The Influence of Inspection and Monitoring on the Phased Construction of the Barragem de Cerro do Lobo

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SYNOPSIS. The SOMINCOR S.A. Neves Corvo mining complex is located near Castro Verde in southern Portugal. The mine commenced processing copper and tin ores in 1988, the storage capacity for the resulting residues (tailings) and process water supply being provided by the Barragem de Cerro do Lobo. This embankment, constructed between 1988 and 2005, comprises a complex zoned rockfill dam designed to store the sulphidic tailings generated during ore processing sub-aqueously to prevent acidification. The embankment periphery has been extensively instrumented for both operational and performance monitoring, and throughout both construction and operation has been subject to independent annual inspection. The paper demonstrates the benefits of independent inspection, combined with instrumentation and monitoring to meet the requirements of safety and stability as well as the constraints of environmental compliance and mine tailings storage requirements.

BACKGROUND

The Neves Corvo Mine is located in the southern part of Portugal on the south-western limit of the Iberian pyrite belt, and was developed from 1985 onwards by Somincor S.A., a joint venture between Rio Tinto Zinc plc and the Portuguese State Mining Company, (Real and Franco, 1990). The mine complex is located some 20km south of Castro Verde in the Alentejo region of Portugal between the villages of Neves and Corvo, Figure 1, and includes underground operations, twin process plants and, some 5km to the east of the mine facilities, a tailings management facility, the Barragem de Cerro do Lobo. Production from the mine has risen over this period from 1.6Mt/yr to 2.3Mt/yr in recent years and is targeted to increase to more than 2.5Mt/yr in future. Between 90% and 95% of the mine throughput is produced as process waste (tailings), which has a specific gravity of 4.1 and contains more than 85% pyritic materials. These tailings are pumped from the process plant site to the depository in the Cerro do Lobo basin as a slurry at

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a pulp density averaging 20% with a pH of 10, (Cambridge and Coulton, 1990).

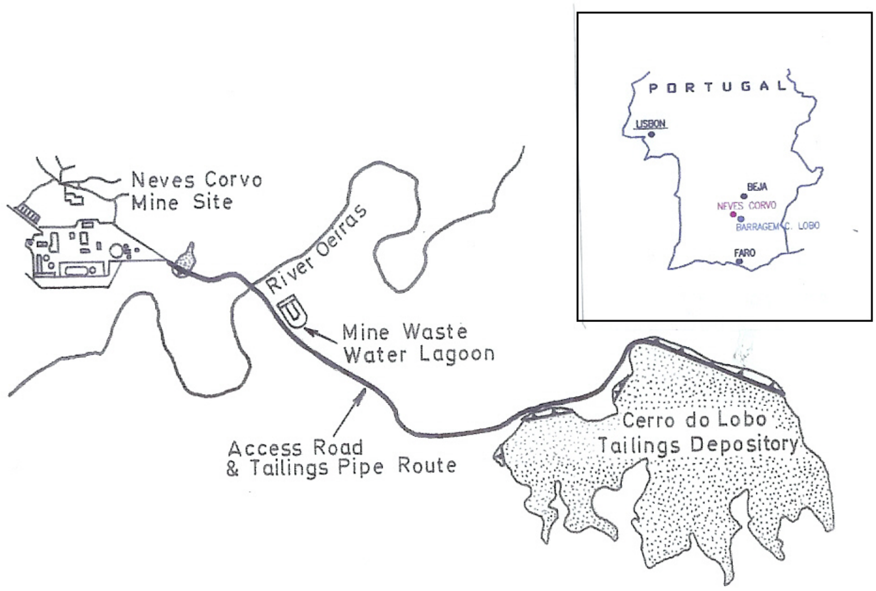

Figure 1. Project location plan

In order to store the anticipated volume of tailings to be produced throughout mine life, a stage-constructed deposition facility was required, Figure 2. This tailings management facility comprises a principal embankment dam across the Lajes Stream, a tributary of the Oeiras River and ultimately of the Guadiana River, together with three saddle dams and appurtenant works, and was constructed in four phases between 1987 and 2005. The first phase of construction was completed in October 1988 and the fourth in 2005, increasing the capacity of the facility from $6x10^6m^3$ to more than $20x10^6m^3$ and the height from 28m to 42m. Tailings were to be stored sub-aqueously with 1metre of water cover, thus preventing oxidation of the pyritic waste and, in addition, reducing the possibility of wind erosion. The geological setting for the embankments is characterised by greywackes and shales which exhibit relatively low permeability and suitability for the storage of the pyritic wastes. The embankment periphery, which now extends over 3.3km, has been extensively instrumented for both operational and performance monitoring. In addition, the facility has been subject to independent annual inspection throughout both construction and operation, and the instrumentation and monitoring data to similar scrutiny.

