# Grouting Treatment Design in Foundation and Abutments of La Yesca Hydroelectric Project

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ABSTRACT: The embankment structure of La Yesca Hydroelectric Project is integrated by a 220 m high Concrete Face Rock Fill Dam, founded over igneous rock of heterogeneous structure and properties. Due to the abutments complex geology and the underground structures that must be protected of seepage, a series of nine adits have been designed for continuing the grouting treatment from the Plinth. Considering as reference the previous studies on the zone, next subjects are presented: the preliminary criteria for treatment, the results obtained during construction stage so far, the design adjustments and the evaluation of this design under an observational and iterative methodology, based on information analysis generated before, during and after rock mass grouting.

RESUMEN: La estructura de contención del Proyecto Hidroeléctrico La Yesca, la integra una cortina de enrocamiento con cara de concreto de 220 m de altura, desplantada sobre rocas ígneas de estructura y propiedades heterogéneas. Debido a la compleja geología de los empotramientos y las estructuras subterráneas que deben ser protegidas del embalse, se han proyectado una serie de nueve galerías que darán continuidad a los tratamientos mediante inyecciones desde el Plinto. Tomando como referencia los estudios previos de la zona, se presentan: los criterios elegidos preliminarmente para la ejecución de los tratamientos, los resultados obtenidos hasta la fecha durante la etapa de construcción, las adecuaciones realizadas al diseño y la evaluación de éste bajo una metodología observacional e iterativa, que se basa en el análisis de la información generada antes, durante y después de la inyección del macizo rocoso.

## 1 INTRODUCTION

In a Concrete Face Rock Fill Dam (CFRD), the grouting treatments, Plinth and concrete slab, represent the elements that guarantee the project watertightness. The position of these elements, outside the body of the embankment, constitutes an advantage in the construction process, since it separates foundation treatment of rockfill construction; however, permeability control requirements are greater than those for other sort of dams, due the high hydraulic head that may occur immediately under the Plinth, where also, rock conditions may be unfavourable.

La Yesca project is part of the Santiago River Hydroelectric System and is located between Jalisco and Nayarit states in Western Mexico. Construction works began on September 27, 2007 and is planned to operate in mid-2011. Embankment total height shall be 220 m and will harbour a 2 393 million cubic meters reservoir. Grouting curtain will comprise about 170 000 m drilling distributed in the Plinth and nine grout galleries in abutments.

## 2 GEOLOGY

Derived from satellite imagery and aerial photography, were defined that project area is controlled by a main structural pattern, NW-SW, which defines the Santiago River trend, and other two systems, N-S and E-W, which lead to sudden changes in river trend.

Regional structural framework is dominated by tectonic dynamics, influenced by Cocos, North American and Rivera Plates, which are found in two geological areas, Trans-Mexican Volcanic Belt and Mexican Ignimbritic sequence, both of volcanic origin (Camacho-Segovia *et al.,* 2007).

Rocks exposed in the reservoir are product of a series of volcanic events, volcano sedimentary deposits and intrusive rocks, which gave rise to different lithologic units of andesite, ignimbrite, dacite, lithic tuff basalts and rhyolites.

For the same lithologic unit, characteristics associated to mechanical strength, fracture density, fracture filling and continuity, have significant local variation due to presence of primary geological structures (faults and intrusive rocks) and water seepage throughout these. In general rock mass shows high heterogeneity in relation to its mechanical and hydraulic properties; and due the genesis of its formation, there are not evidence related to increased strength or decreased permeability with deep.

Rock near major geological structures is usually highly fractured and packed with clay, affectation thicknesses ranging from 1 to 10 meters. Many of these structures are oriented so that during the operation stage may represent seepage paths to underground structures or to embankment downstream (Figures 1 to 4).

## 3 PREVIOUS STUDIES

In order to determine the grout curtain characteristics, grouting parameters and implementation criteria, three test sites were studied to determine the rock mass hydraulic conductivity, critical pressure and groutability. The location of these sites is shown in Figures 2 and 4.

