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Numerical analysis and study of stress and deformation in comparison to readings from instrumented swedish boxes in a concrete-faced rockfill dam located in Peru

Análise numérica e estudo de tensão e deformação em comparação com leituras em caixas suecas instrumentadas em uma barragem de enrocamento com face de concreto localizada no Peru

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Abstract: In the field of engineering, Concrete-Faced Rockfill Dams (CFRDs) have been recognized as an increasingly prominent solution, driven by studies and a history of real-world cases. The successful implementation of this type of dam is based on empirical designs, supported by data from previous projects, and monitoring its performance through surveillance. A point of attention is the presence of fissures and cracks in the concrete slab covering the upstream slope, caused by the movement and deformations of the dam's mass. Additionally, the valley geometry between the abutments also plays a crucial role, impacting the redistribution of loads and generating deformations in the mass. This study aims primarily to compare, through computational tools and field data, the behavior of a different material applied in the dam.

Keywords: Rockfill dam with concrete facing; Instrumentation; Stress and deformation.

Resumo: No campo da engenharia, as Barragens de Enrocamento com Face de Concreto (BEFC) têm se destacado como uma solução cada vez reconhecida, impulsionada por estudos e histórico de casos reais. A implementação bem-sucedida desse tipo de barragem se baseia em projetos empíricos, apoiados por dados de obras anteriores e acompanhamento de seu desempenho por meio de monitoramento. Um ponto de atenção é a presença de fissuras e trincas na laje de concreto que cobre o talude de montante, causadas pela movimentação e deformações do maciço da barragem. Além disso, a geometria do vale entre as ombreiras também desempenha um papel importante, impactando a redistribuição das cargas e gerando deformações no maciço. Este estudo tem como objetivo principal comparar, por meio de ferramentas computacionais e dados de campo, o comportamento de um material diferente aplicado na barragem.

Palavras-chave: Barragem de enrocamento com face de concreto; Instrumentação; Tensão e deformação.

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1. Introduction

The construction of dams with the purpose of impounding water for consumption, irrigation, and power generation has ancient roots in various cultures. Over the years, there has been an increase in both the quantity and height of these structures (CRUZ, 1996), resulting in multiple advantages, such as flood protection, water supply, drought resilience, irrigation, navigation, waste management, and electricity production. Technological advancements, including numerical and computational methods, have established a scientific foundation that ensures safety in the design, construction, and operation of dams. The type of dam is determined by site conditions, available materials, and the construction process, with homogeneous earth dams and mixed earth and rockfill dams being the most common due to topography and material availability, designed with versatile foundations for strong soils.

When planning a dam, it is essential to consider various aspects, such as costs, available materials, accessibility, and environmental impact, which influence the choice of the most suitable dam type. The concrete-faced rockfill dam (CFRD) is an option frequently studied and increasingly adopted globally, especially in narrow valleys, due to the balance between cost and safety.

The design of this type of dam takes into account various factors, including the availability of suitable material for the rockfill with the correct gradation and the composition of the materials for the concrete face slab of the dam. The concrete slab not only contributes to overall stability but also plays a crucial role in dam sealing.

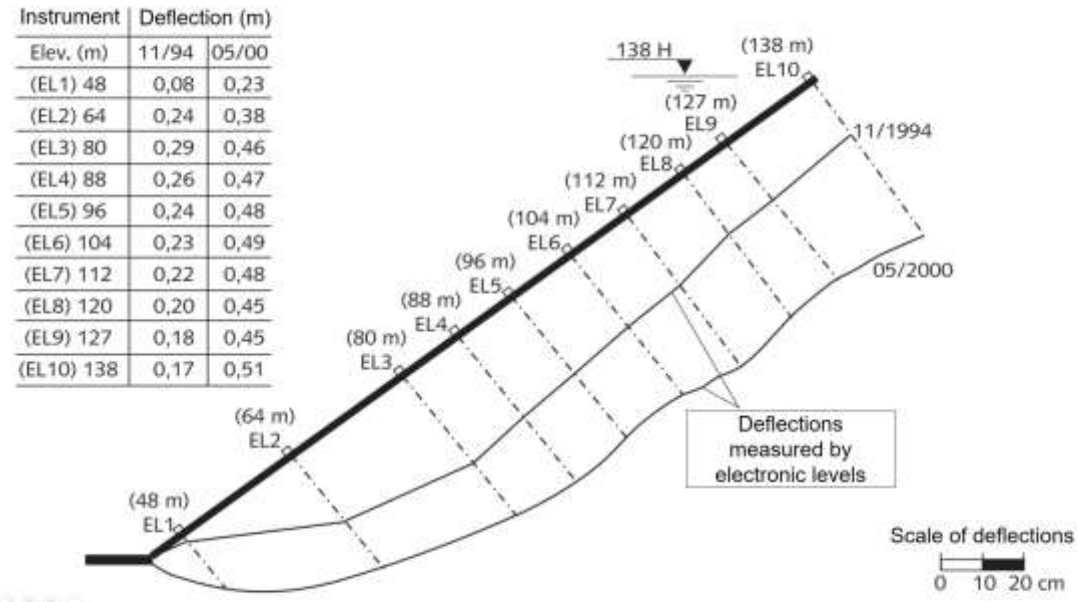
The design of this dam is based on empirical criteria, mathematical models using finite methods, reduced hydraulic models, and previous project experience. Safety is the top priority in this type of construction, from the development of feasibility projects to executive projects, ensuring appropriate construction. It is worth noting that the breach of any dam can have devastating impacts on the environment and society, leading to irreparable losses in social and economic terms.

The approach of the concrete-faced rockfill dam, which combines rocky materials with a concrete layer, offers several advantages over more traditional alternatives, such as earth dams with compacted clay cores and mining tailings dams. The construction methodology of this dam stands out for its agility and speed. The absence of pore pressure in the mass is an additional advantage. The natural stability of the structure and the straightforward treatment of foundations, including plinth injection, allow for greater heights, increasing retention capacity.

The combination of these advantages reflects the increasing construction of this type of dam. The pursuit of safe and cost-effective construction is the primary goal for any developer. A significant concern regarding this type of dam is the upstream concrete sealing slab. Cracking problems in this slab affect the dam's impermeability. The emergence of cracks is often caused by incompatibility between the rockfill inside the mass and the concrete slab. The presence of layers of soil or altered rock in the foundation can also compromise the interaction between the slab and the mass, leading to unfavorable movements and cracks.

The complexity of rockfill analysis arises from simulating compaction, including layer-by-layer embankment replication, roller compactor usage, moisture considerations, material mineralogy, and grain behavior during construction. The design of rockfill structures often relies on empirical geotechnical parameters, supported by literature references and previous project studies, along with continuous monitoring of geotechnical instruments during construction, allowing parameter calibration based on obtained results.

In the study by Penman and Rocha Filho (2000), the evolution of displacements along the concrete surface of the Xingó dam over approximately six years is presented. This evolution process is primarily related to the rearrangement of particles in the concrete, as visualized in FIGURE 1. Remarkably, displacement values increased almost twofold during this period. These changes in displacements are attributed, in part, to the interaction of water infiltration due to the presence of cracks in the dam's slab.



Instrument	Deflection (m)	
Elev. (m)	11/94	05/00
(EL1) 48	0,08	0,23
(EL2) 64	0,24	0,38
(EL3) 80	0,29	0,46
(EL4) 88	0,26	0,47
(EL5) 96	0,24	0,48
(EL6) 104	0,23	0,49
(EL7) 112	0,22	0,48
(EL8) 120	0,20	0,45
(EL9) 127	0,18	0,45
(EL10) 138	0,17	0,51

Figure 1 – Deformations on The Concrete Face of Xingó Dam
Source: Cruz (2014).

