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DOWNSTREAM VALLEY HAZARD CLASSIFICATION OF ITABIRA MUNICIPALITY DAMS

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Abstract. *The potential for dam failures and public pressure for a safer environment make the development of risk evaluation instruments mandatory in contemporary society. In Brazil, Law 12.334 of September 20, 2010 is the new keystone legislation in the field of dam safety. It establishes the national dam safety policy and defines the main instruments for the national dam safety policy, including a system for the classification of dams according to risk and downstream hazard.*
This paper presents the downstream valley hazard classification of five dams located in Itabiruçu Municipality, in the context of the new Brazilian dam safety law.

1 INTRODUCTION

Ageing of dams, changes in hydrologic conditions and increasing population in valleys justify renewed attention to dam safety and valley management. The potential for dam failures and public pressures for a safer environment make the development of risk evaluation instruments mandatory in contemporary society the hazard classification of downstream valleys.

In Brazil, Law 12.334 of September 20, 2010 (the “Dam Safety Law”) is the new keystone legislation in the field of dam safety. It establishes the national dam safety policy, defines which dams would be regulated, creates the National Dam Safety Information System (SNISB) and assigns regulatory authority to specific institutions. More specifically, the Dam Safety Law defines the main instruments for the national dam safety policy, including a system for the classification of dams according to risk and downstream hazard.

The potential for loss of life is the primary factor in determining the downstream hazard classification. It is important to note that hazard classification deals also with socio-economic and environmental impacts. Socio-economic impacts include damage to inhabited dwellings, commercial and industrial buildings, agricultural lands and crops, livestock, roads, highways and utilities, and the associated economic losses. Environmental impacts only address situations where the affected area downstream of a dam failure is environmentally relevant or protected under specific legislation.

The purpose of this paper is to present the downstream hazard potential classification of Brazilian regulation to five dams located in Itabira Municipality, in the state of Minas

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Gerais, namely: Cambucal I and II, Santana, Conceição and Itabiruçu dams. Aside from this introduction, the report is divided into three sections.

In the second section, a summarized description of Brazil's actual dam safety law on what concerns the downstream hazard classification is undertaken. The subsequent two sections present the main characteristics of the Itabira Municipality valley and dams (Chapter II) and the downstream hazard potential classification in the context of the new Brazilian dam safety law (Chapter III). Finally, some final conclusions are addressed concerning the experience acquainted with the practical application of the CNRH dam classification criteria.

2 BRAZILIAN DAM SAFETY LAW

In Brazil the Dam Safety Law. Law 12.334, issued on September 20, 2010, implemented the National Dam Safety Policy (PNSB) for existing and future dams. The law is applicable to dams that impound water for any purpose (e.g., irrigation, water supply, flood control, and hydropower), for the final or temporary disposal of mine tailings, and for depositing industrial waste, provided that these comply with at least one of the following criteria:

- The height of the structure equal to or greater than 15 meters.
- The total capacity of the reservoir is equal to or greater than 3,000,000 cubic meters.
- The reservoir contains hazardous waste.
- The dam classifies as medium or high hazard based on consequences such as loss of human lives or economic, social, and environmental damages.

Following Law 12334, in relation to the hazard, the National Council of Water Resources (CNRH) established Resolution No. 143, dated July 10, which is a dam classification system where dams can be classified by risk category, hazard, and size (storage capacity or volume).

In fact, as required by Law 12.334, the CNRH established two classifications: one, is based on a risk category index (CRI), while the other is based on the associated hazard potential (DPA) in accordance with downstream consequences and reservoir volume.

The CRI classification (Art. 4 and Annex II of resolution CNRH Nº 143) is determined in accordance with the following criteria that may influence the performance of the dam: (a) technical characteristics (CT), existing conditions (EC), and the dam safety plan (PS).