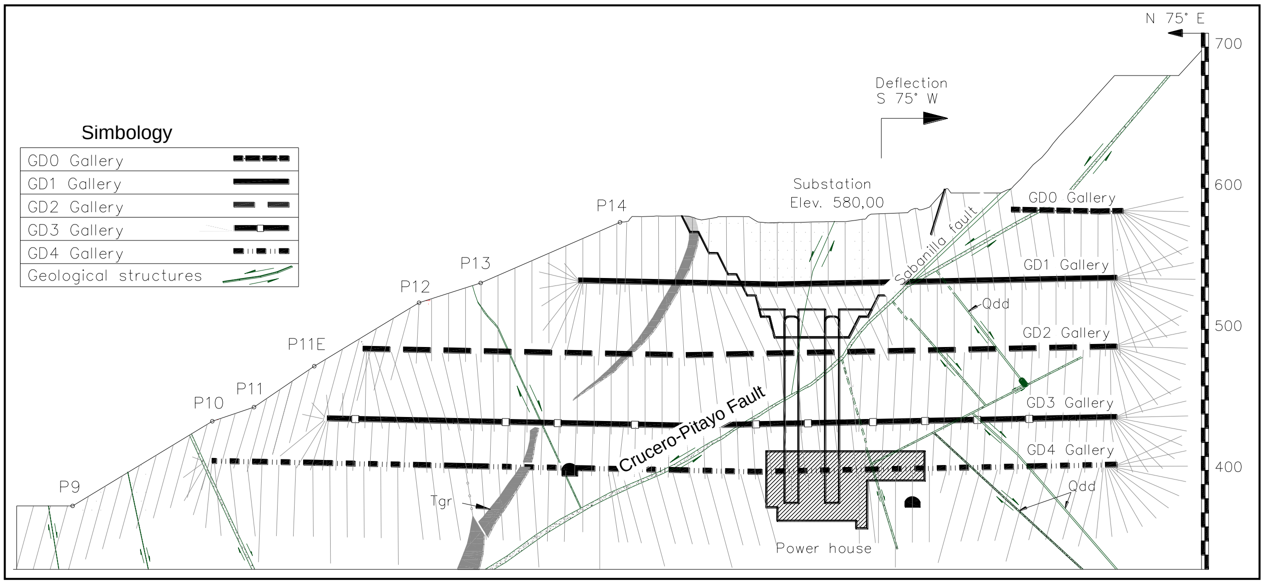


**Figure 1.** La Yesca right bank section through Plinth and galleries axis.

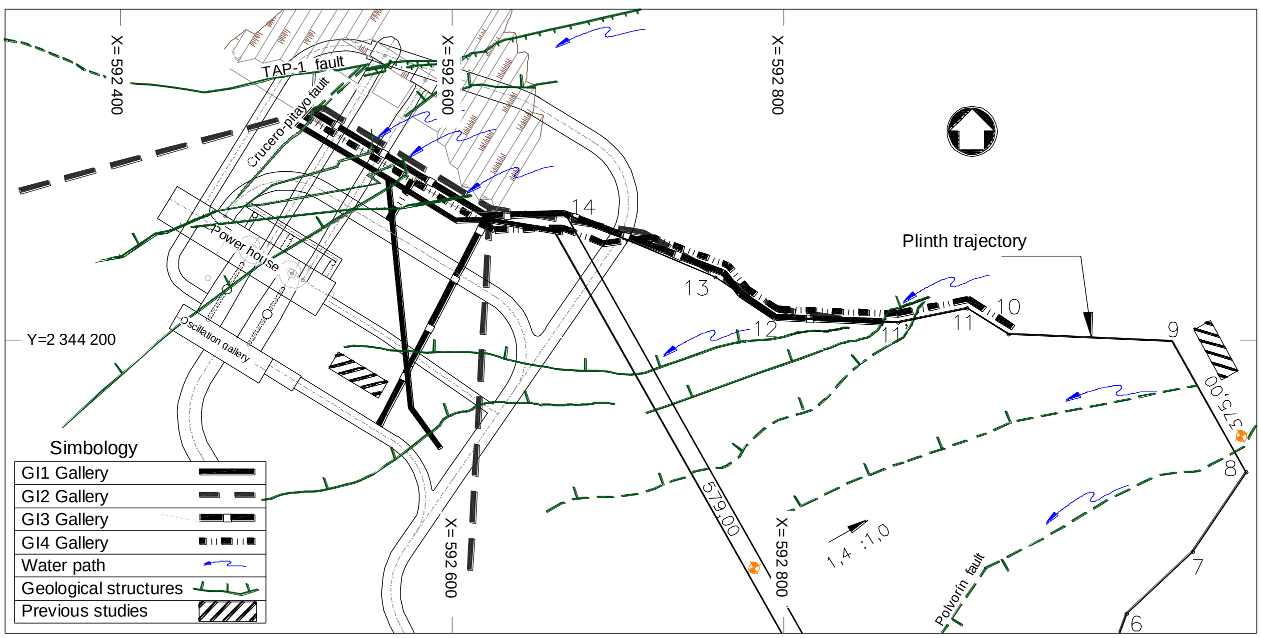


**Figure 2.** La Yesca right bank, Plinth and galleries trajectory, main geological structures and preferential seepage paths.

### 3.1 Permeability and groutability tests.

Hydraulic conductivity was determined in NQ diameter drillholes by Lugeon Water Pressure Tests (WPT); critical pressure was additionally defined by applying pressure up to 1.5 times the maximum hydraulic head during dam operation stage. Results evaluation was based on the criteria proposed by Ewert (1997).

Groutability test with cement mixtures was carried out in NQ diameter drillholes with 5 m maximum stage lengths; rock hydrofracturing or hydrojacking was achieved applying pressure gradually rising up to 5 MPa. Trial results provided initial grouting criteria for Grout Intensity Number methodology (GIN, Lombardi and Deere, 1993).

***Right abutment.*** Tests were performed within an exploratory adit excavated in fair to poor quality rock with clay-filled fractures at elevation 412 (Figure 2). 40 m length boreholes were carried out to evaluate the groutability and permeability behaviour during split-spacing sequence with hole separations from 12 m to 1.5 m. Hydraulic conductivities under 3 Lugeon Units (LU) and 18 l/m average grout consumption were obtained.

