Geological and geotechnical aspects to assist the reclamation of areas degraded by surface mining

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ABSTRACT

Reclamation of surface mines is a crucial environmental issue and a key challenge to the worldwide mining industry. One of the goals of reclamation is to ensure that the area is left in a condition permitting safe future use. Hence, the reconstruction of open pits, waste piles and tailings dams must satisfy appropriate geotechnical stability and safety conditions for the planned use. Landscaping in the final stages is highly relevant as the topography around the mining areas is sometimes dramatically modified by ore extraction. The reclamation strategies must be applied not only after ore exhaustion, but also during its extraction. This is a sound business strategy that leads to considerable environmental benefits and increased security of the mining operations.

1. INTRODUCTION

The environmental question is more crucial in the mining industry today than it has been in the past. In this context, one of the main aspects is the recovery of areas degraded by various activities related to mineral industries, such as ore extractions, waste piles and tailing dams that result from milling processes, among others.

The mining activity is by nature localized to specific areas. It also has a finite lifetime (i.e., the time during which it is deemed to be an economically profitable activity), which can vary between a few years and a few decades. Hence, mining exploitations always involve the temporary use of a physical space. Addressing the use of the lands around the mines following the end of the mine's lifecycle is a decisive question for the sustained development of this important industrial sector.

This paper presents an analysis of geological and geotechnical criteria related to the recovery of degraded areas. It also discusses topographical landscaping approaches based on computational graphical modeling tools that allow exploring various possibilities for desired future land use.

2. RECOVERY OF AREAS DEGRADED BY SURFACE MINING

Already during the second half of the 20th century various communities motivated by scarcity of available areas for housing, industrial use, agriculture, etc, had started a firm initiative demanding the recovery of mined areas, asking for the adoption of more rigid legislation and the implementation of cost financing mechanisms.

In Brazil, recovery of the degraded areas is still limited. However, the tendency is to effectively integrate to the mining target, becoming necessary condition to proper continuity of the mining activities. With the Federal Constitution of 1988, the goal of recovering areas degraded by mining activities was introduced in the constitution, which also regulates the state and municipal policies.

2.1 Characteristics of the Mining Enterprise

The mining activity is characterized by certain peculiarities, which decisively determine the dynamics of the area's degradation. These peculiarities are the mine's lifetime, location inflexibility (i.e., ore body location), the byproducts of mining and milling processes, mine waste disposal areas, and the structural stability of tailings embankments.

2.2 *The Concept of Degradation*

According to Sanchez (1992), the degradation of mining areas can be defined as a set of environmental processes that cause a loss of productivity (from activities other than mining) or decay of the life quality in the area. The main effects of degradation are: a) loss of the natural characteristics; b) undesirable landscape alteration; c) problems of public health and security.

The environmental degradation due to mining activities can be evaluated in terms of the following aspects (Ibrahim, 1996):

- *Physical*: ground compacting, landslides of hillsides;
- *Topographical*: hillside configuration with vertical walls, hillock or land depressions with slope instability problems;
- *Chemical*: ground, water and air contamination, leaching of ground nutrients, solid and/or toxic particle emission in the atmosphere, launching of chemical effluent in the ground and aquifers;
- *Biological*: disappearance or reduction of the fauna and flora.

2.3 *The Recovery Concept*

The recovery concept, following the definittion given by (Bitar et al., 1990), involves the following actions:

- *Restoration*: bringing the rigorously modified place to the pre-existing conditions before the intervention;
- *Reclamation*: returning the modified place in a state such that the ambient conditions closely match previously prevailing conditions;
- *Rehabilitation*: making the area suitable for a given use or ground occupation, in compliance with predetermined aesthetic standards.

Doll (1988) clarifies that the term reclamation is used in general for practical purposes by the American federal and state legislators, and it implies returning the place to the pre-mining conditions (reconstitution of the original contour and re-established communities of plants and animals to the pre-existing levels). The term rehabilitation implies returning the area for steady and permanent use in accordance with a pre-existing plan. This involves the flexibility to promote new uses of the area, different than the original one, especially uses that are more beneficial for the society. The term restoration implies a more complete recovery process, during which one tries to restore with detail the pre-existing conditions in the area.

