

Optimization study for staged construction of Gibe 3 dam

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Introduction

Gibe 3 is an Hydroelectric Plant, located in Ethiopia along the Omo river: it includes a 250m high RCC dam creating a reservoir of 13billions of cubic meters of water, serving a 1870 MW Power Plant.

During the construction of the dam, it was explored the possibility to construct a portion of the dam in two phases, to anticipate the raising of the upstream portion in order to allow early impounding and, consequently, early generation. This paper presents the study carried out about the stability of the gravity dam structure in the hypothesis of construction in two phases.

The two phases construction has the benefit to allow to anticipate the raising of the reservoir water level for energy production purposes, but has implications in the static behavior of the dam, since it changes significantly the stresses distribution within the dam body, that shall be object of careful analysis.

In order to inquire the effects of construction in two phases on the stresses values and distribution, a 2D FEM model was purposely built, to model explicitly dam and rock foundation features. Nonlinear static analysis with staged construction and impounding phases was adopted.

In order to define the minimum volume of the first phase of the dam (here called dam 1 or small dam) that gives a safe state of stress within the dam body, various design scenarios were analyzed in terms of different downstream slopes of the first phase dam.

The downstream slope was the first driving factor for this sensitivity analysis, being directly correlated with the volume of RCC needed for the dam 1, and therefore having a direct impact on time and costs required for its construction. Of course also other parameters were conjunctively investigated (not described in this article), such as joints, thermal effects, seepage, 3D effects.

The results of the study show the importance of the downstream slopes of the first phase on the structural response.

In some scenarios there is a significant decrease of the total stresses in correspondence of the upstream face of the dam, which increases the risk of localized cracks. Moreover, it has been observed, as consequence of the simulated early impounding and staged construction, that the maximum compressive stresses may be localized at the downstream toe of the first phase dam rather than at the toe of the entire dam, with consequent need of review of the RCC zoning design.

For the specific case of Gibe III dam, the study conducted confirmed that an accurate design of the first phase of the dam can make statically viable such staged construction, and it can allow to gain confidence on the possibility to control the effects on the stress distribution of the two phases of construction, for the final benefit of both engineering and construction.

1. State of the Art

The two phases construction for a dam is a technique known in literature [1],[2] most similar in concept to the design of Guri dam (Venezuela) and Ross dam (USA).

Fig. 1 shows two typical configurations of staged construction for a 200m high RCC dam [1],[2]:

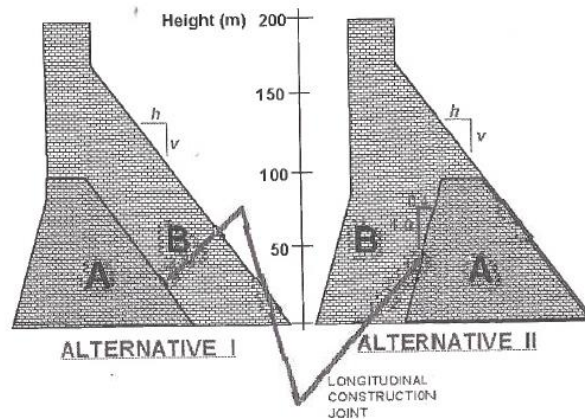


Fig. 1: Two staged construction of a 200 m high RCC gravity dam [1],[2]

The two stages solution foresaw to construct the dam in two phases, through monolith A and B.

When it was explored the possibility to construct Gibe III RCC gravity dam in two stages, the alternative I, was considered.

In the alternative I, Monolith A is on the upstream side, with the construction joint parallel to the downstream of the entire dam. Monolith A is constructed for the first while B follows after some week. Among the advantages of this method there is that the small dam A is completed rapidly and can be used for early impounding, and possibly early generation of energy. On the other hand, an important disadvantage is the tensile concentration at the interface between the two blocks (A and B), at the top of monolith A (which may require steel reinforcement in that zone to prevent crack) and at the heel of small dam.

2. Dam Features

Gibe III is an hydroelectric project, located in Ethiopia and together with Gilgel Gibe (200 MW) and Gibe II (420 MW) is the third plant of Gibe-Omo cascade.

The Ethiopian Electric Power company (EEP) is the employer, Salini-Impregilo S.p.a. the EPC general contractor, Studio Pietrangeli S.r.l. the designer and Studio Masciotta worked as his consultant for dam stability analyses.

The plant has 1870 MW of installed power and 6400 GWh of annual energy production and currently it is the highest RCC gravity dam in the world [3]; its maximum height is, in fact, equal to about 250 m, dam crest length is 960m, with a total volume equal to about 6.500.000 cubic meters.

Construction is almost completed (Fig. 2), while the impounding started one year ago, to anticipate the power production.

During the construction of the dam, it was explored the hypothesis to construct the dam in two stages, solution called "small dam", to anticipate the raising of the upstream portion in order to allow early impounding and, consequently, early generation.

This idea was conceived in the attempt to gain even some weeks of time during the construction, that, by the constraints of the Ethiopian dry/ wet seasons cycles, could have implied much more time (and costs) savings in the overall work and energy generation schedules.