Each criterion is divided into different parameters. The parameters associated with the criteria CT are: height, length, type and age of the dam as well as the design flood return period. To evaluate the maintenance conditions of the dam (EC) the following parameters are used: spillway reliability, intake reliability, aspects related to seepage, to deformation and to settlements and slope deterioration as well as to sluice gates and hydro-electromechanical maintenance. Finally the parameters to classify the PS criteria are: existence of design documentation and of dam safety reports, organizational structure and technical qualification of staff, safety inspection and monitoring procedures, storage/discharge and dam operation procedures.

Based on general risk definition, using CRI as likelihood of failure and DPA as consequences, the mathematical expression for risk evaluation in dam downstream valleys is as follows:

$$\mathrm{Risk} = \mathrm{CRI} \times \mathrm{DPA} \tag{1}$$

Furthermore, in accordance with the general criteria established by the CNRH, categories of high, medium or low risk dams are defined based on their technical characteristics, existing conditions, and compliance with dam safety documentation (i.e., dam safety plan).

Classifications of high, medium or low hazard dams are defined in accordance with the loss of life potential, socio-economic and environmental impacts of a dam failure as well as their storage capacity.

Table 1 presents the criteria to classify the downstream valley hazard potential according to CNRH Resolution No. 143.

Downstream valley hazard	DPA
High	≥ 16
Medium	10 < DPA < 16
Low	≤ 10

Table 1 – Downstream valley hazard classification based on DPA

DPA classification considers the following four parameters: reservoir total volume, loss of life potential, environmental impact, and socio-economic impact. Description of the parameters and the corresponding levels and weights for the DPA criterion are shown in Table 2.

Reservoir Total Volume, hm^3 (a)	Loss of Life Potential (b)	Environmental Impact (c)	Socio-Economic Impact (d)
Small ≤ 5 (1)	NON-EXISTING (no persons permanently or temporarily occupy nor drive in/through the affected area downstream of the dam) (0)	SIGNIFICANT (the affected area of the dam is not environmentally relevant, protected under specific legislation, or lacking its natural conditions) (3)	NON-EXISTING (infrastructure and navigational services do not exist in the area affected by the potential failure of the dam) (0)
Medium 5 to 75 (2)	LITTLE FREQUENT (no persons permanently occupy the affected area downstream of the dam, but a locally-used road exists) (4)	VERY SIGNIFICANT (the affected area of the dam is environmentally relevant/protected under specific legislation) (5)	LOW (a small concentration of residential, commercial, agricultural, industrial areas and infrastructure are in the area affected by the dam, or ports & navigational services) (4)
Large 75 to 200 (3)	FREQUENT (persons permanently occupy the affected area downstream of the dam, plus a municipal, state, or federal highway and/or a possibly permanent place with people that may be impacted) (8)		HIGH (a large concentration of residential, commercial, agricultural, industrial areas and infrastructure, and tourist leisure services are in the area affected by the dam, or ports & navigational services (8)

Very large >200 (5)	EXISTING (persons permanently occupy the affected area downstream of the dam, and lives may be impacted) (12)
DPA = Σ (a - d)	

Table 2: Weight factors to determinate DPA (CNRH).

3 DESCRIPTION OF DAMS AND DOWNSTREAM VALLEY

3.1 Itabira municipality

Itabira Municipality has a population of around 120.000 inhabitants. It is a hillside district with steep topography which relies on a watershed that divides into two hydrographic sub-basins: the Jirau and the do Peixe rivers. It is a wealthy industrial region located in the Minas Gerais' Iron Ore Quadrangle (southern Brazil).

With an annual production of around 50 million tons of iron ore the mining industry surrounding Itabira Complex depends on 3 large mines with an infrastructure of 7 pits, 11 sterile piles, 14 dams and 16 dykes to supply its operational needs as shown in Figure 1.