The Chaglla Concrete-Faced Rockfill Dam, part of the Chaglla Hydroelectric Complex in Peru, is notable for its installed capacity of 450 MW and a height of 212 meters, with a total volume of 8,400,000 cubic meters. The viability of this project was based on practical factors such as the valley's shape, the use of special joint seals, and the incorporation of non-conventional materials. The construction of the dam took place between 2011 and 2015.

The focus is on analyzing the behavior of the Chaglla Dam, using instrumentation and three-dimensional simulations of stress and static deformation. This analysis aims to replace conventional rockfill with gravel, a highly deformable material. The strategy is supported by similar global experiences, where professionals and experts use references from past projects for the sizing and design of Concrete-Faced Rockfill Dams. Dam safety is assessed through monitoring with various types of geotechnical instruments, while economic feasibility is influenced by the availability of suitable materials (FERNANDES, 2007).

The dam plays a significant role in water containment, with a design that considers overtopping. The technique of constructing rockfill dams began in the United States between 1850 and 1870, expanding globally since then. During construction, instrumentation monitors both internal and external global movements of the rockfill.

To predict the behavior of the Chaglla Dam, a three-dimensional stress and deformation analysis is used, comparing results with initial instrumentation readings. Simulation with the use of gravel, an unprocessed material, is also performed. Through the MIDAS GTS NX software and the Finite Element Method (FEM), a comprehensive analysis is conducted, presenting stress and deformation results. Three points near the instrumentation are meticulously analyzed for comparative reference (CRUZ, 2014).

2. Methodology

The Chaglla hydroelectric complex is situated on the Huallaga River in the eastern slopes of the Andes, directed towards the Amazon Rainforest. Its location presents geotechnical challenges due to the terrain characteristics, such as a rocky mass of limestone and rugged terrain with deep valleys and steep slopes. The complex geology of the region, including faults and susceptibility to limestone dissolution phenomena, has made the investigations and project implementation challenging (JEISS, 2015).

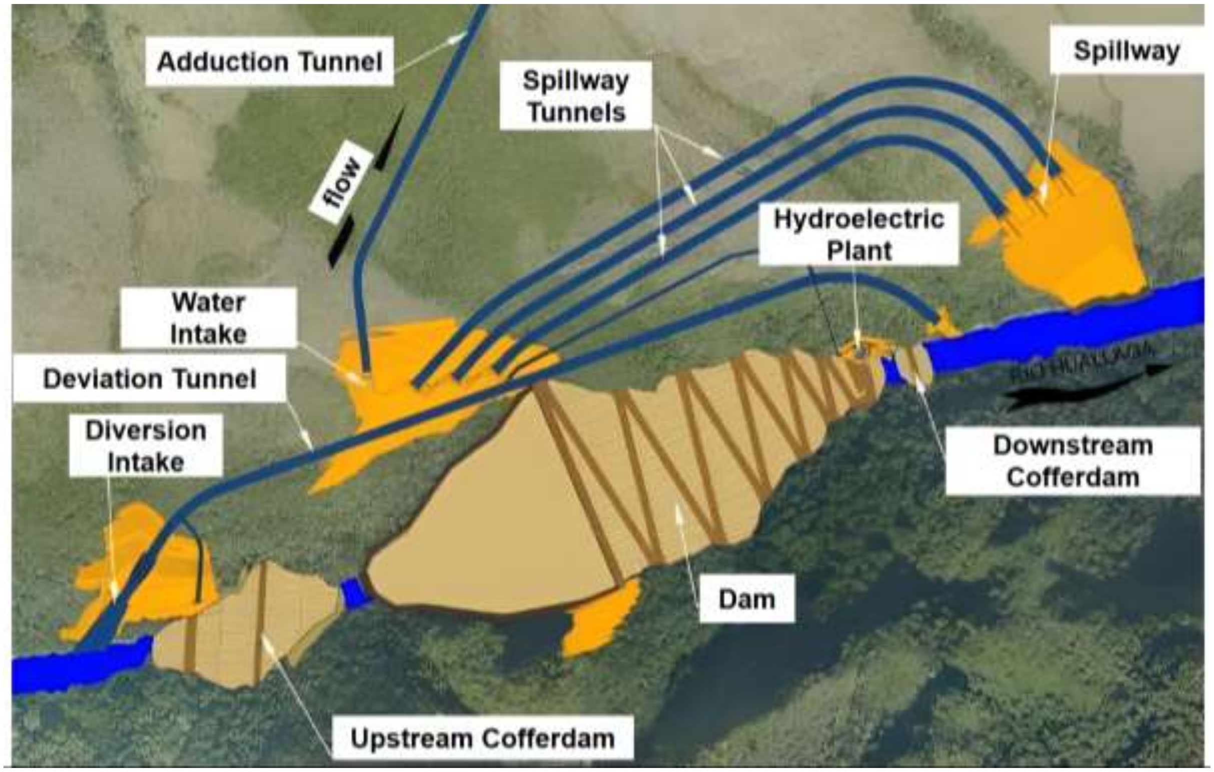


Figure 2 – General Arrangement of the Chaglla Enterprise
Source: Intertechne (2015).

The Chaglla hydroelectric complex encompasses several significant structures. The aduction tunnel, 14.4 km long, represented the largest part of the underground excavations and was built using the Drill And Blast method. The spillway was designed to handle maximum floods of approximately 5600 m³/s and has three pressurized tunnels with radial gates. The open-air powerhouse houses two Francis-type turbines. The dam under study is a rockfill type with a concrete face, 212 m high and about 8,400,000 m³ in volume, located in the Huallaga River valley. The adjacent small hydroelectric plant has an installed power of 6 MW and its aduction tunnels are close to the spillway.

The main project data include a power of 450 MW, location on the Huallaga River, Peru, construction period from 2012 to 2017, maximum height of the main dam of 212 m and spillway discharge capacity of 6,530 m³/s (INTERTECHNE, 2017). When the characteristics of the valley and deformation modulus of the planned rockfill embankment are arranged in the graph proposed by Pinto (2007), shown in FIGURE 3, whose shape factor A/H^2, where (A) represents the area of the concrete face and (H) represents the height of the dam, this factor is quite low, about 1.50 represented in red, with this it is possible to observe that Chaglla is positioned in a zone of the graph where special care is required for the design and execution of the dam, having the blue line as a divider between dams that showed better performance than those that showed some type of incident during operation. The area (A) of the concrete face of the Chaglla Dam is 59,000.00 m².