Fig. 2: Gibe 3 Dam under construction

3. Fem Models

To evaluate the stability and the safety of the dam in two phases, FEM analyses were conducted to explore various scenarios with different downstream slope of small dam respect to the downstream slope of entire dam, to evaluate the best solutions in terms of acceptability of stress configuration according the reference International Standard, USACE [6],[7], and the Design Criteria fixed in the EPC contract.

2D and 3D FEM Models were carried out, but only 2D FEM analyses are shown in the present paper.

The 2D FEM Models include typical sections of the dam, overflow and non overflow type, and a significant portion of foundation rock.

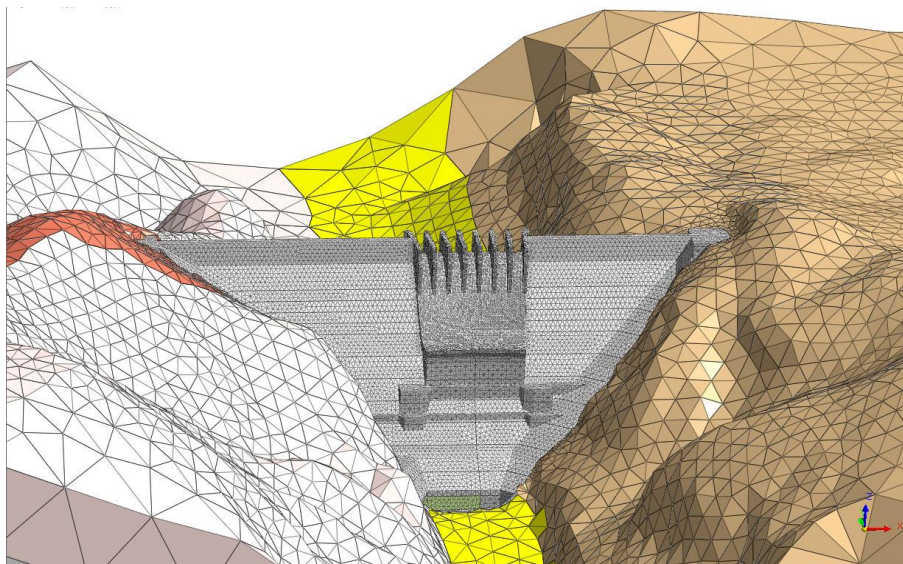
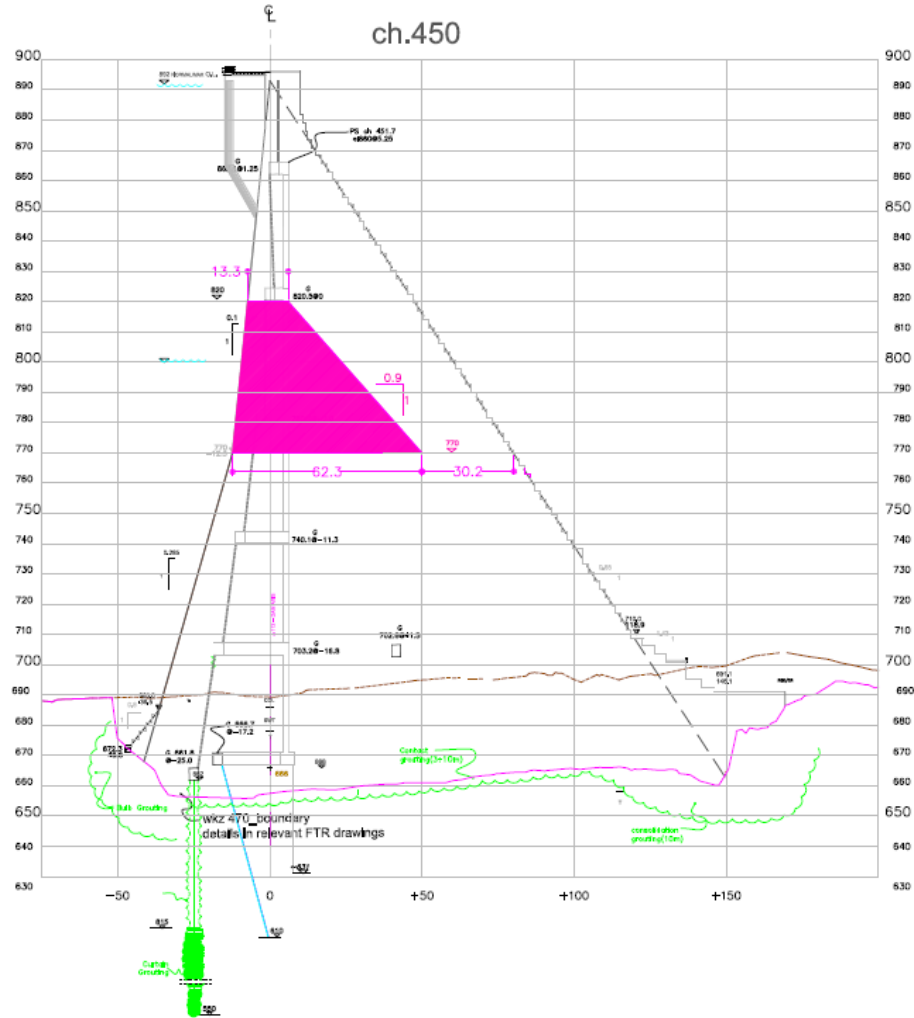


Fig. 3: 3D Gibe 3 Dam Model

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(b)

Fig. 4: Main Non Overflow ch 0+450 :D/S slope for the two phases dam: 0.715:1 (a); 0.9:1 (b).