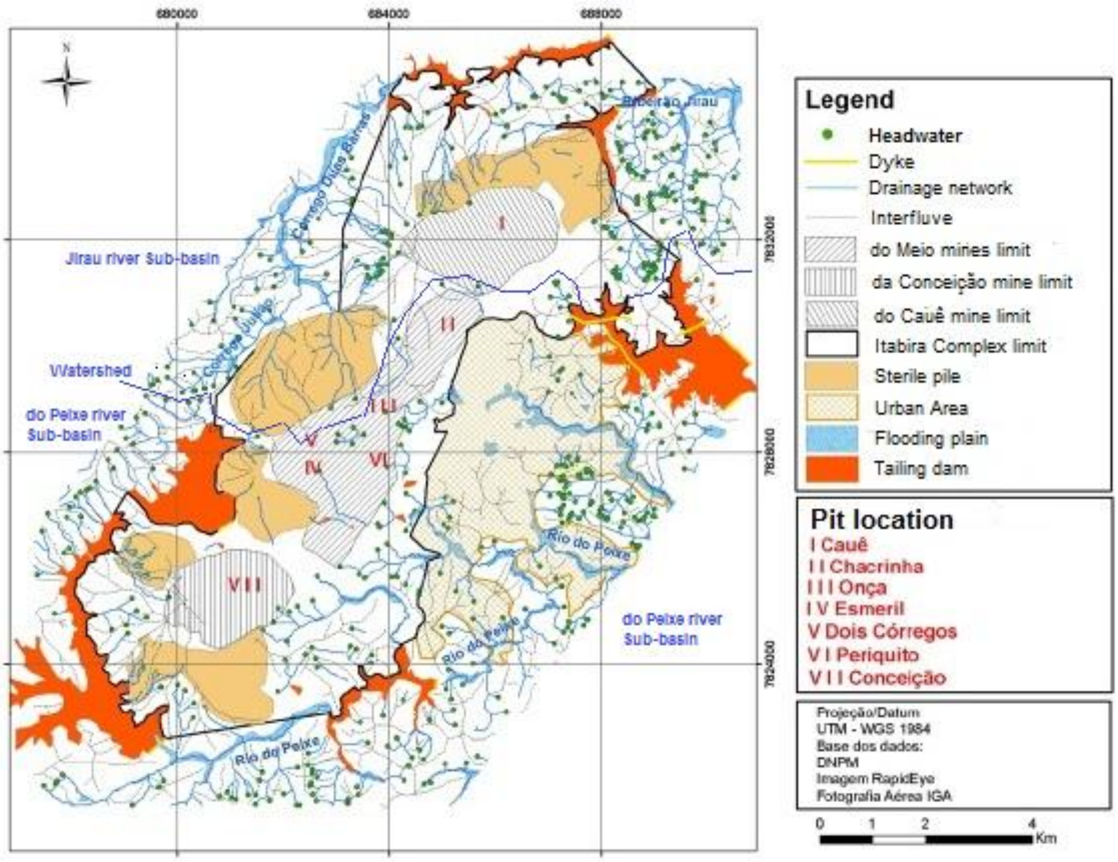

Figure 1 - Itabira Municipality and Mining Complex – Source: C.F.Andrade

These mining infrastructures contribute to constant growth near the valley formed by the do Peixe creek (river) channel. In addition, this region covers two important industrial districts where there are basic heavy industries, a campus university, and growing urbanization as shown in Figure 2.

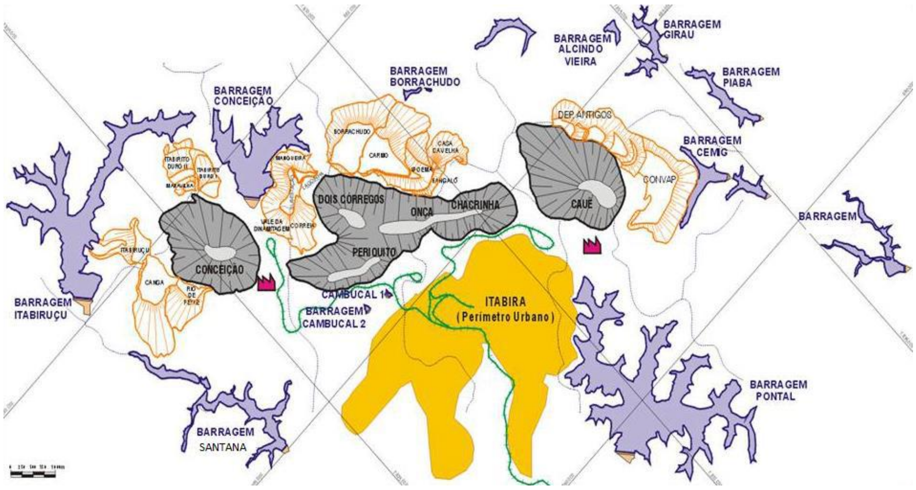

Figure 2 – Geographical growth conditioning – Source: Vale S.A.