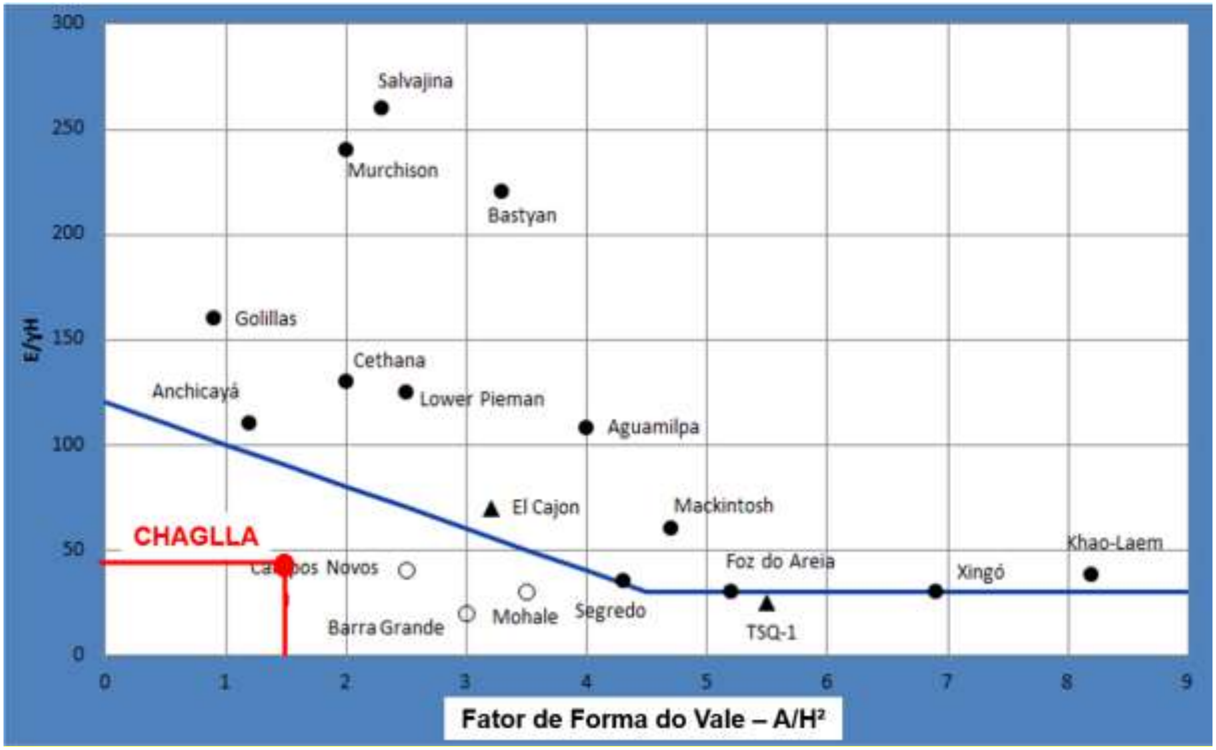


Figure 3 – Relation of the A/H² (Shape of the Valley)
Source: Pinto & Marques (2007).

3. Instrumentation (Swedish Boxes)

Swedish boxes or hydraulic cells are devices composed of concrete blocks, flexible pipes, and interconnected steel pipes, used to measure settlements in embankments during the construction and operation of the reservoir (SILVEIRA, 2006). Usually installed horizontally within the embankment, these cells are interconnected with an instrumentation cabin by air, reading, and drainage pipes.

Through hydraulic connections that cross the embankment, differential settlements between the zones of the embankment are considered to avoid performance problems and collapse (CRUZ, 2014). Other instruments used to measure deformations and settlements include extensometers, electric cells, Km meters, USBR torpedoes, and magnetic rings, with inclinometers being installed in some situations (CRUZ, 2014). For the Chaglla dam, settlement and deformation meters include Swedish boxes, inclinometers with magnetic plates, and topographic points (INTERTECHNE, 2016).

Settlement estimates have proven more realistic for predicting post-construction settlements since modeling the complexities and heterogeneities of embankments in mathematical models is challenging (CRUZ, 2014). In TABLE 1 below are presented post-construction settlements ® and their relationship with the height (H) of the dam (INTERTECHNE, 2015).

TABLE 1 shows that the largest displacements are linked to the construction method if it was cast or compacted. The R/H (settlement/dam height) ratio is not exclusively determined by the construction method as it can vary due to other factors such as base material. The Chaglla dam has compacted embankment and is 200m high, with a post-construction settlement of up to 0.5% of the height (INTERTECHNE, 2015).

Table 1 – Post-Constuction Settlements.

Work	**Country**	**Height (m)**	**Length (m)**	**L/H**	**A/H^2**	**Settlement (m)**	**R/H (%)**	**Construction**
Cogoti	Chile	85	160	1.88	2.21	1.08	1.27%	Cast
New Exchequer	EE.UU	150	427	2.85	-	1.49	0.99%	Cast + Comapacted
Les Fades	França	68	235	46	3.57	0.158	0.23%	Comapacted
Outardes 2	Canadá	55	350	6.36	-	0.007	0.01%	Comapacted
Shiroro	Nigéria	125	560	4.48	-	0.065	0.05%	Comapacted
Fortuna	Panamá	60	300	5.00	-	0.52	0.87%	Comapacted

Souce: Intertechne (2015).

Several factors can affect the mechanical behavior of embankments, as per Materon (1983; cited in Basso, 2007): mineralogy, granulometry, void index, particle shapes, grain fracture resistance, size, texture, water content, and loading speed. FIGURE 4 illustrates the main factors that influence the mechanical behavior of embankments.

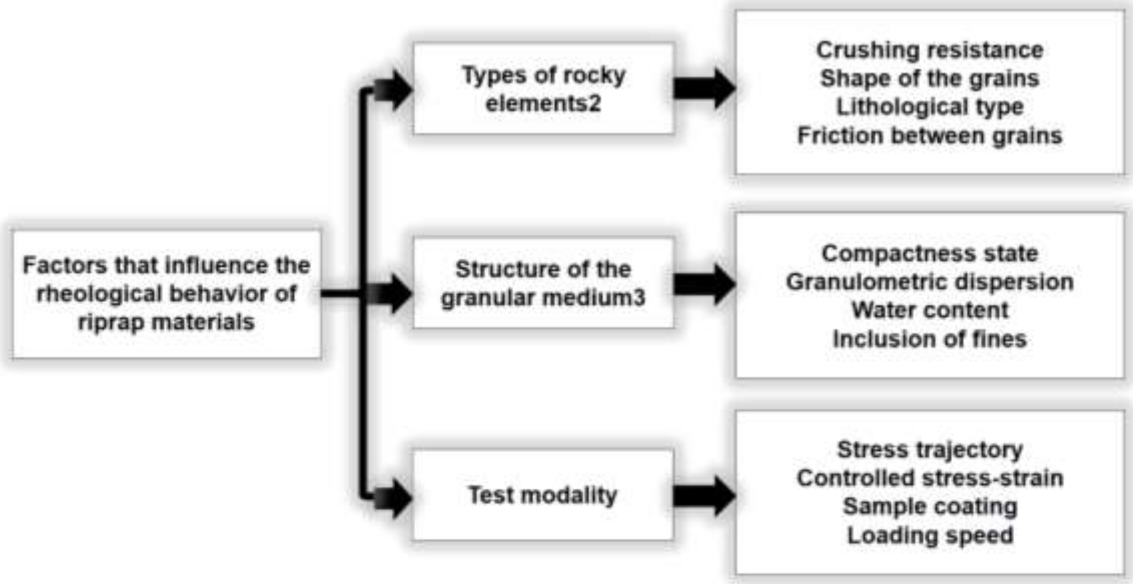


Figure 4 – Behavior Factors of the RipRap
Source: Silva (2007).

At the Chaglla dam, the reference values of the Swedish boxes were determined in an adapted way, considering the specific behavior observed in the construction and filling of the reservoir. These values took into account the differentiated influence of the reservoir thrust, depending on the location and proximity of the instrument to the concrete face (INTERTECHNE, 2015).

Given that the body of the dam contains heterogeneous materials in different zones, sometimes even different in the same zone due to the origin of materials from various loan areas, the analyses of cell settlements were conducted in conjunction with attached instruments. This occurred whenever readings exceeded reference values (INTERTECHNE, 2015).

FIGURE 5 compares the 2016 readings with the reference values of the instruments. These values were established based on statistical data from other works, seeking to predict post-constructive displacements in a more realistic way.