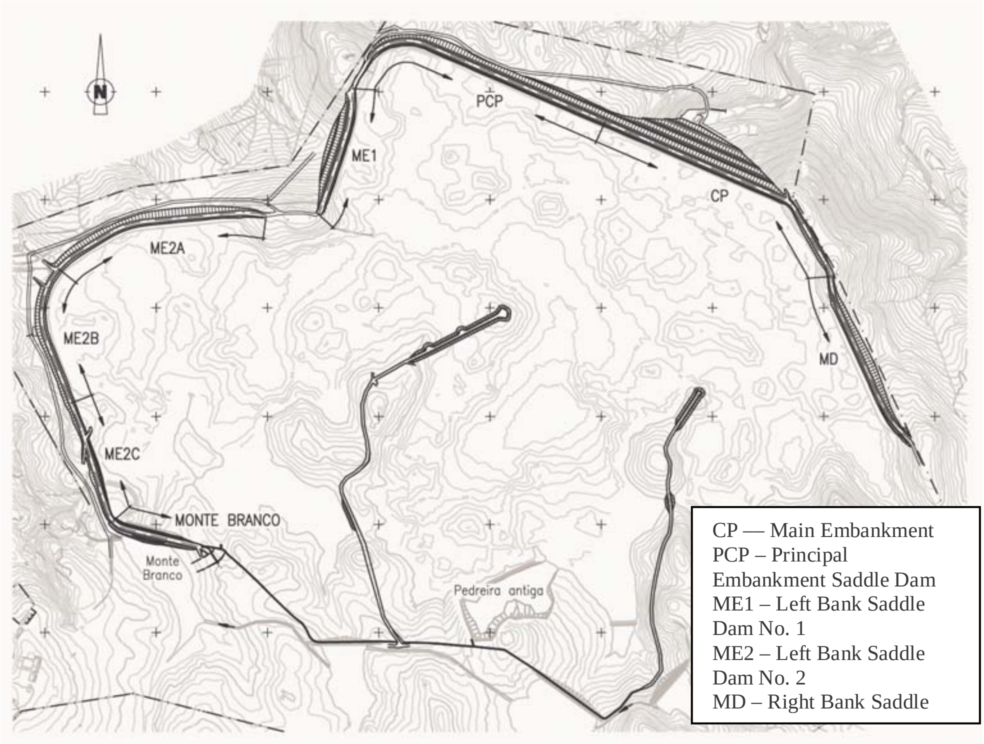

Figure 2. General plan of Barragem de Cerro do Lobo

DESIGN AND DISPOSAL

This tailings disposal facility was ultimately constructed in four phases to meet the demands not only of waste storage but also of process water supply to the plant, (Oliveira Toscano and Cambridge, 2006), as summarized in Table 1 and described briefly below.

Table 1 – Construction Phases

Construction Phase	Crest Level (mOD)	Construction Period
Phase 1	244.00	1987-88
Phase 2	248.00	1990
Phase 3	252.00	1992-93
Phase 4	255.00	2004-05

Phase 1

The Phase 1 works were undertaken under an EPCM contract and involved the construction of the main embankment, together with two left bank saddle dams (ME1 and ME2), to impound a storage volume of some $6Mm^3$. The initial embankment was 28m high, had a crest length of 850m and comprised a rockfill dam with an upstream inclined clay core. Expert review of the design, with particular respect to the proposed embankment cross-section and the geotechnical characteristics and availability of suitable clays, resulted in a modified embankment cross-section, the sloping clay zone being replaced by a narrow vertical core. The revised section included the clay core, downstream filter protection and mine waste rockfill shoulders with slopes of 1:1.8 upstream and 1:1.7 downstream. All seepage from the facility was to be collected via basal blanket drains and fed into seepage sumps located at low spots throughout the periphery. These sumps were fitted with float valve controlled pumps in order to return all seepages back into the main reservoir.