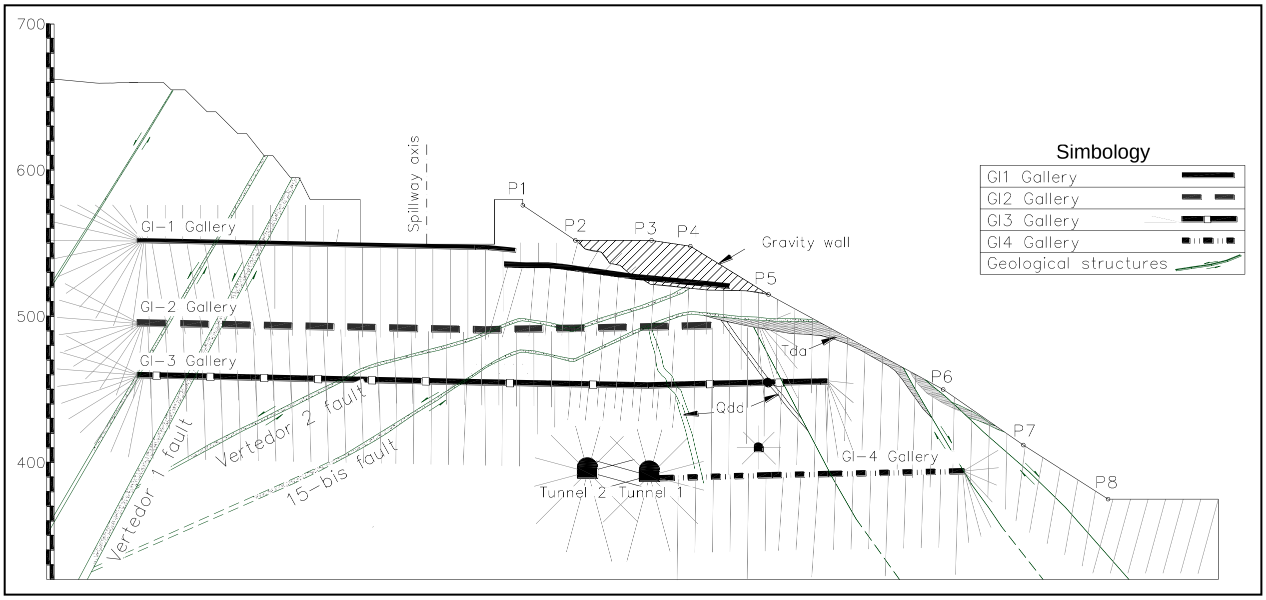


**Figure 3.** La Yesca left bank section through Plinth and galleries axis

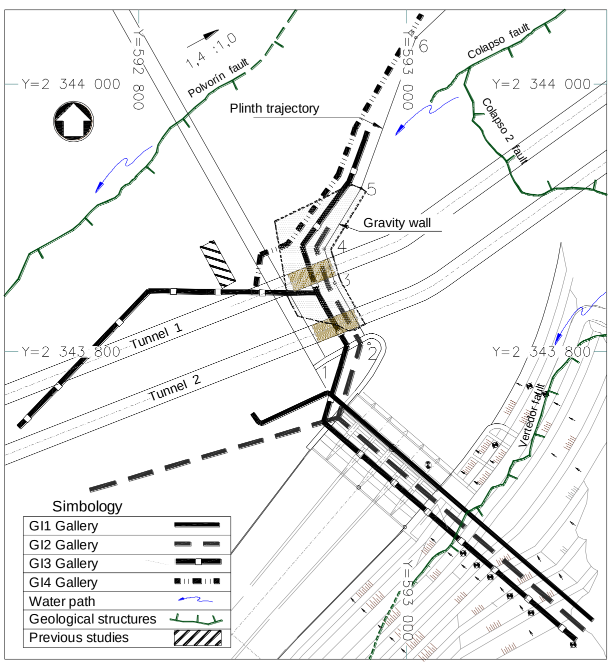


**Figure 4.** La Yesca left bank, Plinth and galleries trajectory, main geological structures and preferential seepage paths.

***Central section.*** Two test boreholes were performed at elevation 396. (Figure 2). Average grout consumption of 13 l/m was obtained and a zone affected by NW-SE fracture system resulted in consumptions over 200 l/m, however, due to its orientation and upstream dip, results were not considered adverse to ensure the section watertightness.

***Left abutment.*** 50 m length boreholes were performed from an exploratory adit at elevation 455 (Figure 4) applying the same test methodology of right abutment. Average hydraulic conductivities about 10 LU, and maximum of 40 LU in intrusive rock contacts were obtained; average grout consumption was around 35 l/m. Applied pressures between 1.0 and 2.5 MPa during WPT and groutability tests, produced high conductivities and grout takes related to hydrofracturing, especially in rock-dyke contacts.

According to permeability results (Figure 5), was possible to define that grouting curtain extension should be governed by the presence of main faults and dykes, whose contacts were susceptible to erosion