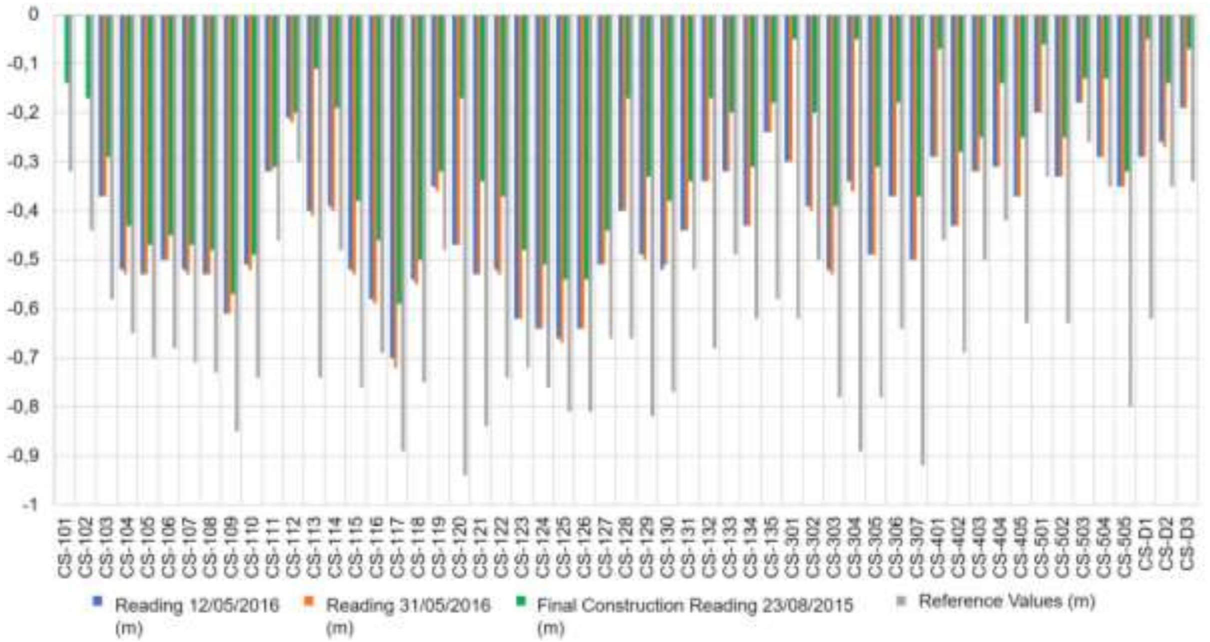


Figure 5 – Reading of Deformations of the Swedish Boxes
Source: Intertechne (2016).

In general, a trend of stabilization is observed in the structures of the Swedish boxes. The deformation of the dam crest after the reservoir is filled contributes about 0.04% to the total deformation recorded (INTERTECHNE, 2016).

4. Strex and Strain Analysis

In this context, we will explore the presentation of computational scenarios that aim to provide a comprehensive understanding of tensions and deformations, with a specific focus on areas adjacent to the monitoring points installed in the Dam. One of the main goals is to enhance the stiffness of the interface between the concrete face and the rockfill, through an alternative analytical approach. The elaboration of this study is based on the principles and objectives of parametric and analytical analysis, seeking to expand and validate attention towards holistic analysis. This involves a direct consideration of the effects of deformability parameters of materials. These parameters include:

The mechanical characteristics of the rocky material used in the construction of the Concrete Face Rockfill Dam, the geometric configuration of the internal layers of the Dam, including the density of materials and their distribution in the planned section, the overall mechanical behavior of both the Dam mass and the support foundation, comparison of material deformability parameters, involving data from laboratory tests and information obtained through retrospective analysis of existing monitoring instrumentation.

The proposed evaluation scenarios mainly encompass the complete replacement of material 3B (Rockfill) with material 3B' (Gravel) through a three-dimensional analysis. In addition, a two-dimensional evaluation will present the replacement of 15 and 30-meter strips, adjacent to the concrete slab, with material 3B' (Gravel). To establish comparisons between three-dimensional and two-dimensional analyses, results were confronted with monitoring measurements obtained in Swedish boxes implemented in the dam body.

In this way, this study led to a complete evaluation between various scenarios, taking into account different characteristics of materials and data provided by monitoring instrumentation. This will play an important role in enriching understanding of structural behavior of a Concrete Face Rockfill Dam.

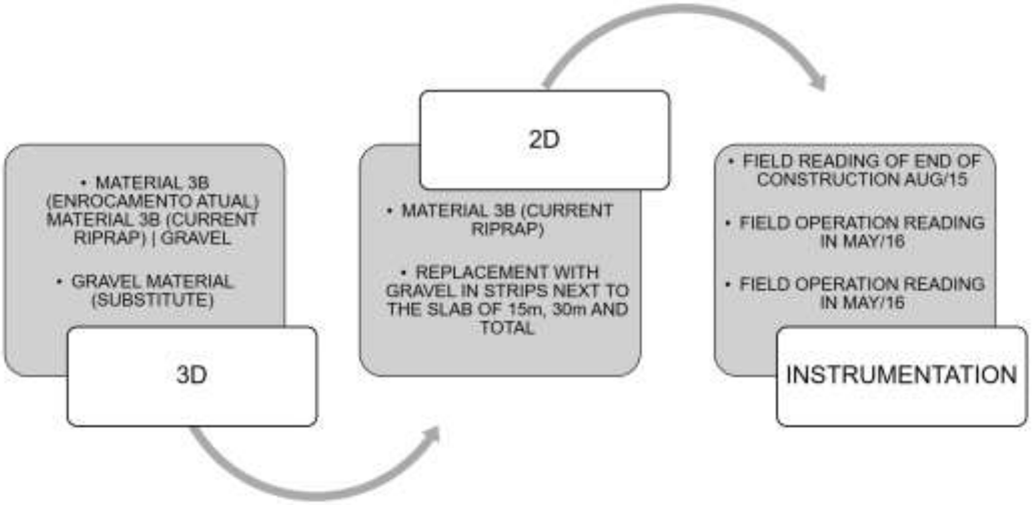


Figure 6 – Evaluation Scenarios
Source: Authors (2017)

In the case of a dam with a height exceeding 200 meters, built in a closed topography valley, as illustrated in FIGURE 7 below, an approach was adopted that includes a step-by-step analysis of the construction process. This approach aims to follow the progression of the landfill increase through evolutionary calculations. The analysis is conducted following the same criterion used for material 3B, which involves considering the construction of the landfill in layers, respecting the stages and construction sequence previously defined by the builder.

Figure 7 – Valley Fitted in the Dam Support Region
Source: Intertechne (2016).

Therefore, during the modeling process, five stages of partial constructive loading were used and a final stage simulating the reservoir loading phase, simulating the schedule and planning elaborated by the builder according to FIGURE 8 below.

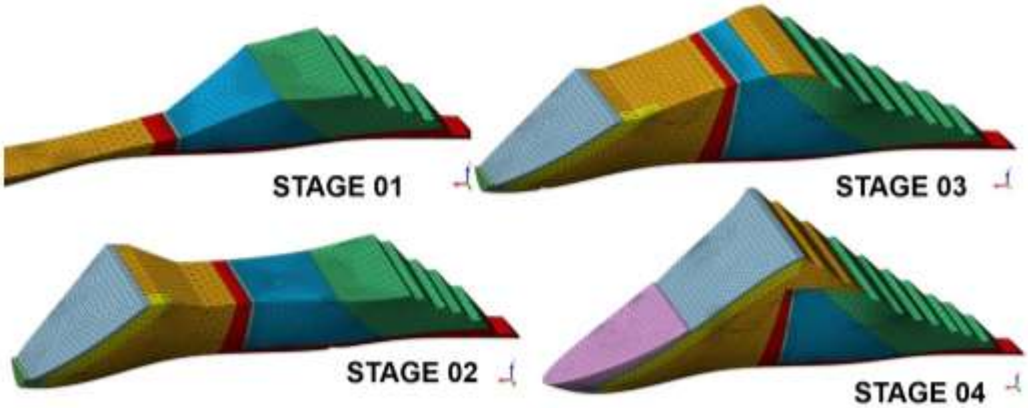


Figure 8 – Stages of Construction of the Chaglla Dam
Source: Intertechne (2017).