Construction of the Phase 1 facility commenced in 1987 and was substantially completed in 1988 in time to receive initial tailings from the process plant at start-up. Instrumentation installed in the embankment and foundations included 19 No. piezometers, continuous flowmeters to record seepage volumes in each sump, and settlement beacons. Environmental performance was to be monitored via a series of external groundwater piezometers, together with seepage quality sampling and testing and annual environmental auditing. In addition to the statutory inspections by the Portuguese dam authority, LNEC, and the designer, Somincor instigated annual audits by the expert reviewer. These inspections and the monitoring data have been instrumental in modifying and improving both the cost-efficiency of all construction stages and also in optimising the tailings disposal operations and process water supply.

Initial Tailings Disposal

Initial tailings deposition commenced into the Barragem de Cerro do Lobo facility in October 1988. The disposal system adopted involved pumping the thickened tailings slurry via a 5km long, 500mm diameter HDPE pipe into a similar manifold system laid on the crests of the main embankment and saddle dams. A series of valved offtakes from the manifold connected to floating HDPE fingers enabled tailings to be distributed throughout the basin, thus minimising dead-storage areas. The operating requirement was to maintain a minimum of 1 metre of water above all deposited tailings surfaces and thus prevent oxidation.

The facility also provided a major source of process water to the metallurgical plants on the main mine site. The return water pumping station controlled process water supply, augmented as necessary by make up from the nearest fresh water reservoir, Santa Clara, some 40km to the south. The operational criteria were therefore to maintain even distribution of tailings across the depository, to control and store runoff from the local catchment and to ensure a continuous supply of process water for the plant. During the initial period, climatic conditions required the storage of significant volumes of process water and resulted in the reservoir level within the BCL rising faster than predicted and, therefore, to prevent any possibility of there being an untoward discharge over the emergency spillway, Phase 2 construction was brought forward. Since 1988 the timing of the construction phases has been driven by water storage requirements rather than tailings deposition. The rate of rise of reservoir with storage of tailings is shown in Figure 3.

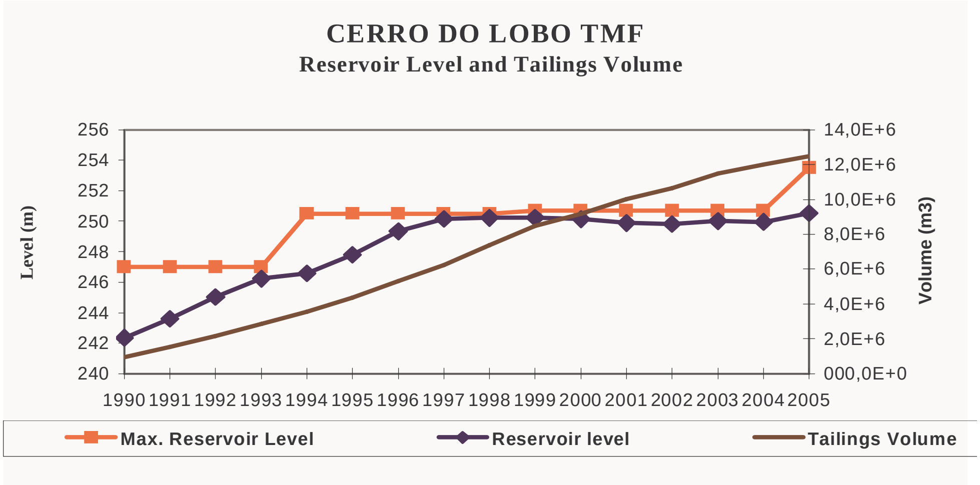

Figure 3. Rate of reservoir rise with stored tailings volumes

<u>Phase 2</u>

The Phase 2 construction was brought forward to 1990 and included raising the crest level by 4m by extending the embankment in the downstream direction, the lateral extension of the existing embankment and saddle dams and the construction of the additional right bank saddle, MD. Again, after expert review of the proposed upstream inclined extension of the central vertical core, the designer replaced the clay with an HDPE liner, (Cambridge and Maranha das Neves, 1991). The modified design section included the installation of double roughened HDPE on a filter blanket to protect against any untoward leakage through the periphery, as well as extending the embankment toe downstream using selected mine waste rockfill and upgrading the seepage control system. The overflow spillway was also relocated to Monte Branco and upgraded to meet international standards for embankment flood design. The Phase 2 construction works were commenced in 1990 under the management of the same EPCM team as for Phase 1. The embankment raise was substantially completed in the same year and included a further 12 No. piezometers, additional seepage monitoring flowmeters and replacement settlement beacons.