The bi-dimensional Finite Element analyses have some basics assumptions: plain strain status, dam and rock are modelled with 4 nodes quadrilateral element (Quad 4) and are assumed both isotropic, the boundaries of the rock mesh are specified at a horizontal distance of 1,5 times the dam height and at a depth equal to the dam height.

The typical size of quadrilateral elements are:

- 3x3 m, in the dam body
- 1x1 m, in the dam body and in the rock near the dam foundation
- 10x10 m, in the rock far from dam-rock contact

To construct the FEM model two main sections were considered: Main Overflow Section and Main Non Overflow section, but only results of the Non Overflow section are described in the present work, for sake of brevity.

The main geometrical characteristics of Non Overflow section are summarized below:

- $H = 238$ m max. height above foundations
- $z = 896.0$ m a.s.l. crest level
- $z_{\min} = 658.0$ m a.s.l. lowest point level

The small dam base is at elevation 770 m a.s.l., while its crest is at 820 m a.s.l.. The U/S slope of the dam is 0.1:1, while the D/S slope is equal to 0.715:1 for the first solution and 0.9:1 for the second solution. The small dam crest

width depends on the chosen D/S slope: 11 m for the first solution and 13.3 m for the second solution, in any case it shall remain sufficiently wide to allow to pass with dozers, trucks, rollers and equipment needed for RCC construction. Fig. 5 shows the zoning adopted for the non overflow section, and the main features of the materials:

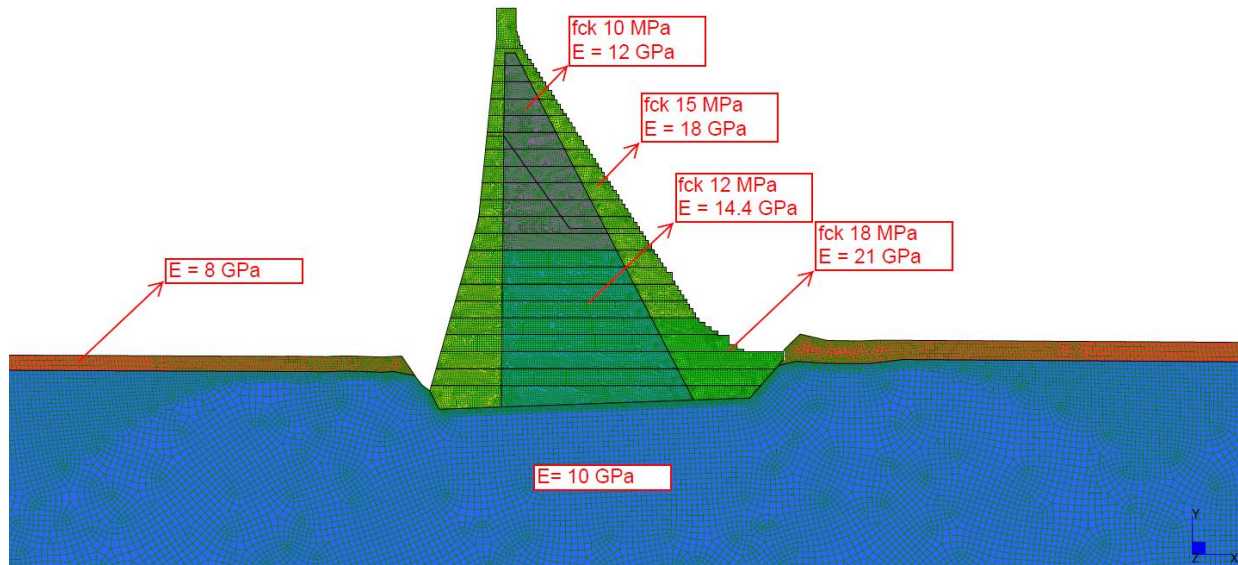


Fig. 5: Non Overflow section : FEM MODEL

3.1 Loads

The loads considered for the Non linear static analysis with staged construction are: dead loads, headwater pressures referred to the Normal Operating Condition level (892 m a.s.l.), tail water pressures referred to the Normal Operating Condition Level (677 m a.s.l.) , uplift pressures and silt pressure [5].

The loading conditions were obtained from the EPC Design Criteria and the USACE gravity dam manual [6],[7], and they have been updated considering the construction in two phases. Following loading conditions were deemed more representative for the purposes of stress analysis within the dam body:

- Operating Level of small dam (early generation) el 815 m a.s.l.
- Normal Operating Condition (Dam 1 + Dam 2) el 892 m a.s.l.

4. Stress Analysis: Results and comparison between small dam and entire dam

The stress analysis was carried out by means of FEM methodology with Non Linear Static Analysis with Construction Stages.

