technique;
- Material 3: 8.20 m layer of waste released by the upstream technique.

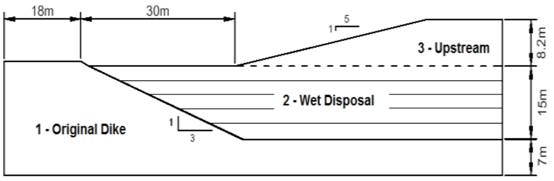


Figure 2. Typical Cross Section of the Residue Area [1]

The reservoir has a 15 m thickness. The filling was performed at a variable release rate of over time [2], and was performed in 2200 days (6 years approximately). The upstream operation was run in three consecutive stages of release of waste and consolidation time (Table 1).

Table 1. Stages of Upstream Operation

Stage	Layer thickness (m)	Time (days)	
		Construction	Consolidation
1	1.20	150	90
2	3.20	270	90
3	3.80	210	-

The waste area was instrumented during all implementation stages. During the filling, the bathymetric survey was performed in order to monitor the residue level in the tank over time.

During the upstream operations, the settlements were monitored. For this, settlements plates were installed throughout the area of waste.

Records of field instrumentation are presented in Section 4, together with the numerical predictions.

Figure 3 shows the residue area after filling the reservoir.

Figure 3. The Residue Area [1]

III. NUMERICAL ANALYSIS

The numerical simulation was accomplished with the Plaxis program, of finite element. The numerical results were confronted with the geotechnical field instrumentation, in order to verify the applicability of the program in analysis of the waste areas behavior.

Plaxis is a finite element program developed specifically for analysis of deformation and geotechnical stability. The analysis may consider the condition of plane strain or axisymmetric [3].

The finite element mesh is generated automatically, with elements of 6 or 15 nodes. After generating the mesh, the initial conditions of the problem are defined, taking into consideration the presence of water.

The calculation can be divided into stages in order to reproduce the constructive process in the field. Figure 4 shows the geometry adopted in the analysis. The layer of 15 m residue foundation (Material 2) was divided into five sublayers in order to represent the variation of the geotechnical parameters with depth. The upstream residue layer of 8.20 m (Material 3) was divided into 3 sublayers, to reproduce the various stages of release and the consolidation time established during the construction process (Table 1).

The dike of compacted soil (Material 1) was represented by elastoplastic model Mohr-Coulomb. This model is characterized by a linear elastic behavior until the rupture strength envelope defined by the Mohr-Coulomb. The adopted parameters are presented in Table 2.

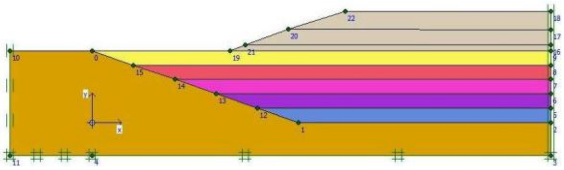


Figure 4. Geometry Adopted in Numerical Analysis

To representation of stack (Material 3) was adopted the linear-elastic model, which is defined only by the parameters of elastic material (E e □). The choice of this model aimed to represent the overhead imposed by the stack on the residue foundation (Material 2). This material also suffers densification by own weight, and the most representative constitutive model should consider the possibility of consolidation. However, given the complexity of the problem, we chose to neglect the deformations due to the consolidation of this material. The parameters of material 2 also are presented in Table 2.

The Material 2 was represented by Soft Soil Model. This model allows the reproduction of the deformations of soils of high compressibility and low permeability.

Table 2. Material Parameters: Dike and Upstream Stack

Material	Constitutive Model	Parameter	Value
Dike	Mohr-Coulomb	γ	19 kN/m^3
		E	50,000 kN/m^2
		ν	0.30
		c’	5kPa
		ϕ’	35º
Upstream Stack	Linear-Elastic	γ	16 kN/m^3
		E	2,000 kN/m^2
		ν	0.30

Note: γ = specific gravity; E = Young modulus; ν = Poisson ratio; c = cohesion; ϕ’ = friction angle

The residue parameters were defined from the laboratory tests performed in the waste area [4].

The experimental program consisted in characterization of the waste and determination of the compressibility and permeability, from a consolidation tests. Figure 5 shows the distribution of specific gravity with depth, determined from characterization tests. In the surface of the foundation, the specific weight has a value of 15.70 kN/m^3, increasing with depth up to the value 16.44 kN/m^3 in the bottom of the foundation. This distribution was represented in numerical analysis, as shown in Table 3.