In Brazil, recovery as defined by law is closer to the rehabilitation concept, because it allows for the possibility of different future uses. Therefore, as defined by the Federal Decree 97,632 article 3°, of 1989, recovery has as objective the return of the degraded land to a form of use, which is in accordance with an agreed upon plan for ground use, and aims at the environment stability of the area.

2.4 *Future Use of the Area*

Objectives of future use are determined by the necessities of land resources. At the same time, availability of materials and equipment restrictions may have an important effect on the recovery options.

A general recovery objective would be reconstructing the land with a view to maximizing utility and versatility for future uses. The concept of utility is broader than the concepts of productive use, and it also embodies the idea of complementing other existing land resources, thus supplying a regional lack.

3. GEOLOGICAL-GEOTECHNICAL CONDITIONS

In order to make plans for future use, it is necessary that the diverse structures due to the mining activity in the area such as excavation slopes, embankments and waste piles maintain an adequate level of security for years. Hence, knowledge of the geologic and geotechnical conditions is a basic prerequisite for mitigation measures in these areas. These conditions usually involve: geometric factors, rock structures, water presence, rock alteration and rock stress.

The geotechnical problems are, in most cases, associated with the stabilization of pit slopes, waste piles and tailing ponds. Other issues, such as the soil compactness, tailing ponds settlements and waste piles stability may also be relevant for the intended future land use..

3.1 Methods of Stability Analysis

The methods for calculation of slope stability are in their majority based on equilibrium limit, i.e, the safety factor is expressed as a relation between the moments of the resistant moment and the operating forces; these methods are restricted to the slipping/ rupture phenomena on well defined surfaces.

3.2. Geologic-Geotechnical Investigations

The strength parameters of slopes in poorly consolidated materials without structural features can be defined by simple or triaxial compression tests or by direct shear tests in the laboratory.

In the case of rock massive, the ground behavior will be predominantly governed by discontinuities rather than the properties of the intact rocks. Collapses and instabilities occur exactly in the planes of weakness or discontinuities under the influence of neutral pressure, or along boundaries between lithofacies.

The importance of the geological conditioning factors in these structuralized grounds is reflected in the analysis of slope stability models. Examples of this fact are sliding of wedges, plan ruptures in slopes and fall of blocks in galleries, generated by the intersection of discontinuity planes. Hence, the factors creating instability of rock structures are of geometric nature, with strong planar or three-dimensional characteristics.

3.3 Protection and Stability Measures

Stabilization measures usually involve the construction and maintenance of stable slopes or the reconstruction of damaged slopes.

These works include geometric alterations of the slope (height and angle reductions) to redistribute the mass in a balanced configuration. Slope remodelling and construction of equilibrium benches are also included in this case.

Surface drains help to conduct water inflow through narrow channels, valets, gutters or boxes to safer places. Narrow channels in the benches and water stairs must be constructed for energy dissipation. If the area is replanted, the new vegetation reduces the impact of the rainfall on the land, and it provides as obstacle to the surface flow of water, thus favoring water absorption in ground.

For draining rock massive, horizontal deep drains can be perforated into the structure. Problems associated with the drains are related to chemical encrusting or clogging, which mainly occurs in cases of intermittent flow.

Rock bolting is another very common protection measure for excavations that represent significant risk of instability. For small drops or sliding of blocks, wire netting on the face of the slope can also be effective.

4. TOPOGRAPHIC CONFIGURATION

According to Jansen and Melsted (1988), the topographical configuration is dictated by aesthetic reasons, and in some countries the legal requirements require a close reconstitution of the original surface.

The topographical configuration of the recovered area can vary between the reconstruction of the original shape and the creation of a new environment, by taking maximum advantage of the excavated surfaces generated by mining.

According to Harwood and Thames (1988), the topographical rearrangement besides physical stability must also satisfy the following requirements: aesthetically improve the landscape; return the land to an useful condition; provide suitable grounds for growth of new vegetation; reduce potential erosion; provide conditions for natural draining and control of the water storage; eliminate or effectively control areas of risk to the local community, such as deep lakes or cavities.