During the initial stage of the project's conception by the engineering company, the arrangement of materials in the rockfill dam with a face was strategically planned. The main objective was to confer to the embankment structure a global capacity to resist minimal deformations, harmonizing intrinsically with the topography and composition of the site. Regarding the larger elements of material 3B (Rockfill), the initial resistance parameters were progressively adjusted throughout the dam's construction process.

The deformability indices of the materials were obtained from plate load tests, previously carried out in similar projects, supported by reliable technical references and the experience accumulated by Intertechne in comparable ventures. In addition, the deformability indices were refined using tools such as the Swedish box and magnetic plates, contributing to more precise calibration. The optimization of this parameter was carried out during the dam's construction, through the application of a three-dimensional model that considered the evolution of conditions throughout the process.

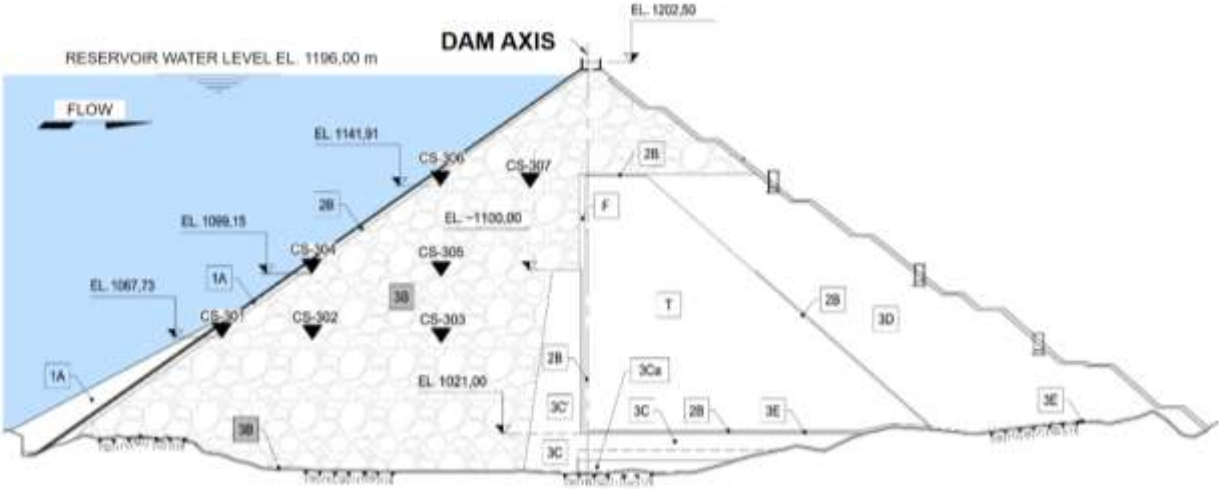


Figure 9 – Typical Section of the Dam
Source: Intertechne (2017).

Figure 10 – Material 3B Rockfill and 3B' Gravel
Source: Odebrecht (2014)

Table 2 – Dam Materials

Zone	**Material Description**	**Ø Max (cm)**	**Fines (%)**	**Layer Thickness (cm)**
1A	Silt - Colmatant Material	0,10	-	25,00 (LOOSE)
1B	Random	20,0	Sem finos	40,00 (LOOSE)
2A	Sand	1,91 (3/4")	< 5%	40,00
2B	Single Transition	10,00	< 8%	40,00
3B'	Natural Gravel From The River Bed	50,00	< 8%	60,00
3B	Healthy Rock Rockfill	50,00	< 8%	60,00
3C	Healthy Rock Rockfill	70,00	< 5%	80,00
3C'	Healthy Rock Rockfill	35,00	< 5%	40,00
3Ca	Rockfill With Fines	70,00	< 10%	80,00
3D	Healthy Rock Rockfill	70,00	< 8%	80,00
3E	Fine Rockfill	30,00	< 10%	80,00
4	Healthy Rock Blocks Arranged On The Downstream Face Of The Dam With Most On The Horizontal Face	120,00		
F	Filter	20,00	< 5%	40,00
T	Material Of Moderately Or Slightly Altered Or Fractured Rock	35,00	< 15%	40,00

Source: Intertechne (2015).

Table 3 – Geotechnical Parameters of the Materials.

Zone	**Material**	**Specific Weight**	**E (MPa)**	**Poisson**
1B	Random	20	80	0,3
3A	Rock Riprap Sã	20	110	0,3
3B	Rock Riprap Sã	21	110	0,3
3B’	Natural Channel Gravel	21	180	0,3
3C	Riprap With Fines	21	100	0,3
3D	Rock Riprap Sã	21	100	0,3
-	Alluvium	20	110	0,3
-	Concrete	25	21000	0,25
F	Filter	20	110	0,3
T	Medium Or Little Altered Or Fractured Rock Material	21	80	0,3

Fonte: Intertechne (2015).

Next, a simulation of three-dimensional and two-dimensional stress and strain behavior is presented through numerical modeling. This simulation was conducted primarily using the MIDAS GTS NX software, which executes the model analytically through the Finite Element Method (FEM). However, it allowed for the evaluation of the results of the behavior of the Chaglla concrete-coated riprap dam, if material 3B’ (gravel) were employed in zone 3B (riprap) of the zoning. The analysis was carried out using a model based on a Linear Elasticity equation. Thus, the three-dimensional studies and simulations present results related to the displacements of the riprap mass. This would allow a comparison with data from measuring instruments during the final phase of construction.

5. Three-Dimensional Analysis (3d)

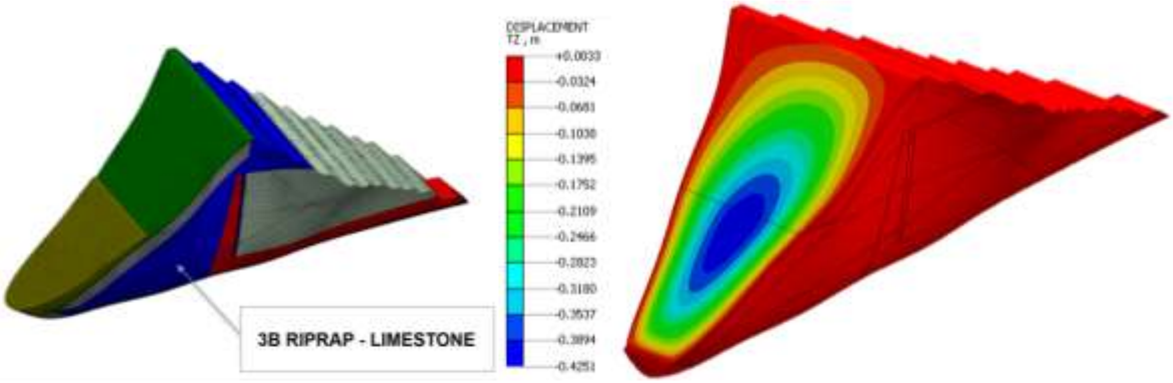


Figure 11 – 3d Analysis - Isometric View of the Dam with The Design Materials - Material 3b
Source: Authors (2017)