Herein after the results of small dam solution are reported in terms of stress status, to evaluate the best constructive configuration, and are compared with the results of original entire dam solution for Normal Operating Conditions with reservoir at elevation 892 m a.s.l..

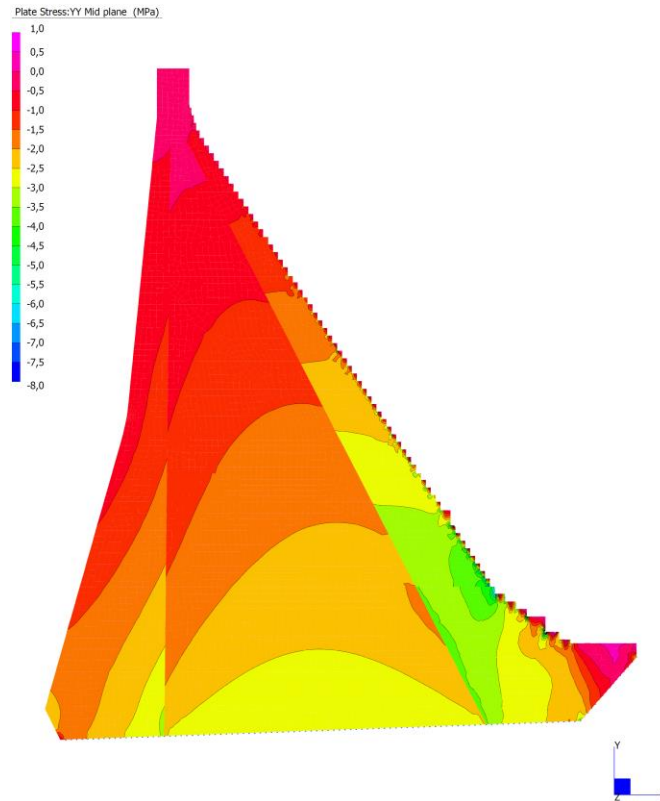
To obtain the best configuration, the stress status in the dam must be acceptable according to the limits fixed by USACE codes [6],[7], and Design Criteria, with particular reference to the stress distribution on the upstream face of the dam, that must remain in compression for a hydrostatic pressure discounted by 50%.

In fact, according to the EM 1110-2-2200, page 3-5 [6], uplift within the body of a conventional concrete dam shall be assumed "to vary linearly from 50% of maximum head water at the upstream face to 50% of tail water at downstream

face” , and EM 1110-2-2006 at par. 5-2 [7], confirms that the prescription is applicable to RCC dams, with certain characteristics.

Initially the stress status for the traditional scheme was analyzed.

Fig. 6 shows, for the referred scheme of traditional whole dam construction, the stress map and the trend of total vertical stresses on the U/S face, for the main non overflow section (ch. 0+450) and for the representative loading condition of Normal Operating Condition: from the results it is clear how the solution of the entire construction phase is acceptable in terms of vertical stresses along the U/S face, so the design in terms of U/S, D/S slopes and RCC zoning is correct.



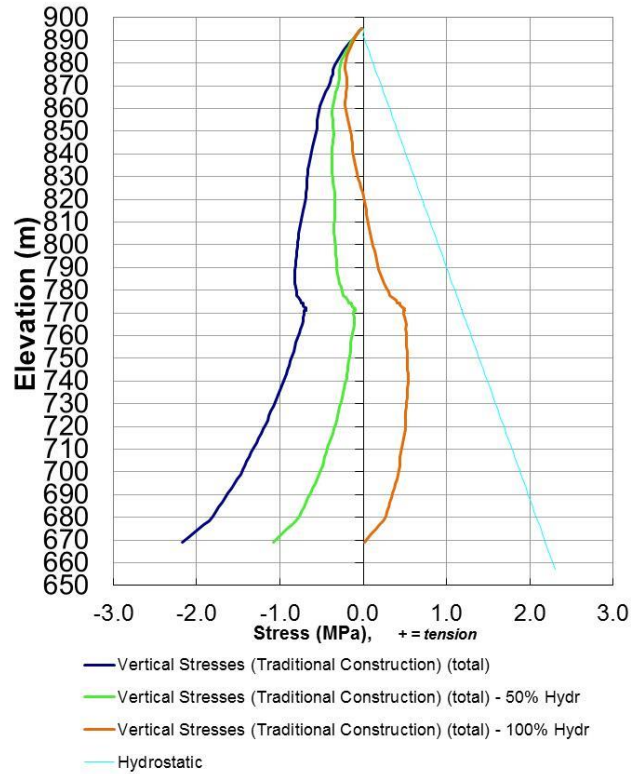


Fig. 6: Results of the traditional dam construction, in terms of vertical stresses.

The construction in two phases with partial impounding changes the stress distribution within the dam body: generally the effect of the small dam construction is an increase of compressive stress at the D/S toe of the small dam and a decrease of stress in the u/s heel of the small dam too. The causes of these phenomena will be analyzed afterwards.