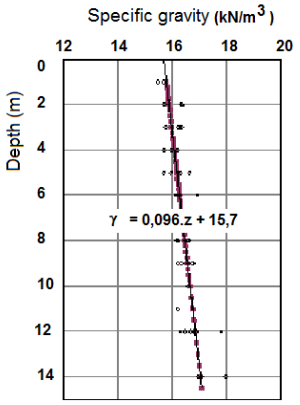


Figure 5. Distribution of specific gravity with depth

The test results of consolidation indicate a sharp drop in the values of voids at low effective stresses (Figure 5). Similar results in bauxite residues were reported in the literature [5, 6]. The values of compression index (C_c), ranged between 0.34 and 0.41, averaging 0.38.

Triaxial tests showed zero value for cohesion and friction angle equal to 40º. Table 3 presents the geotechnical parameters adopted for material 2.

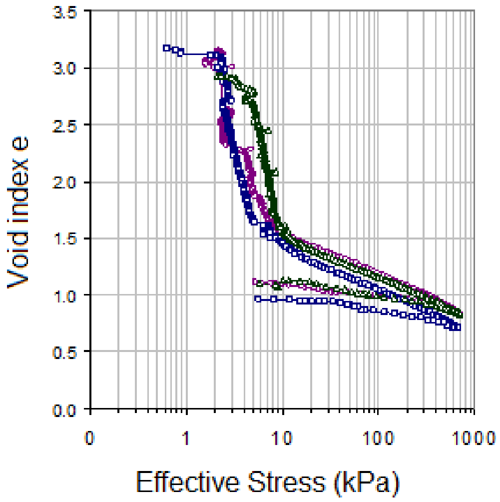


Figure 5. Consolidation Tests Results [4]

Table 3. Geotechnical Parameters: Material 2

z (m)	C_c	γ (kN/m^3)	e_o	k_y (10^{-6}cm/s)	k_x (10^{-6}cm/s)
1.5	0.38	15.88	2.17	1.95	2.15
4.5		16.19	2.05	1.73	1.91
7.5		16.50	1.92	0.15	0.17
10.5		16.80	1.79	0.14	0.15
13.5		17.10	1.67	0.12	0.13

3.1. Filling Phase

Figure 6 shows the phases included in the numerical analysis to simulate the filling of the reservoir. The insertion of each layer to waste time filling followed established in the project. The curve of residue height versus time provided by the program was compared to the bathymetry of the field.

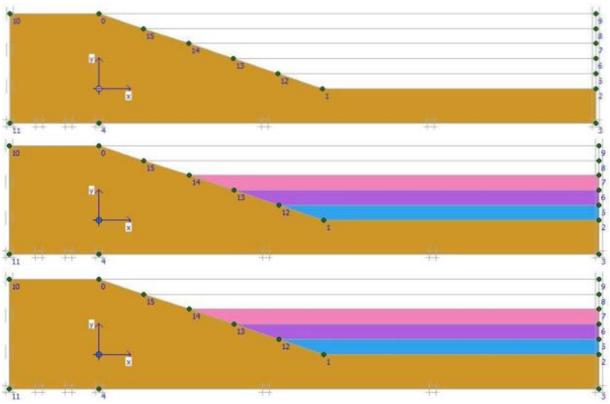
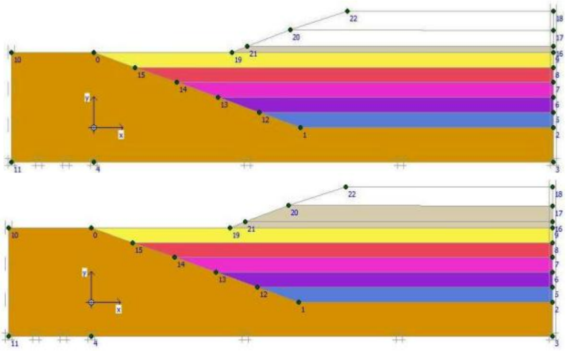


Figure 6. Filling Phases

3.2. Upstream Stacking Phase

Figure 7 presents the phases included in the numerical analysis to simulate the upstream stacking. This analysis considered the times of launch and consolidation given in Table 1.

The settlements provided numerically were compared with the field instrumentation results (settlement plates).



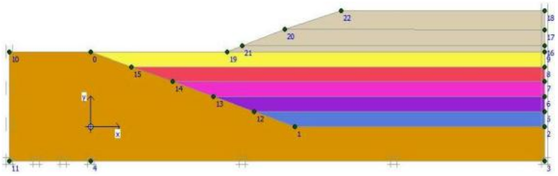


Figure 7. Upstream Stacking Phases

IV. ANALYSIS OF RESULTS

4.1. Filling Phase

Figure 8 compares the bathymetric results with the filling numerical results over time. There is a proper fit between the numerical predictions and experimental results. The lifetime reservoir difference between of the numerical and experimental results is 50 days. Small differences can be attributed to the methodology of field executive.