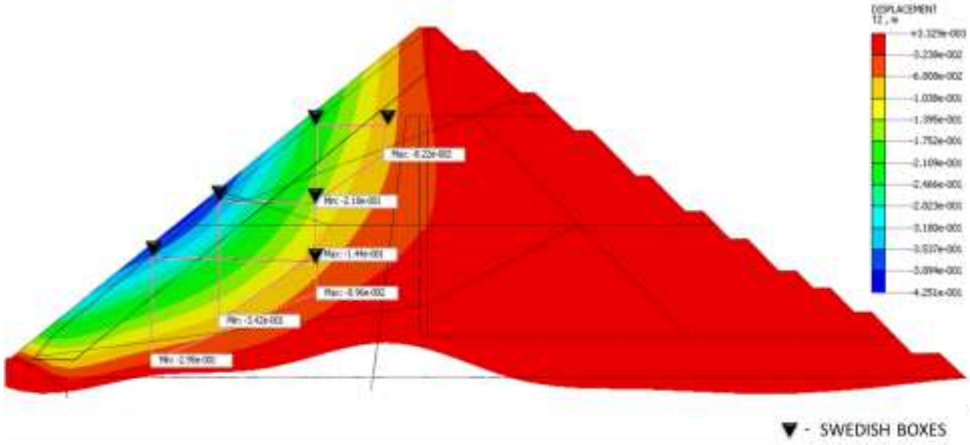


Figure 12 – Material 3b - Current Riprap Vertical Displacement Midas Model - Swedish Boxes
Source: Authors (2017)

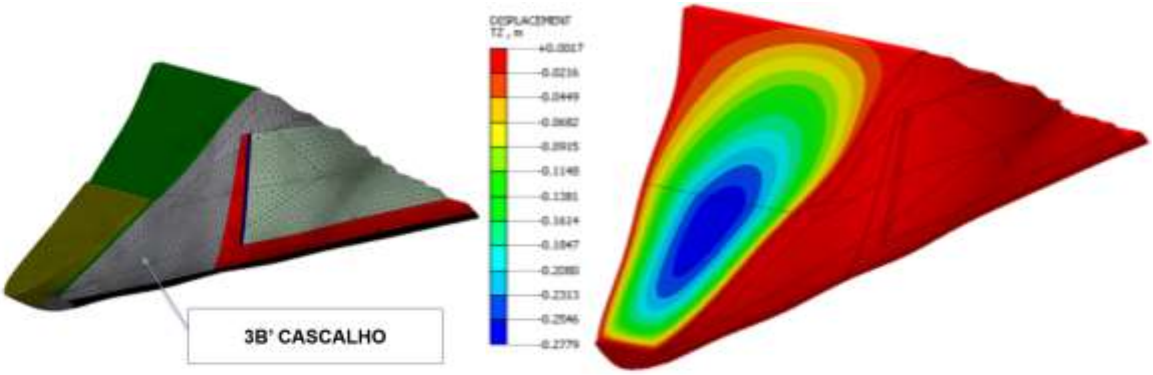


Figure 13 – Material 3b' – Gravel – Isometric View
Source: Authors (2017)

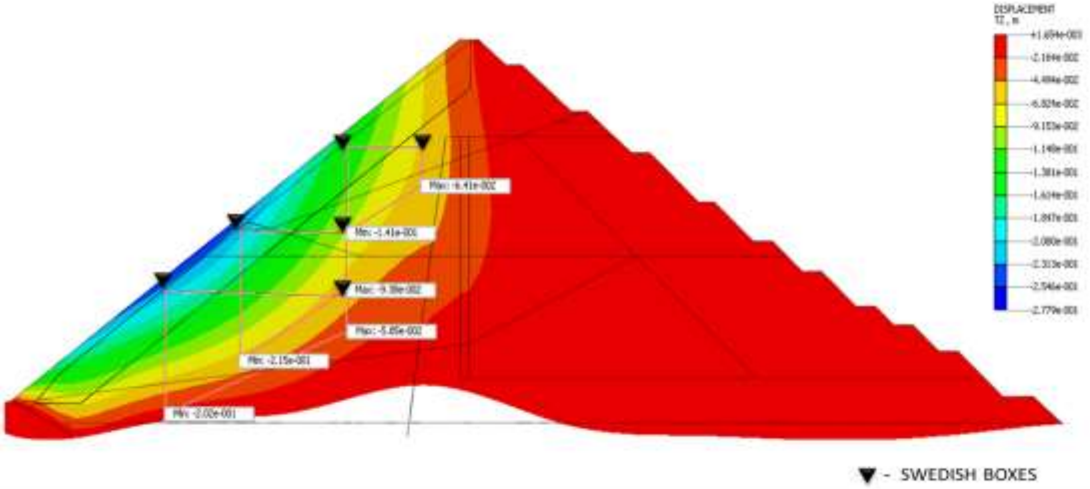


Figure 14 – Material 3b' - Gravel Vertical Displacement Midas Model - Displacement in the Swedish Boxes
Source: Authors (2017)

From the two-dimensional analysis carried out in two distinct scenarios for comparison purposes, as shown in TABLE 4 below, it is evident that the most effective alternative consists of the complete replacement of the Riprap 3B material by Gravel. The numerical simulation revealed that at the most critical point, using the 3B material, there is a displacement in the direction of the slab of 51 cm, while with the 3B' material (Gravel) this displacement is reduced to just 34 cm. In other words, the deformation of the Gravel is 18 cm less than that of the 3B material. Summarizing the results for the other scenarios, in sections of length 128 m, the displacements in the direction of the slab are as follows:

Material 3B - Riprap = 0.51 m

Material 3B' - Gravel = 0.34 m (Total Replacement)

This represents a notable improvement of approximately 67% in reducing displacement in the direction of the slab when opting for Gravel material instead of Riprap 3B.

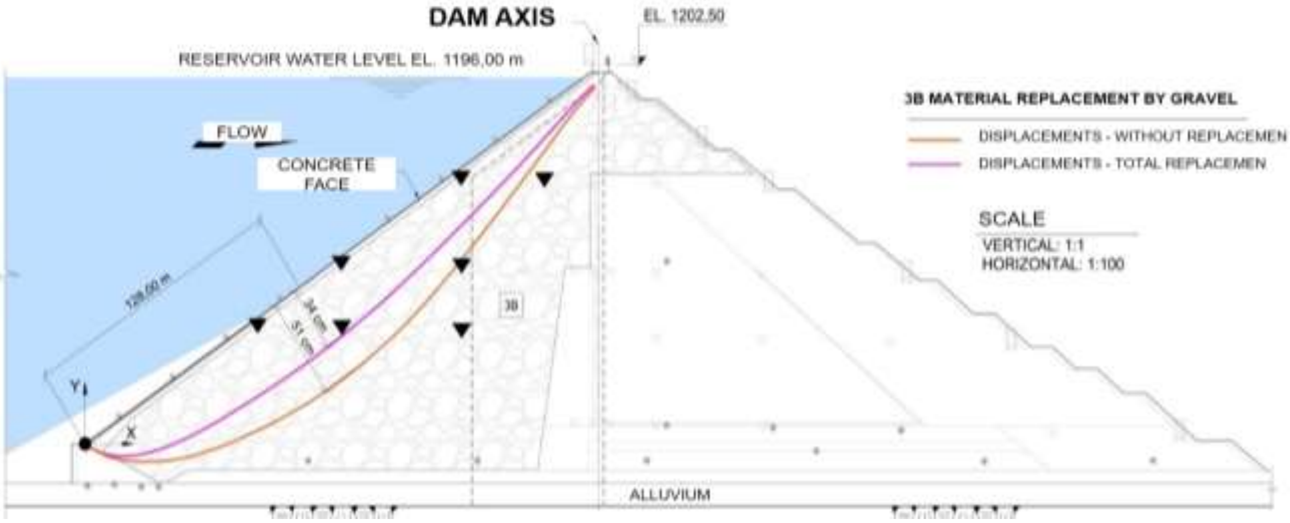


Figure 15 – Slab Displacements (3d Model)
Source: Authors (2017)