In particular, the second aspect is dangerous: however, a good design of a phased construction with an appropriate slope can lead to economic advantages, avoiding at the same time the underlined problems.

A first hypothesis analyzed for the small dam configuration consisted in a downstream slope of the of small dam equal to 0.715:1, parallel to the downstream slope of the entire dam, the aim was to minimize the volume of RCC of the small dam.

The main geometrical characteristics of the small dam with 0.715:1 D/S Slope were the following:

- $h = 50$ m a.s.l. max. height above the base
- $z = 820.0$ m a.s.l. crest level
- $z_{\min} = 770.0$ m a.s.l. lowest point level
- $c = 11$ m crest width
- $Su/s = 0.1H / 1V$ small dam u/s face slope
- $Sd/s = 0.715H / 1V$ small dam d/s face slope

This solution leads to a stress distribution on the upstream face of the dam, that is not acceptable neither for the EPC Design Criteria nor for prescriptions of USACE Codes [6],[7], as Fig. 7 and Fig. 8 show:

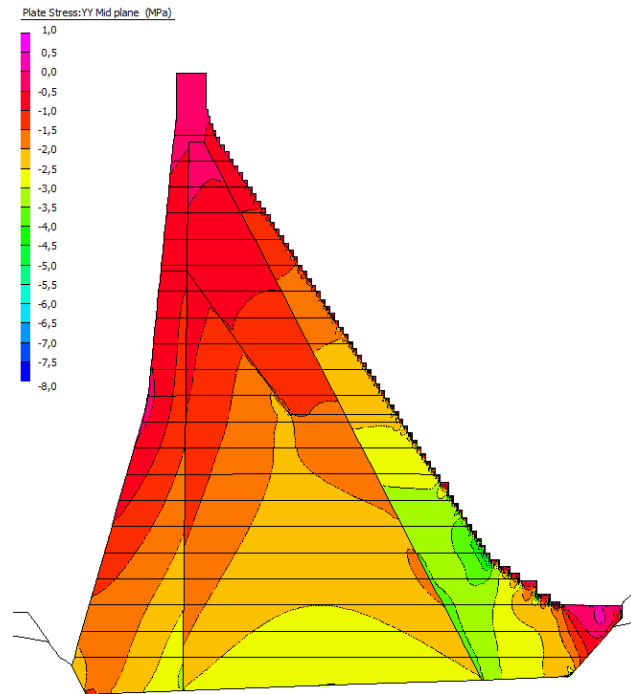
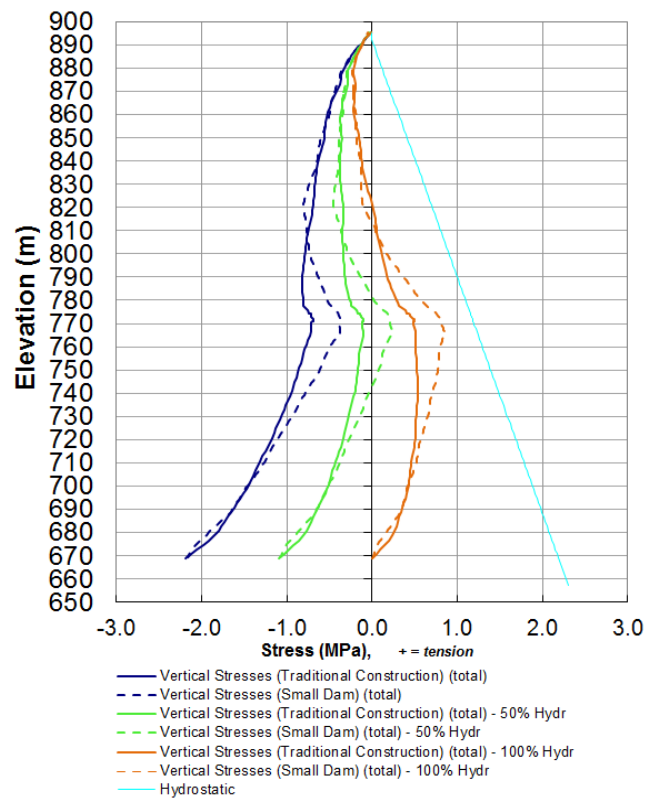
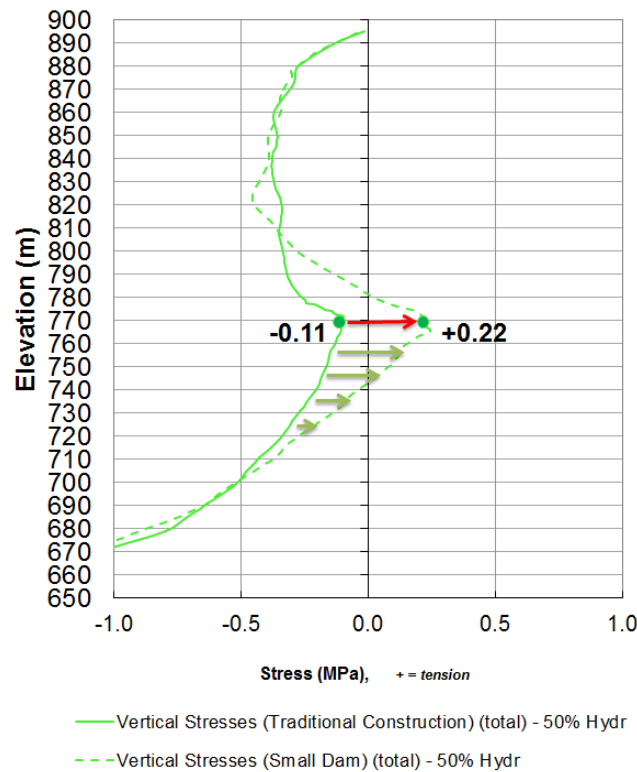