Phase 3

The Phase 3 lift was again undertaken ahead of schedule due to the demand for water storage at a time when mine throughput was increasing and climatic conditions in Alentejo were unusually wet. The Phase 3 construction involved a further 4m raise, with an additional extension of the embankment in a downstream direction using similar construction techniques to those employed for Phase 2. The increased crest elevation also necessitated extension of the saddle dams and the modification of the emergency overflow spillway to raise the maximum reservoir level.

Embankment construction commenced in 1992 using a local contractor supervised by Somincor, and was completed in 1993. The embankment raise was substantially completed in the same year and included a further 4 No. piezometers, additional seepage monitoring flowmeters and replacement settlement beacons.

Embankment Monitoring 1994-2003

Extensive performance monitoring was undertaken between Phases 3 and 4 with particular respect to structural stability, deposited tailings densities, water balance, piezometric data and seepage volumes and quality, (Oliveira Toscano and Fonseca, 2004). The annual expert audits offered the opportunity to regularly assess geotechnical and geochemical performance and to review the ongoing instrumentation data with respect to the need for the construction of the final permitted raise.

The water balance modelling indicated the benefits, both operationally and environmentally, of reducing the volume of run-off reporting to the reservoir. The construction of five 5m to 6m high embankment diversion dams was proposed along the southern periphery, to be interlinked by a deep overflow channel to divert catchment runoff around the facility and bypass the tailings reservoir. These dams were constructed in 1996 and reduced the effective catchment area from 4.0km^2 to 1.91km^2.

Tailings disposal monitoring had been undertaken on a continuous basis from early on in the project. During Phase 2, sub-aqueous tailings densities were predicted initially from a series of bench scale drained and undrained column tests. Subsequently, large-scale sedimentation tests were undertaken on site in 2m high columns. These tests indicated the long-term density of the submerged tailings to be of the order of 1.5 t/m^3 to 1.6t/m^3, (Cambridge, 1993-97). Annual hydrographic surveys were undertaken to define the settled tailings surface and thus to assess the stored densities in the depository. The density determinations are presented in Figure 4, which shows the trend towards an average density value of 1.58t/m^3, consistent with the laboratory data. The differences between field and laboratory data almost certainly arise from edge effects which influence sedimentation tests in small diameter columns. However, the column tests proved to be a reasonably accurate indicator of long-term sub-aqueous deposition and, together with the updated water balance predictions, indicated the need to instigate the final permitted raise of the facility in 2004 to meet predicted mine production to 2012.