at lower pressures than those generated during dam operation. On the other hand, according to trial results, was established that rock mass general permeability not represent a risk for ensure the project watertightness, but due to rock heterogeneity, systematic exploration boreholes were adequate during construction stage.

Groutability studies evidence the use of moderate grout intensity (GIN between 1000 and 1500 bar·l/m) to increase penetrability, considering the rock mass average competence to hold pressures about 4.0 MPa with grout consumption around 30 L/m (Figure 6).

## 3.2 Grout mix design

In order to define the properties of different grout mixes, laboratory and field test were conducted under following guidelines: water-cement ratios between 0.8 and 1.0; bentonite amount less than 1.25%; and super-plasticiser between 0.5% and 1.75%; all percentages in relation to cement weight.

Grout mix choice was based on the fracture characteristics assessment and the influence of rheological grout properties in treatment efficiency, Table 1 was used as qualitative reference.

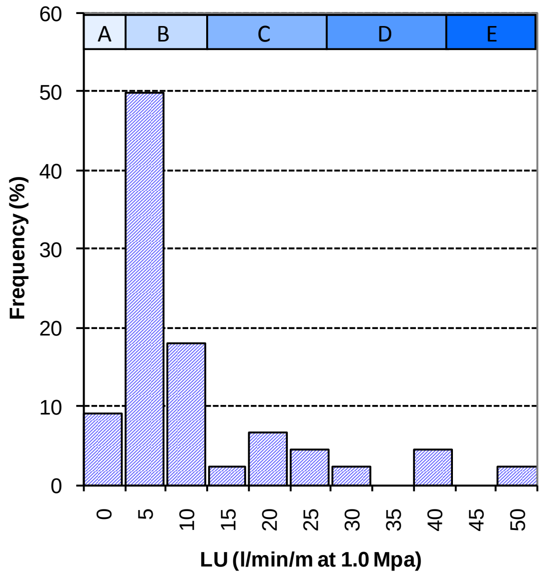


**Figure 5.** Hydraulic conductivity frequency in Lugeon units for three sites evaluated during studies. (A) Impermeable, (B) Slightly permeable, (C) Permeable, (D) Very permeable, (H) Highly permeable.