Fig. 7: Vertical Stress distribution for Normal Operating Condition (dam 1+ dam2) for D/S Slope of small dam with D/S Slope 0.715:1 for Two Phase Construction





(b)

Fig. 8: Vertical Stress distribution for Normal Operating Condition (dam 1+ dam2) on the upstream face for traditional construction and small dam (a); Particular: Water Pressure Discounted 50% (b)

Fig. 8, shows the distribution of vertical stresses along the u/s face of the dam: the dotted line represents the vertical stresses along the upstream face for the two phases construction solution, while the solid line represents the same output for the traditional construction solution.

In particular, blue lines represent the distribution of total vertical stresses along the u/s face, green lines represent the distribution of effective vertical stresses along the u/s face, evaluated considering the total vertical stresses and subtracting to them the 50% of hydrostatic load, orange lines represent the distribution of effective vertical stresses along the u/s face, evaluated considering the total vertical stresses and subtracting to them the 100% of hydrostatic load.

It's clear that the construction of small dam leads to a decrease of the U/S vertical stresses, in particular at 770 m a.s.l. elevation, where the decrease is so important to change the compressive stress (equal to -0.11 MPa) to tensile stress (equal to + 0.22 MPa), as show in Fig. 8(b).

The causes of this change is due to the staged constructions and early impounding: in fact, when the small dam is ended, the upstream face is subject to an hydrostatic pressure up to 815 m a.s.l. (early impounding) to allow early generation: this involves the development of some stresses in the dam, that keeps memory of these stresses, changing the final distribution of stresses, too.

Since this configuration was not acceptable because it didn't comply with EPC Design Criteria (for which the vertical stresses must remain in compression all along the dam upstream face), the downstream slope was changed from 0.715:1 to 0.9:1, with the aim of limiting the aforementioned criticality.

The main geometrical characteristics of the small dam with 0.9:1 D/S Slope where the following:

- $h = 50$ m a.s.l. max. height above the base
- $z = 820.0$ m a.s.l. crest level
- $z_{\min} = 770.0$ m a.s.l. lowest point level
- $c = 13.3$ m crest width

- $S_u/s = 0.1H / 1V$ small dam u/s face slope
- $S_d/s = 0.9H / 1V$ small dam d/s face slope

Fig. 9 shows the stress map of the proposed small dam, while Fig. 10 shows the differences between the vertical stress along upstream face between the proposed small dam solution and the traditional construction solution:

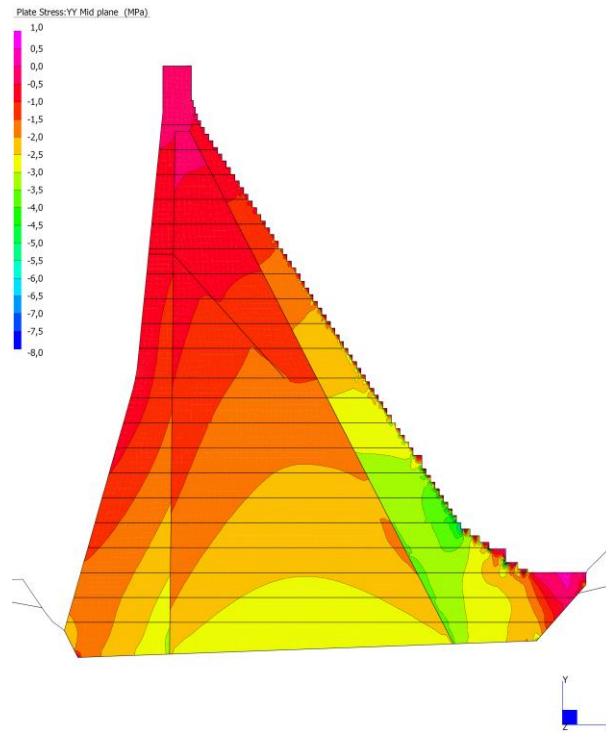
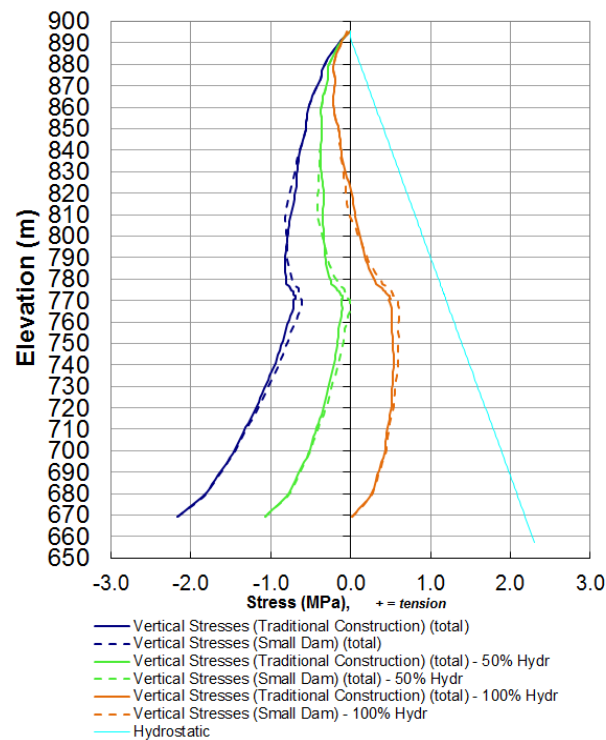