It is important to emphasise that the Brazilian legislation does not require restructuring of the area to its original condition, which is often impossible. Instead, each case is analysed in terms of its specific characteristics in order to adopt the best possible solution.

4.1 Compatibility with the Geological-Geotechnical Conditioning Factors and Erosion Control

The land configuration for an effective recovery plan requires an improvement of the entire area. The morphology and the course of the water flows are interrelated. Hence, the two must be jointly considered in order to reach a balance between constraints of productivity, physical stability, and erosion control. The recovery procedure must provide ways of "land-sculpting" in order to attain a dynamic balance with the surrounding environment.

4.2 Future Use Compatibility

The topographical configuration must be adjusted to the intended future use. An important application in the open-cast mining is the management of water resources by the construction of settling ponds and other structures to provide water, water-flow control, and solid-particle sedimentation.

The feasibility of building water reservoirs depends on the shape of the recovered surface and, therefore, the final topographical configuration either allows for them or excludes them. Good-quality water is a valuable resource in localities that are deficient in water. Hence, construction and efficient use of water reservoirs is an attractive alternative.

Some topographic characteristics favor agricultural uses. Compared with the traditional methods of preparation and grading of terrained surfaces, the creation of depressions or basins can reduce water flows up to 75%. While in the lands prepared for the traditional agricultural methods, as trenching and ploughing, the soil loses the water retention ability in 1 to 2 years, horizontal cavities maintain the capacity for 10 to 50 years. These cavities, which are excavated by crawler tractors, are recommended for all slopes in mined areas, especially those with inclinations exceeding 20%.

Lands with moderate inclination are a scarce resource in many regions. Surface smoothing can offer better options for agriculture or urban development than original terrain surface.

Topographic requirements for reforestation are generally less critical than for pasture or agriculture, and therefore little work is required on the soil. Many times the smooth surfaces obtained do not compensate for the resulting soil compactness.

If wild life preservation is the objective of the future land use, some techniques are suggested to reintroduce extinct fauna (Williams et al., 1990). For example, these include remodeling the topography, creating undulations, non-drained surface depressions and small-scale topographic non-uniformities; reworking rock walls, retaining high slopes in quarries and deep diggings, creating re-entrances, and foreseeing water lakes or reservoirs.

Therefore, it is recommended to create diverse small "hills" between 1 and 2 m high as well as small, smooth and flat depressions for water accumulation. These elements will contribute to the attraction of animals in the recovered area.

4.3 Landscape Aspects

These must be determined in the pre-planning phase, in order to establish the landscape features of the region. When possible, they should be surveyed, described and registered in drawings and photos before any human action. The points of visual monitoring should also be indicated in maps as future points of reference (Williams et al., 1990).

4.4 Computational Modeling

Computational 3D models of terrain surfaces are a tool of great utility that allows diverse simulations of topographical configurations, calculating land subsidence and also a quantitative assessment of volumes and areas of the different alternatives.

4.4.1 Mined Areas

As a result of the excavations water from the surface or ground water (through seepage) tends to accumulate. Therefore, flooding of open pits, especially in rock, is the most common solution. Open-pit filling with soil is rarely used, except for pits of small depth. In general, open-pit filling requires a large volume of material (an open pit in rock may involve depths of ten or hundreds of meters), making this alternative economically impractical. In addition, there is the issue of procuring enough material volume, which may degrade the area that supplies the filling material.

The sequence of Figures 1 and 2 show a schematic of a topographic configuration before and after mining. The open pit is flooded by natural water from the surface and the underground, and is thus converted into a lake. This is a typical solution for excavations in rocky soils (except for hillside excavation).

4.4.2 Areas of Waste Deposition

The volumes of waste piles can be considerable, as in the case of iron mines. The geotechnical criteria in the waste piles are of fundamental importance for the stability control of the configuration, but they are also related to aesthetic issues and adaptation to the local landscape. Another alternative is to take advantage of the topography of these deposits for other purposes (industrial hangars, habitation centers).