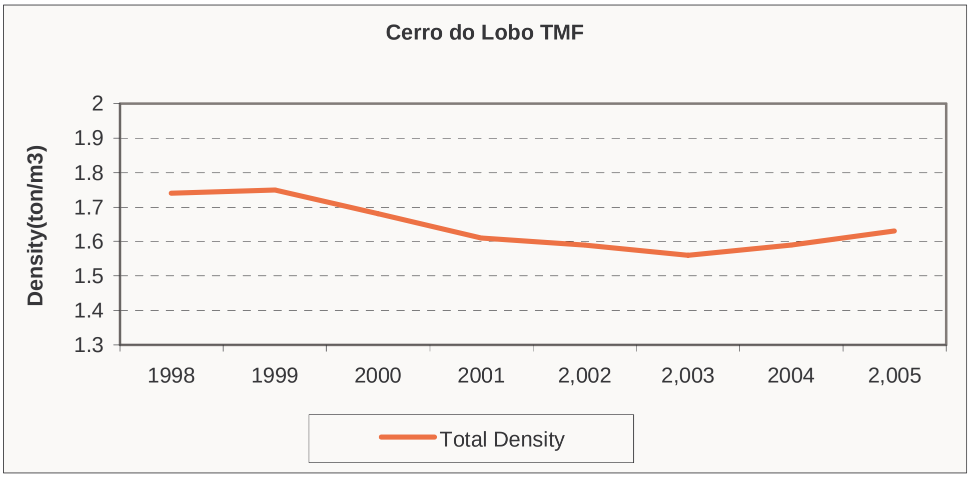

Figure 4. Density measurements for tailings deposit

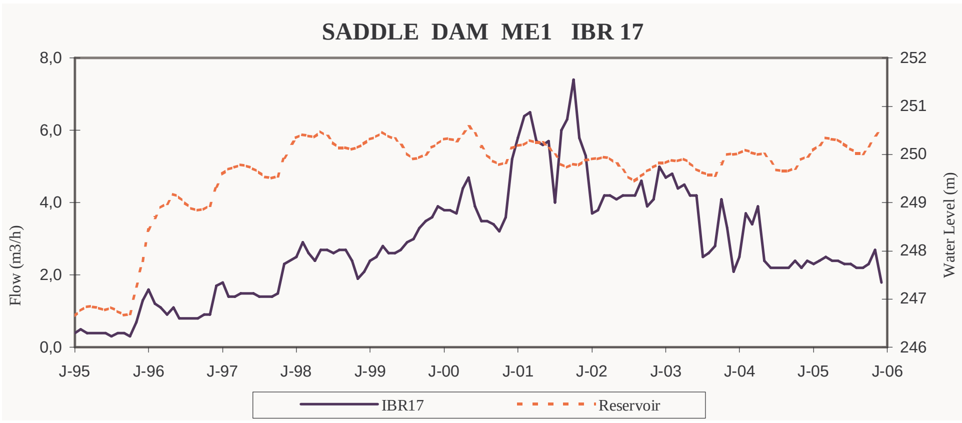

Figure 5. Seepage volumes with time for IBR17

Seepage volumes exhibited a steady increase during the initial deposition period. However, as tailings deposits developed across the storage area, consolidation reduced their vertical permeability, effectively sealing the basin. By 2001 total seepage volumes from the depository had begun to decline at each embankment, Figure 5, despite the difficulties experienced in creating a uniform deposit of tailings across the basin.

Seepage quality monitoring over this period revealed the increasing occurrence of acidic runoff from the embankment slopes. The seepage data, in particular, indicated a direct correlation between seepage, pH and rainfall intensity, and the occurrence of seasonal acidification of the downstream embankment faces, Figure 6. Investigation revealed that this acidification was as a result of previously unidentified rockfill zones incorporated into the embankment section and which included modest yet destructive quantities of pyrite. The precipitation-induced acidification (oxidation and flushing cycle) led to a marked seasonal reduction in the pH of the seepage and to the breakdown of rockfill particles, resulting in increasing fineness of the fill and reduced shear strength. The consequent lower permeability led to a small but noticeable rise in piezometric levels in the embankment shoulders. The reduced pH posed long-term environmental performance concerns, not only for seepage quality but also for closure and final surface rehabilitation.