Fig. 9: Map of Vertical Stress distribution for Normal Operating Condition(dam 1+ dam2) for D/S Slope of small dam 0.9:1: Two Phase Construction



(a)

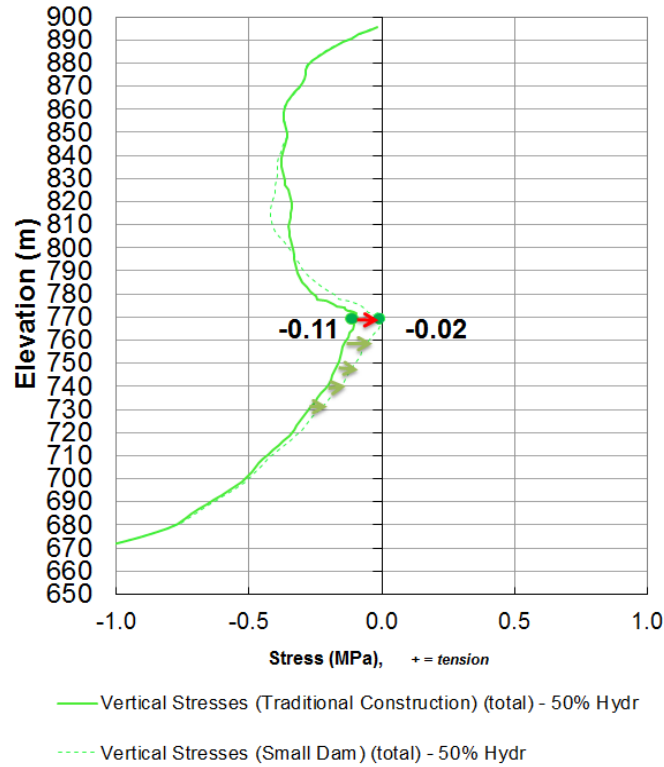


Fig. 10: Vertical Stress distribution for Normal Operating Condition(dam 1+ dam2) on the upstream face for traditional construction and small dam : Various Water Conditions (a); Particular: Water Pressure Discounted 50%

This solution leads to acceptable stress distribution in the dam body, in particular along the upstream face: it can be noted that with these hypotheses, the two phases construction doesn't change in a significant way the stress status, as can be observed from the comparison between Fig. 6 and Fig. 9 and from Fig. 10: the differences in the stress field between the two hypotheses of construction sequence are not relevant.

The Fig. 11 shows the delta of stresses between the two construction methods, and it is clear that the construction in two phases produces an increase of stress at the d/s toe of the small dam (about 0.3 MPa) and a decrease of the vertical stress in the u/s heel of the "small dam" (about 0.1 MPa), that is however acceptable.

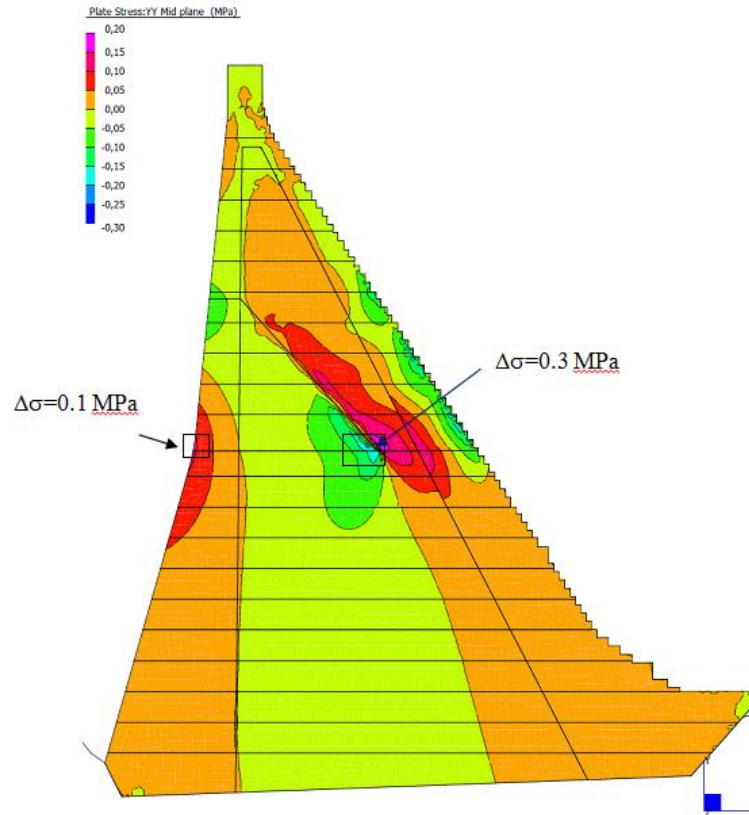


Fig. 11: Delta of vertical stress, Construction in one and two phases –NOC –Section ch. 0+450