Figures 3 and 4 present a graphical illustration for different two waste pile configurations at the same area. The first alternative is a conventional stack of linear faces. The second is a stack that improves geotechnical stability: its faces are shaped in agreement with the natural contours, and an asymmetric stack at the top diminishes the effect of an excessively rectilinear contour. The total volume of the two configurations is practically the same. Using graphical simulation it is possible to verify the improved result of landscaping in the second configuration.

5. CASE STUDIES

5.1 Industrial Sand Mining

Industrial sand in São Paulo State is extracted

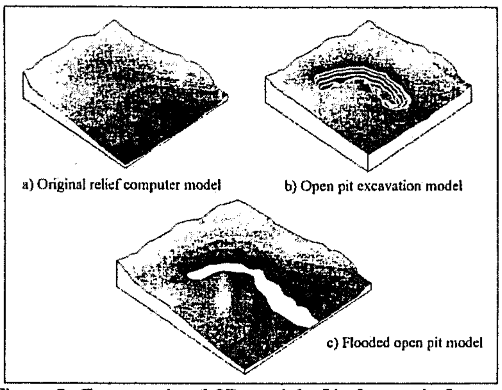

Figure 2. Computational 3D model of before and after mining with flooded open pit

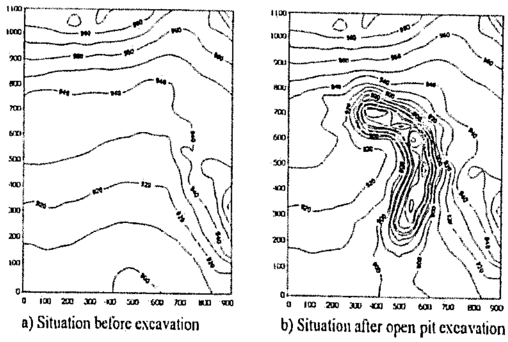

Figure 1. Topographic view before and after mining

by mechanical excavation in open pits, in contrast to the sand normally used for civil construction, which is extracted by hydraulic jets or dredging of stream beds.

The most important company producing industrial sand is the Mineração Descalvado located near of São Carlos City, SP (Fig. 5).

The excavation is carried out in three sets of benches, with average height varying from ten to fifteen meters (Fig. 6). Each group of benches corresponds to a different sandstone layer (Santa Rita Formation, close to the surface, Botucatu Formation, in the middle, and Pirambóia Formation, deeper). The contaminant content varies in the layers (Fe_2O_3, clay).

5.1.1 Geological-Geotechnical Studies

The handled materials are waste and sands with relatively poor geomechanical properties. Although they consist of sandstones, which have good initial cohesion, exposure to the atmosphere and water quickly cause their degradation and make them critical factors for slope stability.