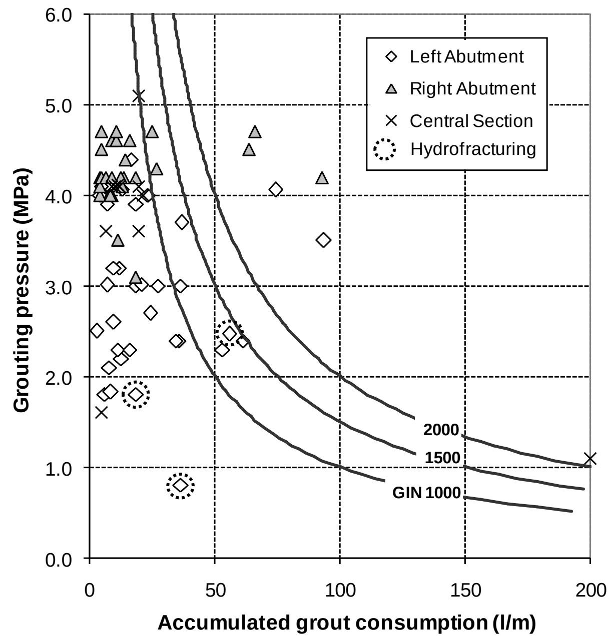


**Figure 6.** Previous studies groutability test data.

**Table 1.** Importance of different factors on grout functionality related to fracture aperture: ++ represents high importance, + important, - not important. (adapted from Eriksson, 2002).

| Factor | Tight ≤ 0.1 mm | (-) ← aperture → (+) | Open > 1 mm |
|---|---|---|---|
| Low cohesion | ++ | + | - |
| Low viscosity | ++ | + | - |
| High penetrability | ++ | + | - |
| Low bleed | - | + | ++ |

**Table 2.** Grout mix specified properties

| Property | Value | Measurement equipment |
|---|---|---|
| Apparent viscosity | 29 - 33 s. | Marsh Funnel |
| Density | 1.69 - 1.57 g/cm$^3$ | Mud balance |
| Sedimentation | ≤ 4% | Graduated glass cylinder |
| Cohesion | ≤ 0.2 mm | Slotted plate |
| Filtration coefficient | ≤ 0.6 min$^{-0.5}$ | API Filter press |

Largest percentage of evaluated sites was distinguished by closed fractures or impermeable filled and little erodible fractures. According to the qualitative approach and groutability test results, w/c ratios between 0.7 and 0.9 increases the treatment effectiveness, however, applicability of this mixture was questionable for main fault and dikes zones. Finally, specified rheological and mechanical properties for the grout mix during construction stage were defined as shown in Table 2.

## 4 GROUT CURTAIN CHARACTERISTICS

### 4.1 Plinth

Plinth was founded in slightly deformable and non erodible rock; in cases were geometry forced to intersect areas with presence of faults, dikes or disturbed rock, it was removed and restored with concrete up to a depth of 2.5 times the geological structure thickness.

Plinth thickness varies from 0.70 to 1.0 m; the external slab has a minimum width of 4.5 m; and the internal slab was sized with Bayardo-Materon criterion (personal communication, 2004) which considerers the Rock Mass Rating (RMR) and hydraulic head over the section, obtaining required internal widths from 0 to 14 m.

Boreholes arrangement for grouting treatment from Plinth contemplates a main deep line and two blanket lines with average length of 55, 20 and 10 m respectively.

### 4.2 Grout Galleries

Treatment from galleries includes a deep grout line and three lines of connection holes, which aim to give continuity to the grout curtain between galleries. Vertical separation between galleries is about 50 m; their length at right abutment was defined to protect the powerhouse from seepage; and for the left abutment grout curtain was extended to intersect main geological structures that could represent seepage pathways (Figures 1 to 4).