A certain importance has the longitudinal joint between phase 1 and phase 2. In particular, to prevent that the joint could represent a weak interface, proper measures aimed at controlling the uplift along the contact should be adopted, including:

- A drainage gallery at the bottom of the joint.
- A watertight system at the upstream face on the horizontal lift of RCC at the contact between the two phases (for instance with external water stop).
- A proper treatment of the RCC joint at the contact between first and second stage construction, with green cutting and mortar bedding mix application in order to ensure good bonding and low permeability.

5. Practical advantages

The two staged construction has different advantages, as discussed in paragraph 1, above all from the economical point of view.

With the adoption of the traditional solution (construction of A and B part together) Fig. 12(a), the construction time of the part of the dam between 770 and 820 m a.s.l. was evaluated about 9 months (270 days).

In case of two staged construction for the initial hypothesis of D/S slope of 0.715:1, the time to arrive with the first portion of the dam (part A) at elevation 820 m a.s.l. was estimated to decreased to about 3.3 months (100 days). However the first solution, called in Fig. 12(b) A1, if on one hand reduces the volume of RCC, on the other hand leads to tensile stress on the upstream face which that are not acceptable. So, the second solution A1+A2, with D/S slope of 0.9:1, that involved acceptable stresses, implied a construction time for the first portion of the dam of about 4 months (122 days), with a difference in respect to the previous solution of only 22 days.

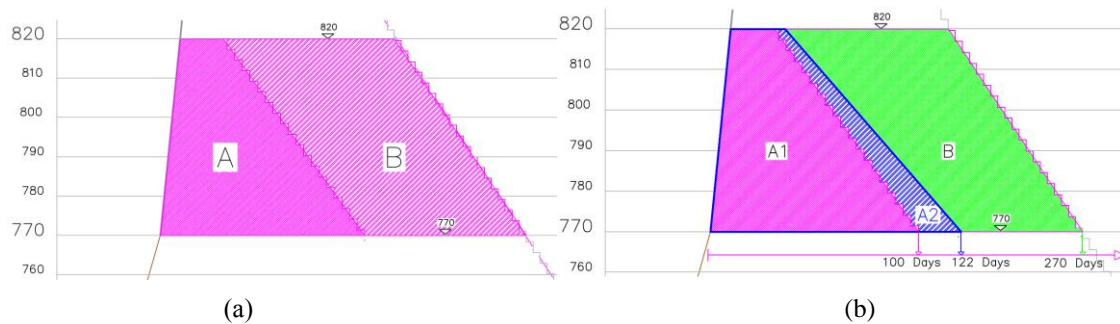


Fig. 12: Two monolithic blocks of different construction solution (a); Construction time for different adopted solutions (b)

In any case the staged construction analyzed offered the possibility to anticipate by about 5 months (150 days) the attaining of elevation 815, and consequently to anticipate relevant impounding, attaining the minimum exceptional water level at which the wet commissioning of the units could have commenced.

Finally, for the case of the Gibe III, even if the study demonstrated its viability and benefits, the dam staged construction was not adopted, for other constraints linked to the need to close the river diversion at the beginning of the dry seasons and also to the program of construction of the Power House and in particular to the availability of the electromechanical units.

6. Conclusions

This paper presents a study about the stability of Gibe 3 gravity dam in the hypothesis of construction in two phases (small dam).

During the construction of the dam, in fact, it was explored the possibility to allow early impounding and, consequently, early generation through a construction in two phases (Dam 1 + Dam 2).

Different scenarios were investigated, such as D/S Slope of Small Dam, joints, thermal analysis, seepage, 3D FEM model, not shown in this paper, that focus on the D/S Slope of Small Dam.

The construction in two phases with partial early impounding changes the stress distribution within the dam body increasing the compressive stresses at the D/S toe of the small dam and decreasing of stress in the u/s heel of the small dam too.

For this reason, a parametrical study about this aspect was conducted. The study started from the hypothesis of 0.715:1 D/S Slope of Dam 1, with the aim of minimizing the volume of RCC, and ended with the optimized solution of 0.9:1 D/S Slope, that confirmed to be the best compromise between the desire to reduce at minimum the time of first phase of construction and the static needs imposed by the dam design criteria of International Standards used (USACE, [6],[7]).

The study confirmed that an accurate design of the first phase of the dam can lead to an acceptable status of the stresses in the dam body, allowing to reduce significantly the construction time to reach a certain elevation required for impounding and power generation needs.

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