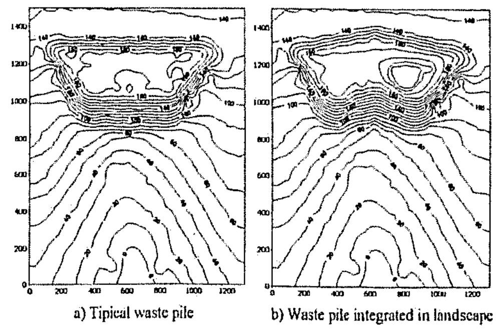

Figure 3. Typical and optimised waste pile

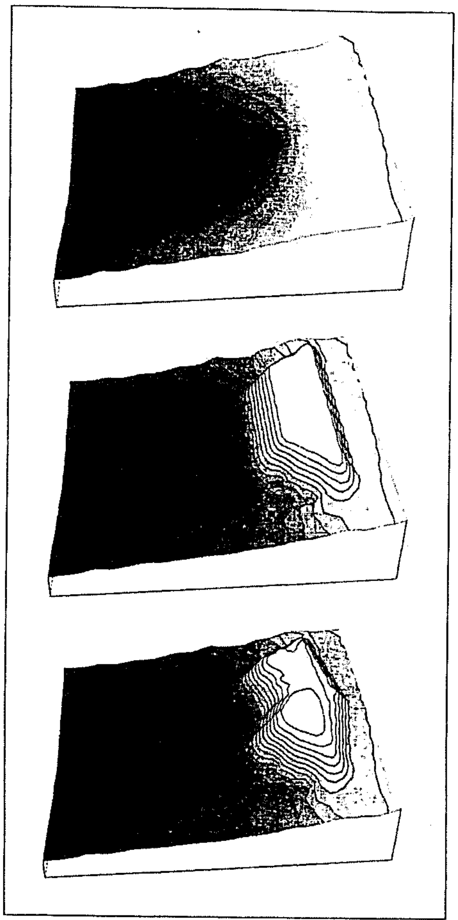

Figure 4. 3D views of computer models

To configure the final excavation, the company carried out laboratory tests on undisturbed samples, collected at each one of the sand layers, to determine the attrition angle, cohesion and others parameter for slope modelling. Slope stability analysis was performed to verify the safety factor. The

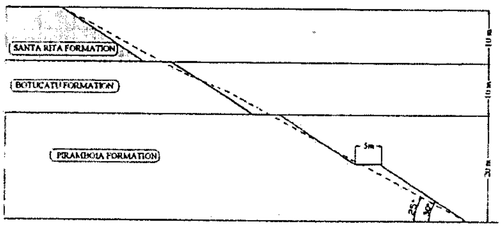

Figure 6. Final excavation of sandstone slope

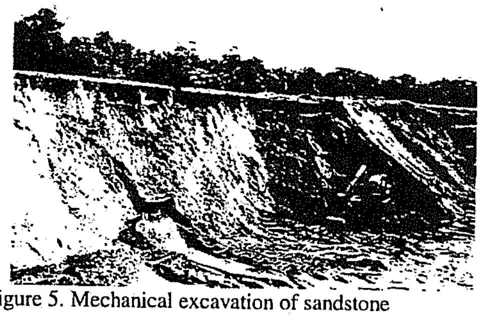

Figure 5. Mechanical excavation of sandstone

determination of slope angles for the final configuration of the excavation pit was based on the circular-rupture method of Hoek & Bray.

5.1.2 Area Recovery Measures

The excavation is in a depressed area where water accumulation occurs. It is necessary to remove this water by continuous pumping. In the future, the mine would be flooded after closure. The solution foreseen by the company is to fill up the cave partially with soil, during extraction activities (estimated to last more than 15 years) in order to obtain a surface level sufficiently high to protect against water inflows and to conduct it out of the excavation.

5.2 Iron Ore Mining

The ore formations of hematite and itabirite are weathered and friable with low mechanical strength, thus requiring typically intensive geotechnical works for their exploitation (Fujimura and Nieble, 1990). Large volumes of waste removal are required, due to the extensive scale of production and the large dimensions of the excavation. The relation waste/ore in weight or cut off grade is usually in the range 0.5 to1.0.

The region nominated "Quadrilatero Ferrífero" in Minas Gerais State concentrates the largest number of Brazilian iron ore companies. Amongst them, the Corrego do Feijão mine of the Ferteco Company situated in Brumadinho, MG, about 50 km from Belo Horizonte, was selected as an example of iron open pit mining.

5.2.1 Geological-Geotechnical studies

In the Córrego do Feijão open pit incoherent itabirite C4 (soil) and C3 (weathered soft rock)

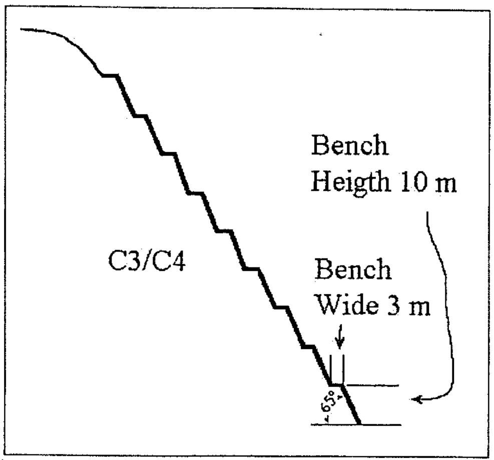

Figure 7. Final slopes of iron ore open pit

appear in great amounts. This fact led the Ferteco Company to launch a characterization program and laboratory tests on undisturbed samples to evaluate geotechnical parameters such as Casagrande Index, plasticity, humidity, density, uniaxial compression strength tests and direct shear tests.