The infrastructure of this area counts on a well-developed road and rail network, communication and water supply system and a robust medium and high voltage electricity distribution network.

Also in this valley, very close to the urban area, lies an important dam recently built for water supply named Santana Dam. Ponds and lagoons lie in close proximity suggesting that this area is prone to flooding.

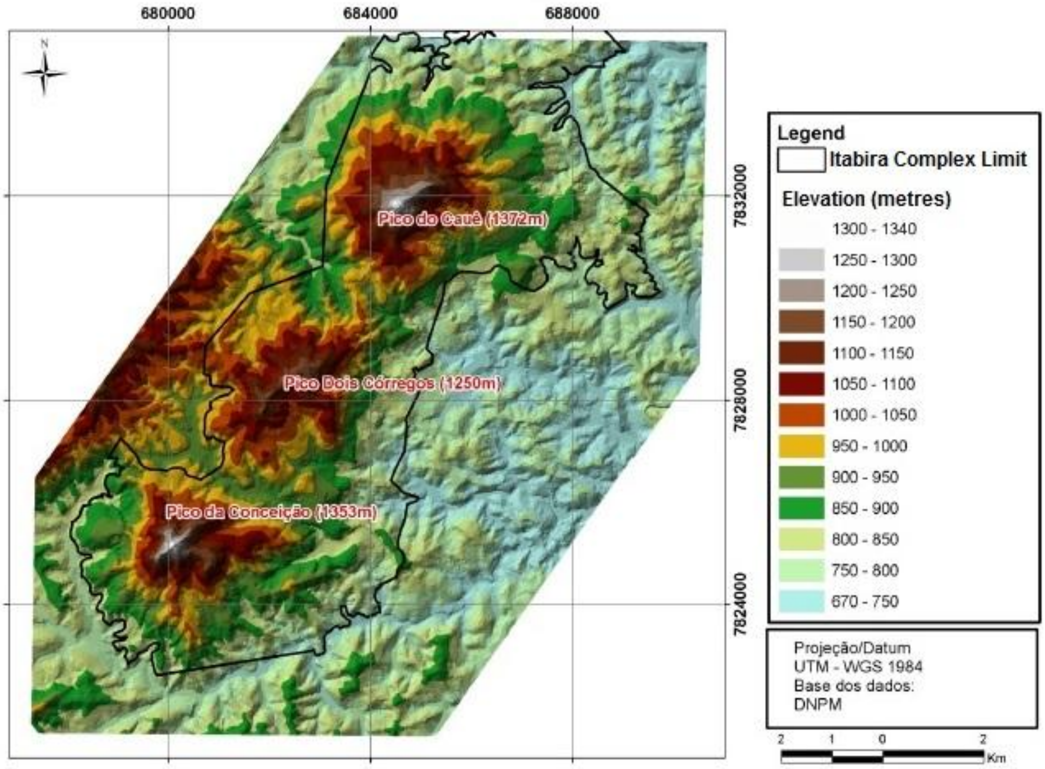

Figure 3 – Itabira Complex hypsometry – Source: C.F.Andrade

Upstream and very close to this dam there are four embankment dams: Itabiruçu, Conceição and Cambucal I and II. The first two are for tailing impoundment and the last two are for impoundment of liquid material generated by mining activities.