Table 4 – Comparison Table of Vertical Displacements

Swedish Box	Installation Quota (m)	Vertical Displacement Midas Material 3B (m)	Vertical Displacement Midas Gravel (m)	Final Reading Construction 23/08/15 (m)	Reading 12/05/2016 (m)	Reading 31/05/2016 (m)
CS-301	1067.69	-0.30	-0.20	-0.05	-0.30	-0.30
CS-303	1065.31	-0.09	-0.06	-0.39	-0.52	-0.53
CS-304	1099.15	-0.34	-0.22	-0.05	-0.34	-0.34
CS-305	1097.80	-0.14	-0.09	-0.31	-0.49	-0.49
CS-306	1141.91	-0.22	-0.14	-0.18	-0.37	-0.37
CS-307	1141.07	-0.08	-0.06	-0.37	-0.50	-0.50

Source: Authors (2017)

6. Two-Dimensional Analysis (2d)

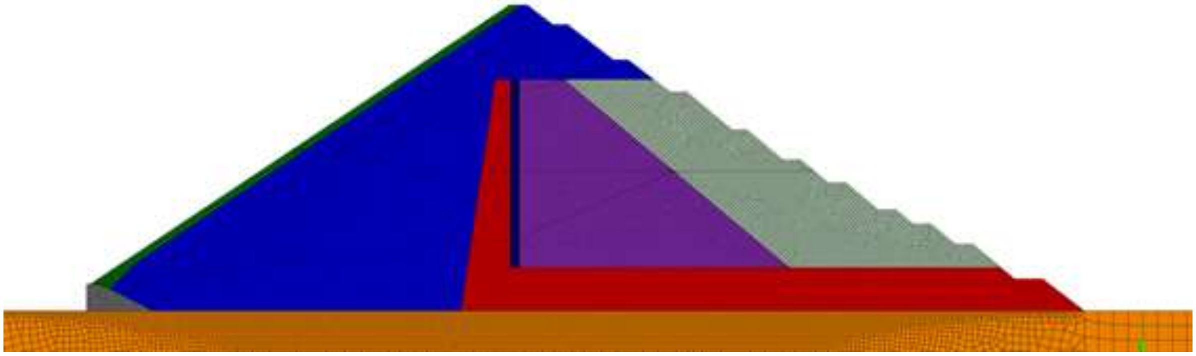


Figure 16 – 2d Analysis - Cross Section of the Dam as the Design Materials
Source: Authors (2017)

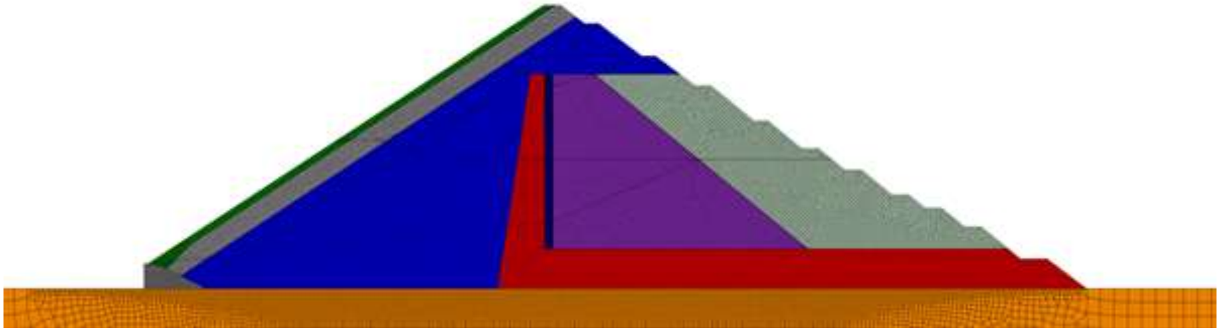


Figure 17 – Analysis - Cross Section of the Dam with 15m Replacement of Material 3b by 3b'
Source: Authors (2017)

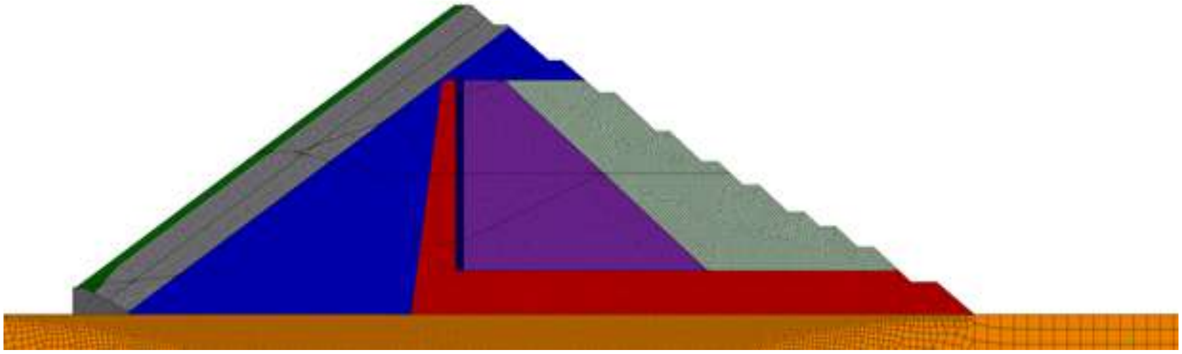


Figure 18 – 2d Analysis - Cross Section of the Dam with 30m Replacement of Material 3b by 3b'
Source: Authors (2017)

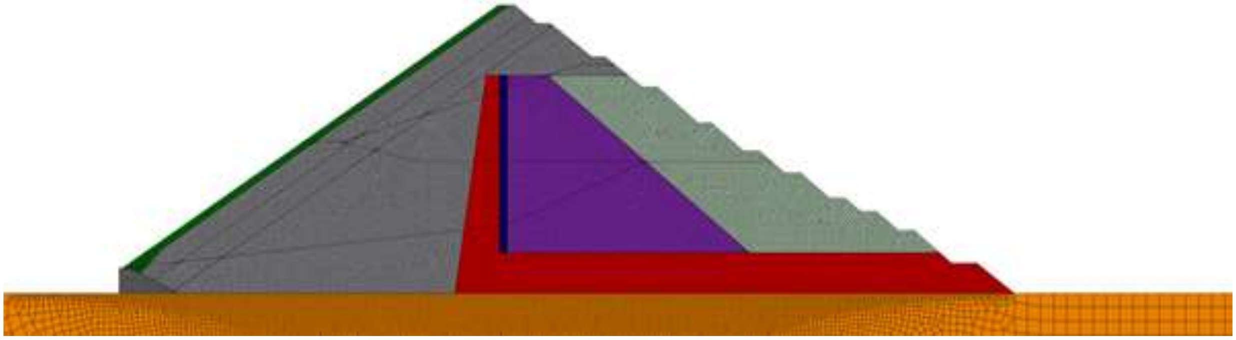


Figure 19 – 2d Analysis - Cross Section of the Dam with Total Replacement of Material 3b by 3b.
Source: Authors (2017)

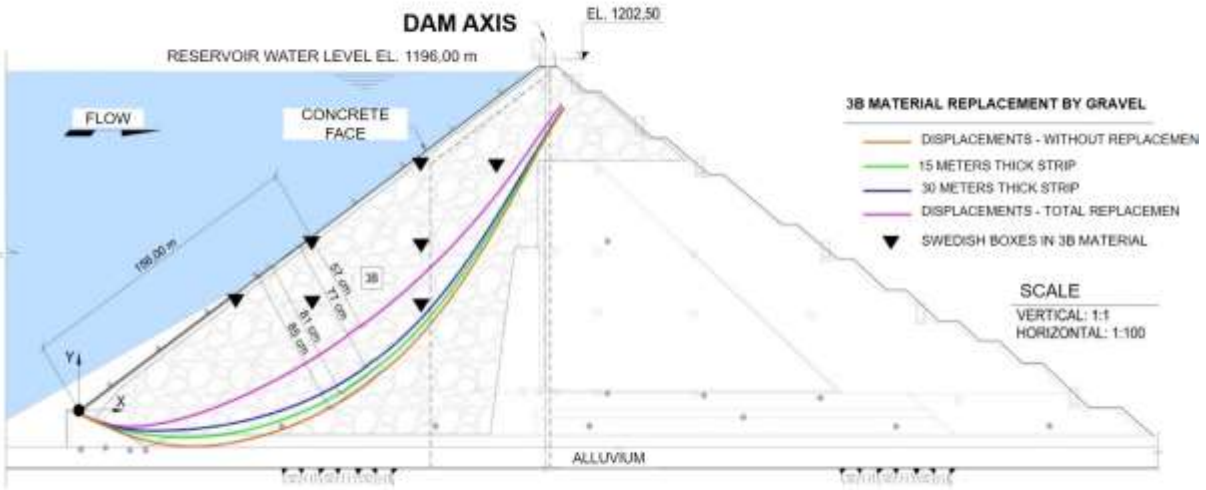


Figure 20 – Displacements of The 2d Model Slab - In the Typical Design Section.
Source: Authors (2017)