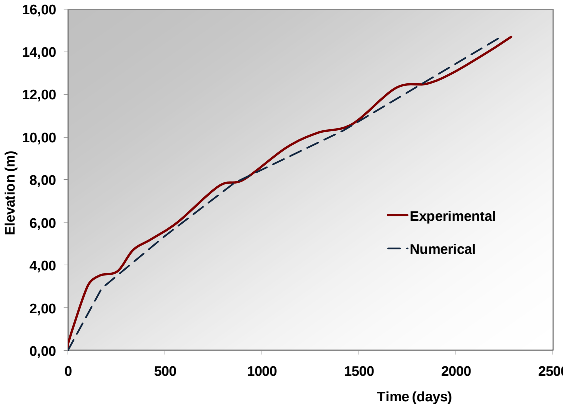


Figure 8. Filling: Numerical Results versus Experimental Results

4.2. Upstream Stacking Phase

Figure 9 shows the evolution of settlements provided by the Plaxis and the measurements of the settlement plates over a period of 800 days (27 months). The final settlement is expected to be 1.3 m, achieve in 10 years.

It can be observed that the values provided by Plaxis proved to be close to the average of the measured in the field. The numerical analyses provide 67 mm of settlement, after 800 days. The variability in the readings of the settlements plates can be attributed to non-uniformity of the deposition process of wastes in the reservoir area. Thus, one can assume that the release process adopted in the region of the plate PR-01 is fairly compatible with the sequence of design reproduced in the numerical analysis.

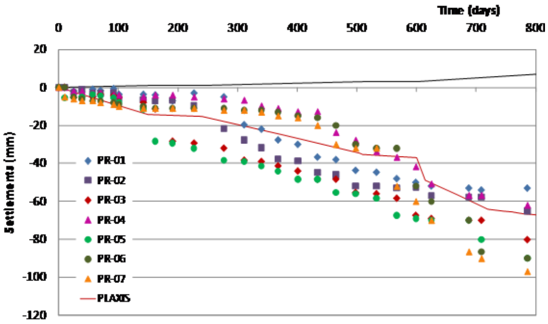


Figure 9. Evolution of settlements

V. CONCLUSIONS

This paper presented the numerical simulation of a deposition area of bauxite waste, during the phases of filling and upstream stacking, with a finite element program.

The representative parameters of residue were obtained from laboratory tests performed on samples collected in the area. The model was calibrated confronting numerical results with field instrumentation.

In the filling phase, the response of the program proved to be consistent with the results of the field bathymetry, with a difference of 50 days between numerical prediction and the actual filling. Given the complexity of the problem analyzed, this difference can be considered not significant and represents an error of 2%.

Numerical settlements were also consistent with those measured in the field. It is believed that the methodology adopted in the PR-01 region is reasonably compatible with the sequence established in the project, reproduced in the simulation.

The results of numerical analysis showed the applicability of the Plaxis program to reproduce the behavior of waste disposal areas during different stages of operation.

ACKNOWLEDGEMENTS

The author gratefully acknowledge the financial support for this work provided by the Brazilian Science Foundation's CAPES, CNPq and FAPERJ.

REFERENCES

[1] Lima, J. de (2008). Numerical Simulation of Residues Areas During the Upstream Operation. Dissertation. State University of Rio de Janeiro, 101p. (in portuguese).

[2] Costa Filho, L. M.; Pedrosa, S. B M; Sieira, A. C. C. F.; Silva, M. R P (2006). Behaviour of an upstream stack formed with geotextile wrapped dikes. 8th International Conference on Geosynthetics, Yokohama. v. 1. p. 1-1.

[3] Brinkgreve, R.B.J. (2002). Finite Element Code for Soil an Rock Analyses. PLAXIS -

2D user´s manual. Rotterdam, Netherlands, Balkema.
[4] Bedin, J., (2006) Interpretation of Piesozone Tests in Bauxite Waste. Dissertation. Federal University of Rio Grande do Sul. 150p. (in portuguese)
[5] Santos, P. S. (2000). Science and Technology of Clays.- V1, 2a ed., Ed. Edgard Blücher Ltda. (in portuguese)
[6] Villar, L.H.A. (2002). Study of Density and Drying of Waste Bauxite Mining & Processing. PhD Thesis, Pontifical Catholic University of Rio de Janeiro. 461p. (in portuguese)