However, one of the great problems of Rock Mechanics (also in the case of structured soil) is to estimate the strength as a function of the soil's discontinuities. In consequence, it is typical practice to assay intact rocks, without breaks, and at the other extreme the residual soil, in which the geological structures have little or no influence on the strength. The properties of the rock mass usually take values between these two extremes. The exact values are affected by the discontinuities. Thus, to avoid extraction of samples, which is very problematic in this type of material, sometimes interpolation of the extreme values is adopted as an approximate estimate for a rough calculation of mechanical properties of the rock masses. From these data and by means of computational calculations based on numerical modeling methods, the final open pit configuration is attained (Figs 7 and 8).

Figure 8. Final slope of iron ore mine

In addition to achieving acceptable safety factors, because the structural components have a strong effect on stability, the slopes must be mapped periodically until they reach the final configuration. The stability of the bedding planes in relation to the excavation must be analysed by means of the Schmidt-Lambert diagrams.

5.2.2 Area Recovery Measures

Restitution of benches must be performed during mining operations in descending direction (from highest to lowest), in proportion to the excavation works concluded in these benches. The water flow stairs should also be extended to each new bench, in descending direction.

Waste disposal is always a critical activity, because the waste has low mechanical characteristics, occupies large volumes and requires extensive disposal areas for its accumulation (e.g., hillsides), which are not always suitable for this function. In proportion to the benches formed, narrow channels and water stairs should be added to the drainage system for slope stability maintenance. Draining efficiency in the waste piles is especially important, due the poor properties of this material, which is highly susceptible to erosion and instabilities.

5.3 Crushed Stone Quarries

Quarries are an important mining activity, since they produce crushed stone for civil construction. Especially for quarries in the proximity of urban centers, issues such as vibration, air-stroke, rock throwing and recovery of the degraded areas acquire greater significance.

Various types of rock are mined, but the most common in the State of São Paulo are granite, limestone and basalt.

In particular, the stability of benches, aesthetic features, open-pit dimensions and excavation depth, frequent flooding by water inflows are the major questions related to the recovery of degraded areas.

Area Recovery Measures

A case of recovery involving a deactivated quarry is the old "Chapadão" quarry, located near Campinas, SP, which was transformed into a recreation area (Ulisses Guimarães Place). The hillside basalt quarry was exploited for many years.

A main aspect of the recovery effort was the management of underground and pluvial water drainage. The open pit works as a natural large ditch that catches and accumulates water due to the large contributing surface area and the low permeability of the rock. Therefore, the water inflow tends to be significant, especially during rainy periods, and an efficient drainage system was needed to conduct the water flow outside of the open pit.

6. CONCLUSIONS

The analysis of the geological and geotechnical conditioning factors in recovered areas of mining activities are essential for achieving stability conditions in the physical environment. Knowledge of the factors that control the geotechnical stability of the slopes supplies valuable information for planning future compatible uses of the area, based on the establishment of a sustainable recovery plan that ensures necessary safety conditions.

For the selection of the best topographic configuration the 3D surface model of computational simulation is a useful tool that supplies important information in aesthetic and quantitative terms regarding the technical and economical analysis of diverse recovery alternatives.

In each case, the geological-geotechnical conditioning factors associated with the accepted standards of drainage, topography, and regional characteristics of the local physical environment must be considered and evaluated in the recovery plan.