The hypsometry of this region as shown in Figure 3 indicates the vulnerability of the do Peixe creek valley in front of these five embankment dams. The Itabira Complex topography presented in the hypsometry indicates that Itabira Municipality is located between elevations 850m and 750m, and the do Peixe creek valley is located between elevations 750m and 670m indicating a drop of some hundred meters in a horizontal distance of approximately 5 kilometers, leading to steep slopes very close to, or even higher than, the critical slope and, depending on the water flow severity, it can lead to a torrential runoff regime ($Fr > 1$), in a supercritical flow.

3.2 Cambucal I and II dams

Cambucal I and II embankment dams are intended for the retention of liquid material from mining activities and solids from erosive processes enhanced by anthropic activities.

Interesting enough, there is an advanced erosive process on Cambucal I's left abutment, which could jeopardize its stability.

Both dams intercept the headwaters of a stream of the do Peixe river, and despite its low impoundment storage capacity, approximately 2 hm^3, they are located upstream of an important urban road with a considerable slope.

3.3 Santana dam

Santana embankment dam is a large weir quite close to an urban area. Its ridge is at the elevation of 750m, approximately, and presents a height of approximately 60 meters, damming a tailing volume of 11 hm^3. It was recently built and is intended to supply the mining operation as well as part of municipalities' water needs. It is in close proximity to two others tailing impoundment dams: one medium reservoir (Conceição) and another very large reservoir (Itabiruçu).

3.4 Conceição dam

On the west side of Itabira is Conceição embankment dam, built in the early 1980s between the do Meio and Conceição mines, with the purpose of intercepting Conceição creek in order to retain tailings generated in the mines and to provide process water for mining operations.

Its ridge is at the elevation of 970m and presents a height of approximately 60 meters damming a tailing volume of 40 hm^3.

Immediately downstream there are three sterile waste piles: Mangueira, Dinamitagem valley and Correia. All of them have already presented instability and are located quite near to the outlet stream as shown in Figure 1. This proximity can compromise the piles' stability, increasing significantly the volume of the flood in the event of a dam break.

3.5 Itabiruçu dam

Three kilometers upstream and 80 meters above Santana reservoir is the Itabiruçu tailing impoundment embankment dam. It was built in the early 1980s with a height of 50 meters and its original design foresaw a future raise of 20 meters. This raising took place in the early 2000s. It has a tulip intake followed by a 500 meters long gallery to control the reservoir level and a spillway on its left abutment, whose apron is very close to a federal highway which dangerously crosses its discharge flux. Its ridge is at the elevation of 830m and presents a height of approximately 70 meters damming a tailing volume of 230 hm^3.

The geology of this region presents residual soils, alluvial deposits, saprolitos and fractured schist. Although this is not an ideal setting, its bearing capacity is enough for a stable equilibrium condition, as long as the calculation assumptions are kept.

After construction the tailing deposition upstream gives rise to tensile stresses which are absorbed by the dam itself. Nevertheless during the construction of the downstream raising a new temporary configuration of tensile stresses occurs bearing more traction on the dam. This temporary tensile stress configuration is very difficult to combat and may give rise to severe and permanent consequences such as cracks or even angular/vertical displacements of the structure. This new configuration shall be classified as <u>Extreme Danger</u>. Moreover, during the dam raising the abutment foundation can generate settlements higher than previously expected leading to a stress decrease in the contact increasing the risk of fracking (hydraulic fracture) classified as <u>Dangerous</u>.

The concrete gallery is located in a region with a great possibility of occurrence of residual soil with high compressibility causing vertical displacements higher than the deformation capacity of the structural material causing the appearance of voids which, with the raising of the reservoir level, may eventually cause leaking of water under pressure through its joints with disastrous consequences for the dam structure.

Nearby the left bank of the outlet stream there are two sterile waste piles: Canga (Superior and Inferior). These piles have already presented a serious instability history in its drainage system. The proximity can compromise the piles' stability, increasing significantly the volume of the flood in the event of a dam break.

4 DOWNSTREAM HAZARD POTENTIAL CLASSIFICATION OF ITABIRA MUNICIPALITY DAMS

Having established the context of dam classification, the CNRH methodology was applied to evaluate the hazard potential of the five dams located in Itabira Municipality based on the consequences resulting from a dam failure (Table 3).