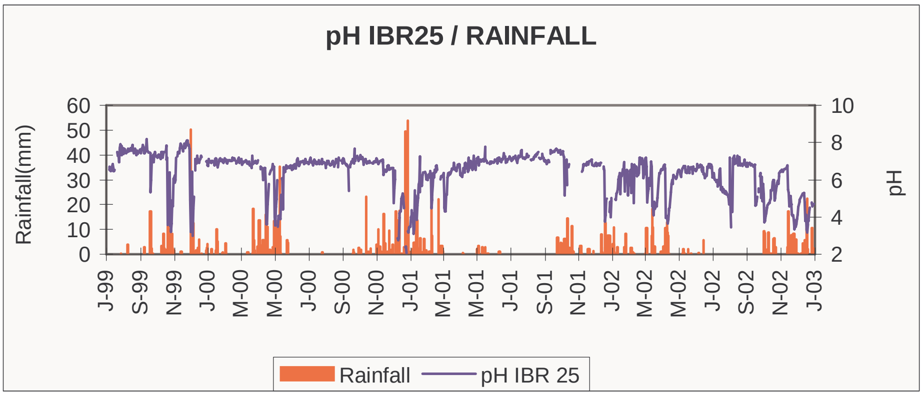

Figure 6. Correlation of seepage pH with precipitating events from IBR25

As a result, a series of boreholes were put down at selected locations throughout the embankment to identify the depth extent of any deterioration and to obtain samples for geotechnical and geochemical analysis. Further hydraulic piezometers were installed in these boreholes to enable any untoward rise in phreatic surface as a result of changes in the characteristics of the fill to be monitored. The investigation indicated that oxidation was apparently limited to the outer face of the embankment but that zones of potentially destructive quantities of pyritic fill had been included in the embankment section. Laboratory analysis indicated reduced shear strength of the oxidised fill and led to a stability review and further modification of the Phase 4 embankment cross-section. The revised section was designed to ensure long-term integrity and to prevent future deterioration of the existing rockfill. Percolation through the downstream face was to be minimised by utilising acid- and weather-resistant coarser, clean, competent rockfill from a nearby quarry. The seepage control system was also upgraded to maximise seepage capture and return and to minimise seasonal movement of piezometric levels within the embankment shoulders, thus inhibiting the oxidation/acidification cycles.

<u>Phase 4</u>

The most recent construction phase, completed in late 2005, involved raising the crest to the ultimate permitted level of 255mOD, giving a maximum embankment height of 42m and a peripheral length of 3327m. The reservoir at top level now contains some 20.4Mm^3 of storage and has a surface area of some 1.8km^2. The embankment raise entailed extending the HDPE membrane throughout the periphery of the embankment, raising the downstream face and modifying both toe drainage and seepage control systems.

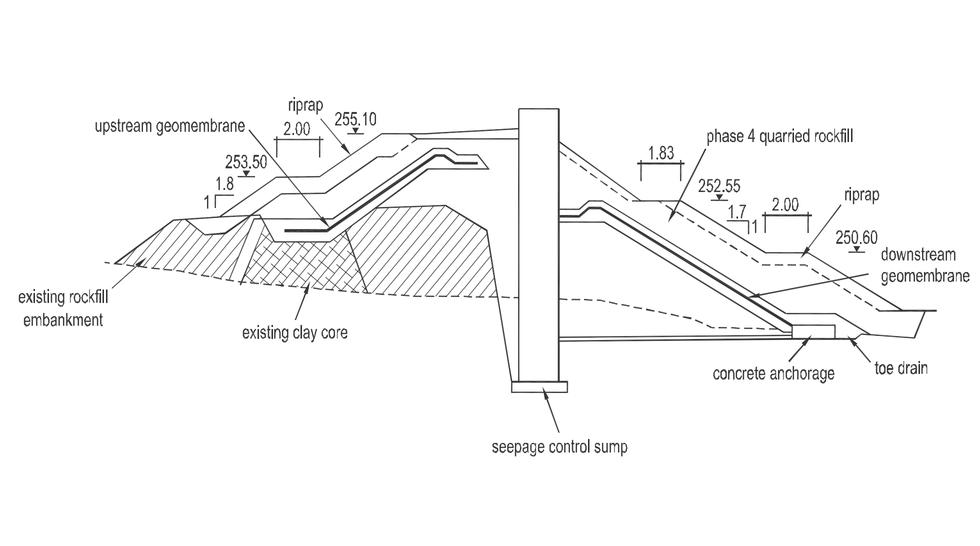

Figure 7. Cross-section through the Monte Branco embankment

During this phase of embankment raise, both the emergency overflow structure and siphon drawdown facility were relocated and the final diversion dam, Monte Branco, at the extremity of saddle dam ME2, completed. This small dam could be inundated on both upstream and downstream faces, and thus included seepage control via a deep sump located on the centre line of the embankment to prevent any potentially contaminated seepage from being discharged into the diversion system, Figure 7.