## 5 GROUTING TREATMENT DURING CONSTRUCTION STAGE

### 5.1 Grouting parameters and criteria

Grouting process employed in La Yesca is based on GIN methodology, which aims to limit the grouting course through a maximum pressure, a maximum volume and a maximum grout intensity given by the product of the grouting pressure (P) and accumulated grout volume per hole meter (V)

Selected GIN number was 1500 bar·l/m with three peak pressures, 2.0, 3.0 and 4.0 MPa, and a general maximum volume of 200 l/m; these values are applicable to three different areas defined by rock features and hydraulic head over the section (Table 3).

Basic grout mix used during construction stage has a w/c ratio of 0.72, 1.19% of super-plasticiser and 0.4% of bentonite (all by cement weight). Type II Portland cement with average Blaine finesses of 5200 $cm^2/g$ was employed.

Grouting is performed in ascending stages of 3.0 length in shallow zones and 7.0 m length at depth. Split spacing sequence is applied considering 12 m separation between primary holes until 3 m between tertiary holes; depending on the grout consumption evolution between stages, quaternary holes each 1.5 m are eventually implemented.

**Table 3**. La Yesca grouting parameters. Pp= peak pressure, P=applied pressure in the interval

| Elev. | GIN (bar*l/m) | Pp (MPa) | Interval (m) | | P (MPa) |
|---|---|---|---|---|---|
| | | | Gallery | Plinth | |
| 580 to 495 | 1500 | 2.0 | 0-0.5 | | 0.3 |
| | | | 0.5-5 | 0.5-2.0 | 1.0 |
| | | | --- | 2.0-5.0 | 2.0 |
| | | | From 5 to bottom | | Pp |
| 495 to 410 | 1500 | 3.0 | 0-0.5 | | 0.3 |
| | | | 0.5-5 | 0.5-2.0 | 1.0 |
| | | | --- | 2.0-5.0 | 2.0 |
| | | | From 5 to bottom | | Pp |
| 410 a 325 | 1500 | 4.0 | 0-0.5 | | 0.3 |
| | | | 0.5-5 | 0.5-2.0 | 1.0 |
| | | | --- | 2.0-5.0 | 2.0 |
| | | | From 5 to bottom | | Pp |

Prior to grouting process and immediately after drilling, holes are washed with water and air to remove drilling product and erodible fracture fill. Sections above water table are saturated in 20 m stages at 1.0 MPa during 30 minutes or until a cumulative volume of 200 l/m.

To finalize each stage, grout take less than 5 l/min for 3 minutes with specified pressure must be obtained.

### 5.2 Grouting methodology

Control of grouting progress is done through real-time monitoring of pressure evolution and cumulative grout volume. Figure 7 illustrates a GIN diagram with diverse grout paths. This diagram shows a target point *G* where nil flow and acceptable energy value between Em and EM (±10% specified GIN for this project) are reached.

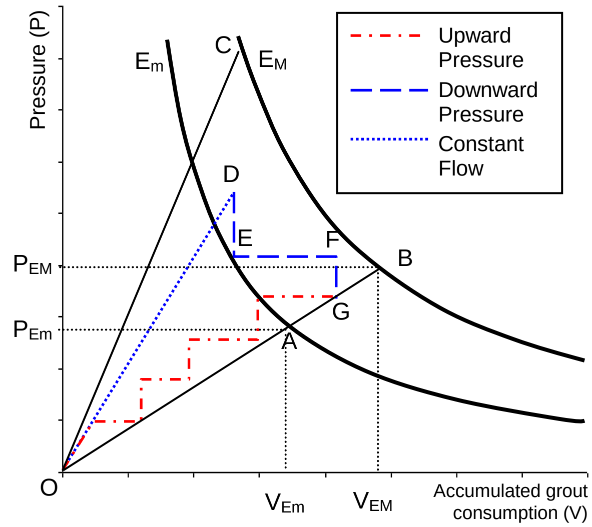


**Figure 7.** Grouting paths in GIN diagram (adapted from El Tani, 2009).

*OG* line represents a grouting path with nil flow and, therefore, infinite grouting time, on the other hand, OC path represents a grouting with the maximum possible flow.