Through the analysis in four distinct scenarios using a two-dimensional approach, it is noticeable that the most effective solution consists of the complete replacement of Material 3B by Gravel. This is particularly evidenced at a critical point, where the deformation reaches 85 cm with the use of Material 3B, while with the adoption of Gravel (designated as 3B'), the deformation is reduced to 56 cm. In other words, the replacement by gravel results in a reduction of 29 cm in deformation, compared to the use of Material 3B.

The other scenarios also showed efficiency in replacing the main material of this dam body, following are the values obtained in the two-dimensional analysis:

Deformation in the slab direction with Material 3B (As per Project) = 0.85 meters
Replacement by gravel - Extension of 15 meters = 0.81 meters
Replacement by gravel - Extension of 30 meters = 0.77 meters
Replacement by gravel - Total replacement = 0.57 meters

Therefore, it is possible to verify a reduction of approximately 67% in the displacement in the slab direction when opting for total replacement by gravel.

7. Results and Discussion

In this segment, we present the outcomes and a synthesis of the three-dimensional and two-dimensional analysis, considering the comparison between the replacement of Material 3B, originally planned as riprap, by Gravel (3B') in various volumetric proportions. These proportions were discretized into bands parallel to the slope of the concrete slab, located on the upstream back. TABLE 5 and FIGURE 21 below illustrate the behavior trend of the materials during the replacement process. However, it is noticeable that as more material is replaced, the deformation decreases, which results in an improvement in the stiffness and behavior of the rocky material.

Table 5 – Slab Displacements versus Replacement of Material 3b With Gravel

Material	Gravel Replacement Thickness (M)	Replacement Area (M^2)	(%) Function of the Area	Displacements In The Center of the Slab (2d Analysis) (M)	Displacements In The Center of the Slab (3d Analysis) (M)
3B	0	-	0%	0.85	0.51
GRAVEL	15	4,557	23%	0.81	0.47
GRAVEL	30	9,351	48%	0.77	0.42
GRAVEL	45	13,827	71%	0.66	0.38
TOTAL	100	19,547	100%	0.57	0.33

Source: Authors (2017)

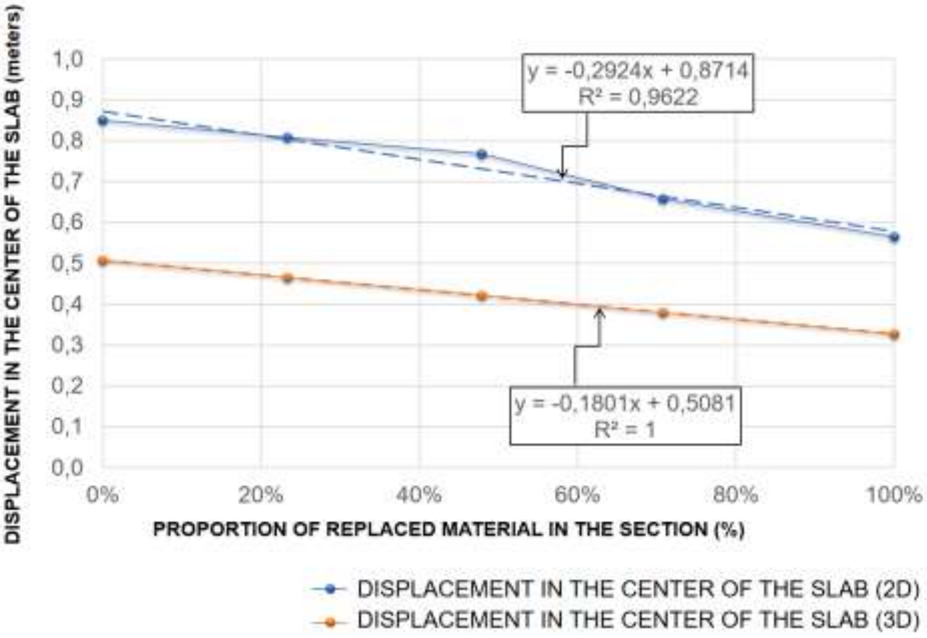


Figure 20 – Slab Displacements X Replacement of Material 3b with Gravel
Source: Authors (2017)

8. Final Considerations

The main geomechanical characteristics of rockfill to evaluate its overall behavior are shear strength and deformability. If these parameters do not match the actual applied stress limits, phenomena such as differential settlements and cracks can occur, potentially compromising both the functionality and safety of the dam structure.

The differences between the materials are mainly based on their shape. Material 3B (rockfill) originates from explosive excavations and consists of irregularly shaped blocks with sharp edges. This characteristic directly influences the compaction of the fill, as during the process, the blocks tend to break at the edges, generating a significant amount of fine particles in the zoning of Material 3B. On the other hand, Material 3B' (gravel), in addition to meeting the project's granulometric requirements, has a rounded shape that facilitates fitting during compaction with a pneumatic roller.

Among the relevant qualities for this execution process are low alterability, which prevents disintegration and improves durability; mechanical strength appropriate to service demands; and suitable shape and granulometric distribution to ensure structural stability. A notable difference between the rockfills is the deformability modulus (E), which shows a discrepancy of 70 MPa.

The analysis of the results obtained through simulations with mathematical models in Midas software, along with the comparison of data obtained from monitoring instruments, leads to the conclusion that exploring alternatives in dam design results in tangible benefits. This approach allows for the prediction of scenarios considering sustainability, costs, timelines, and the availability of natural resources within a reasonable proximity. Detailed investigation of materials and foundations through geotechnical tests is fundamental for a cohesive and accurate project, aiming to anticipate the structural behavior of the dam and its post-construction impacts.

In the context of constructing this type of dam, it becomes evident that behavior trends are expressed through data and results from numerical modeling. Even when based on empirical parameters, these models can be adjusted during the construction phase through readings from installed monitoring instruments. It is important to emphasize that numerical modeling of stress and strain plays a crucial role in the comprehensive analysis of a dam's behavior, as seen in the case of the Chaglla dam. This approach should be employed from the construction phase to the reservoir filling and can extend throughout the dam's entire lifespan.

The main objective of this study was to compare the substitution of Material 3B (rockfill) with Gravel 3B', observing superior performance with the use of Gravel. The simulations indicated lower deformations, especially in the region near the concrete slab, where the most critical point showed a displacement reduction towards the slab of approximately 67%. The difference in the deformability modulus is the parameter that directly influences the deformations obtained in both two-dimensional and three-dimensional simulations using Midas software.

After all the analyses, a highly relevant practice was the observation of monitoring data obtained through instruments installed throughout construction. In addition to comparing the projected data, this practice confirms the parameters based on experiences from other works, allowing a direct assessment of structural safety. The measured displacements result from the combination of various stresses occurring in the dam and the rigidity of the structure.

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