Dam	Reservoir Total Volume, hm^3	Loss of Life Potential	Environmental Impact	Socio-Economic Impact
Cambucal I and II	SMALL ≤ 5	LITTLE FREQUENT (no persons permanently occupy affected area downstream of the dam, but a locally-used road exists)	SIGNIFICANT (the affected area of the dam is not environmentally relevant)	LOW (a small concentration of residential areas are affected by the dam, (Itabira city)
DPA=12	(1)	(4)	(3)	(4)
Santana	MEDIUM 5 to 75	EXISTING (persons permanently occupy affected area downstream of the dam, and lives may be impacted)	SIGNIFICANT (the affected area of the dam is not environmentally relevant)	LOW (a small concentration of residential area affected by the dam)
DPA=21	(2)	(12)	(3)	(4)
Conceição	LARGE 75 to 200	LITTLE FREQUENT (no persons permanently occupy affected area	SIGNIFICANT (the affected area of the dam is not environmentally	LOW (industrial areas and infrastructure in

		downstream of dam, but a locally-used road exists)	relevant)	area are affected by the dam)
DPA=14	(3)	(4)	(3)	(4)
Itabiruçu	VERY LARGE >200	LITTLE FREQUENT (no persons permanently occupy the area, but a locally-used road exists – MG129)	SIGNIFICANT (the affected area of the dam is not environmentally relevant)	NON-EXISTING (infrastructure and navigational services do not exist in the area affected by the potential failure of the dam)
DPA=12	(5)	(4)	(3)	(0)

Table 3: DPA classification of analyzed dams

Therefore, from the five analyzed dams, four were classified as medium hazard (Cambucal I and II dam, DPA scored 12; Conceição, DPA scored 14 and Itabiruçu scored 12); Santana was classified as a high hazard dam (DPA scored 21).

It is important to note that downstream hazard potential classification in this case revealed to be obvious and analyses of dam-break flood prone areas is not necessary to be performed because industrial and residential areas clearly exist and economic impacts will most likely occur as a result of an eventual dam failure. In fact, the analyzed dams constitute the typical example where the volume of information required for their classification is not directly related to the importance of the downstream valleys demographic and economic level of occupation. Indeed, paradoxical cases are observed in which the degree of characterization of the occupation in the downstream valleys is much larger in terms of weakly populated areas, than in densely populated valleys. This contradiction arises from the fact that the hazard potential in those former types of valleys can be obvious, as the location in the dam-break flood prone area of important assets and economic developments is, in those situations, easy to be identified.

5 CONCLUSIONS

Tailing dams has specific characteristics such as constant changes in size, reservoir volume and general behavior which continuous and hazardously change its state of stress.

Mine tailings impoundment failures are occurring at relatively high rates. In global terms, the mining industry has experienced several significant tailing impoundment failures over the past 50 years. The rate of failure has actually increased in recent years since a previous peak that occurred in the early-mid 1930's. Many of these failure events have resulted in massive damage, severe economic impact and loss of life. The rate of failure is approximately ten times that for water retention dams.

In Brazil, Law 12.334 of September 20, 2010 (the "Dam Safety Law") defines the main instruments for the national dam safety policy, including a system for the classification of dams according to risk and downstream hazard.

This paper presents an example of the application of the CNRH downstream hazard potential classification of five dams located in Itabira Municipality.

It is important to note that downstream hazard potential classification in these cases was obvious and analysis of dam-break flood prone areas was not necessary because assets clearly exist and impacts will most likely occur as a result of an eventual dam failure.

From the five analyzed dams, three were classified as medium hazard and the two remaining one as a high hazard dam.

Note that those five dams two are small dams, i.e., of relatively low dimension. Therefore, from the experience with the application of CNRH Resolution No. 143 to those practical cases, it was possible to verify that even very small dams can easily have high downstream hazard potential classification. Indeed, the Brazilian regulation, as the ones enforced by dam safety laws in many countries, seems to be rather conservative as it is sufficient a very limited number of individuals at risk to classify a dam as a maximum hazard.

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