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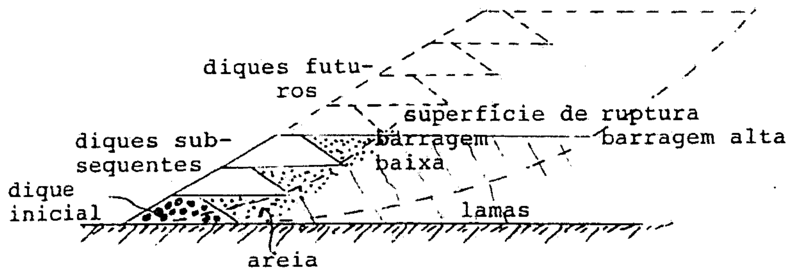

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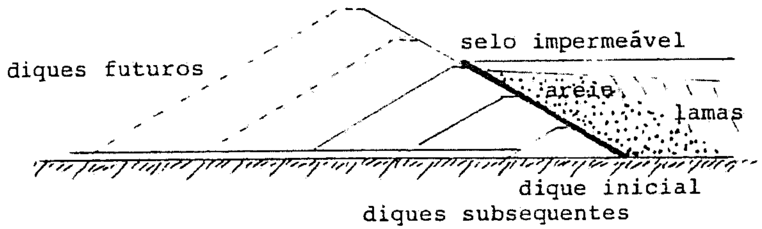

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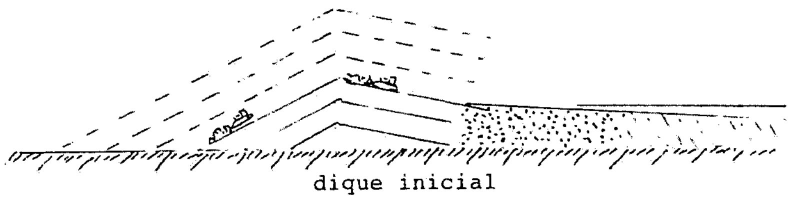

ALTEAMENTO PELA LINHA DE CENTRO

FIGURA 4: métodos de alteamento das barragens

7.2. <u>alteamento a montante</u> ("upstream")

É o método mais barato pois consiste em simplesmente altear a barragem com os rejeitos depositados sobre ela. Veja a figura 4. É também o método mais inseguro pois a linha central da crista desloca-se progressivamente para trás, sobre os rejeitos depositados. A superfície de ruptura passa cada vez mais intensamente por dentro do volume de rejeitos acumulados - se houver uma quantidade de finos elevada é certa a ruína. Por isso este método é limitado a barragens de 30 a 40 m de altura. É essencial que o maciço inicial seja construído com material granular, poroso e de boa drenagem.

7.3. <u>alteamento pela linha de centro</u>

É um método intermediário entre os outros dois, tanto em segurança como em custo. Na face interna (a montante) a deposição do material é feita hidráulicamente e a jusante (face externa) é feita mecanicamente, com todas as precauções necessárias. Veja a figura 4. Existem barragens elevadas por este método a alturas superiores a 40 m.

7.4. <u>problemas especiais</u>

Constitui problema digno de menção a construção de barragens em vales muito estreitos: as cargas verticais no eixo da barragem são maiores que nas bordas, em função da geometria do vale. Em consequência é muito frequente a ocorrência de recalques diferenciais e o aparecimento de trincas no maciço. Esta situação deve portanto ser evitada.

Outro problema, mais frequente em regiões de alta sismicidade, que tem consequências trágicas, é a liquefação do material de construção da barrragem durante terremotos. A barragem literalmente fica liquefeita e liberta toda a massa de rejeitos contidos, que descem vale abaixo destruindo tudo o que encontrarem pela frente. Em 1965 morreram mais que 200 pessoas no acidente com a barragem da mina El Cobre, no Chile, após um terremoto. A massa de rejeitos desceu cerca de 12 Km morro abaixo. Outras 11 barragens fossem destruídas na mesma ocasião. No fim dos anos 70 houve também o rompimento de uma barragem de rejeitos nos Alpes italianos, que riscou do mapa uma estação de esqui situada a jusante.

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DESENVOLVIMENTO DE PROGRAMA PARA O APROVEITAMENTO DE REJEITOS

ORGANIZAÇÃO E METODOLOGIA

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