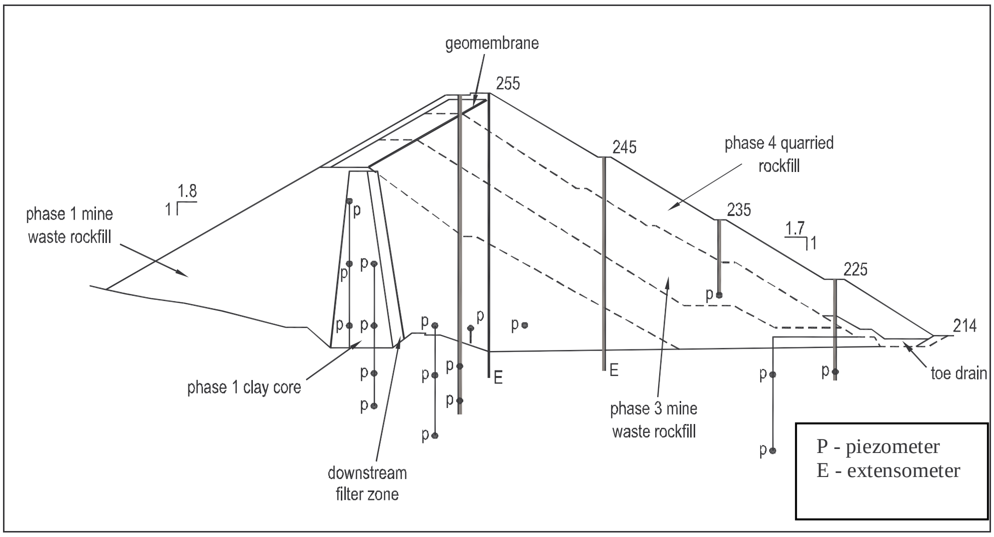

Figure 8. Phase 4 Embankment cross-section showing instrumentation

The final construction phase was undertaken under the management of Somincor by a local contractor, with site supervision by Cenorgeo, (Oliveira Toscano, Romeiro and Almeida, 2006). This phase included further instrumentation, Figure 8, comprising the upgrading of all seepage monitoring flow-meters, the installation of a further 15 No. piezometers, the final settlement beacons, 4 No. inclinometers and 2 No. seismographic stations.

Phases	**Piezometers**	**Survey beacons**	**Neutral pressure cells**	**Seepage flow-meters**	**Inclino-meters**	**Seismo-graphs**
1	**19**	**18**	**6**	**4**		
2	**12**	**26**		**6**		
3	**4**	**36**		**12**		
3/4	**12**					
4	**15**	**41**		**19**	**4**	**2**

Table 2. Summary of Barragem de Cerro do Lobo Instrumentation

SUMMARY

The Phase 4 construction works on the Barragem de Cerro do Lobo tailings disposal facility were completed late in 2005 and included the installation of the final instrumentation and monitoring equipment, Table 2. Throughout the last 18 years, the Barragem de Cerro do Lobo has been inspected and monitored, not only for operational reasons, but also to ensure that the facility performs in accordance with its design criteria. External expert and regulatory inspections have been undertaken for both engineering and environmental purposes, and have ensured that not only are instrumentation and monitoring data recorded but also that they are analysed and the results interpreted regularly. The monitoring data, together with a rigorous internal inspection system, have enabled the Company to adapt the construction and operation of the facility to meet the needs not only of operational efficiency, but also those of international standards of engineering and environmental compliance. The data collected have been used to great effect to improve the performance of the facility and to ensure that all untoward signs have been identified and corrected, either immediately or through subsequent construction phases. Throughout this period the facility has continued to receive tailings from the production plant and to provide a continuous supply of process water. A significant achievement over the operating period has been the use of water balance and tailings disposal modelling to fine-tune water usage. This has lead to a significant reduction (>20%) in freshwater demand from the Santa Clara Reservoir, a major achievement, particularly in the context of the adverse drought conditions recently experienced in southern Portugal. This tailings management facility, with all its modifications, has performed to its design criteria and can be considered to meet the standards demanded internationally for both water dams and mine waste storage facilities. The instrumentation installed will continue to be monitored both during mineral operations on the site and also post-closure until the facility is proven to be benign.

CONCLUSIONS

The Barragem de Cerro do Lobo has been designed to meet the tailings storage requirements emanating from copper production at the Neves Corvo Mine. The embankment and its appurtenant works have been constructed, inspected and monitored over an 18-year period to meet the demands of tailings storage and process water requirements, as well as of legislative and environmental standards. During this period, the successful operation of this facility has been aided by well-planned and rigorous instrumentation and monitoring routines to enable the performance of the facility to be optimised. Expert independent inspections and audits, combined with the internal monitoring system, have ensured the ongoing safety and integrity of the facility, its compliance with the best international standards and full environmental compliance.

As for all mineral operations, the existing orebody will eventually be depleted, but further mineral deposits may be identified. The future of this tailings management facility, should such new deposits prove economical to extract, may involve a further raise, more innovative thinking in design and construction and additional modifications to the embankment cross-section. The instrumentation and monitoring, together with the operator's experience over the last 18 years, will enable the engineering of any new extension or facility to be optimised.

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