GIN methodology in Mexico has antecedents in Aguamilpa (1994) and El Cajón (2007) projects, both located in Santiago River and built in igneous geology. In these projects the grouting process was carried out applied pressure increments up to reach a target flow and pressure (stepped path *OG* in Figure 7).

Currently the process was modified through automated grouting equipment, which allowed constant flow grouting (*OD*) and then a pressure-controlled second stage (*DEFG*) until reach target GIN with practically nil flow.

First procedure, stepped controlled pressure, provides adequate results to define precisely the rock critical pressure which generate unnecessary grout travels; however, grouting times required may be impractical during construction phase.

Constant flow procedure offers advantages related to grouting time, however, critical pressure and GIN value must be properly pre-defined, because during process is complicated to identify precisely the path position where hydrofracturing is generated.

## 6 BEHAVIOR DURING GROUTING PROCESS

### 6.1 Exploratory boreholes.

They are located every 48 m on the grout curtain axis and are designed to identify permeability features by Lugeon tests previous to grouting. With obtained results, was possible to anticipate the rock mass behaviour during dam operation stage; in this manner erodible areas were identified, as well as fractures that presented irrecoverable deformation, which may be unfavourable to guarantee the project watertightness.

60% of programmed Lugeon tests have been carried out so far in the whole Project; average hydraulic conductivities between 0 and 11 LU were obtained in central section, right bank and low areas of the left bank.

Remaining tests will be located on interest areas where seepage paths may arise or where erodible fractures during operation stage may involve fine migration and seepage increments (e.g. Vertedor Fault in left abutment and Crucero-Pitayo Fault in right abutment, see Figures 1 to 4).

## 6.2 Grout curtain.

Grout takes obtained have been below 25 kg/m in both abutments. Low galleries of right abutment (GD-3 and GD-4) presented higher consumption in Crucero-Pitayo Fault affectation zone where average takes were over 30 kg/m and 10% of treatment exhibited consumptions over 100 kg/m; in this zone WPT did not indicate erosion potential in fractures, but high amount of clay led to increase the washing cycles to secure the replacement by cement grout.

In central section of the project smaller consumptions around 10 kg/m have been registered; about 90% of grouted stages reached the specified maximum pressure and only isolated shallow areas had consumption higher than 50 kg/m.

Successful progressive reduction ratios between grouting stages have been registered in whole project (Figure 8); grout take reductions between 6 and 50% have been obtained in left abutment; between 12 and 35% in right abutment; and around 10% in central section.

Grouting treatments in project lower areas have been completed to date and are in progress 75% of works in left abutment and 30% in right abutment

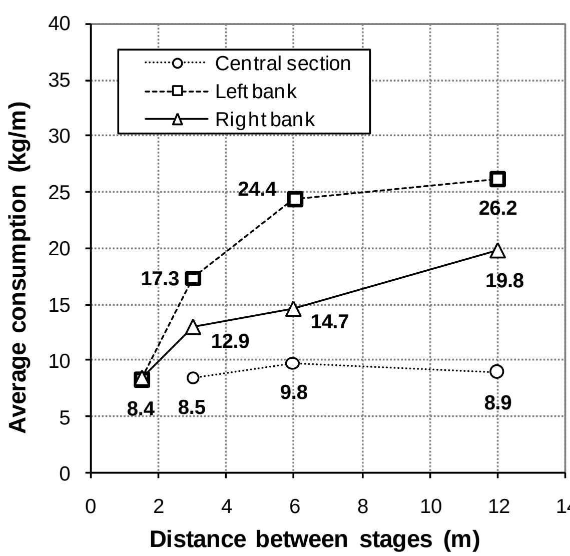


**Figure 8.** Average cement consumption from first to fourth stage holes (January 2011).

## 6.3 Grout mix.

Due fracturing conditions in different project areas, which in general presented minimal aperture or clay-fill, was necessary to re-evaluate the grout mix properties in order to increase its penetrability and reduce its cohesion and viscosity. An alternative mix was designed without bentonite, w/c ratio around 0.7 and super-plasticizer around 0.7% by cement weight.

## 6.4 Behaviour evaluation

In order to evaluate qualitatively the grouting process results, in conjunction with absorptions obtained in exploratory holes, information generated to date was reviewed with the approach exposed by Ewert (1997).

Figure 9 shows grout consumption against LU obtained during treatments execution in central section and abutments.

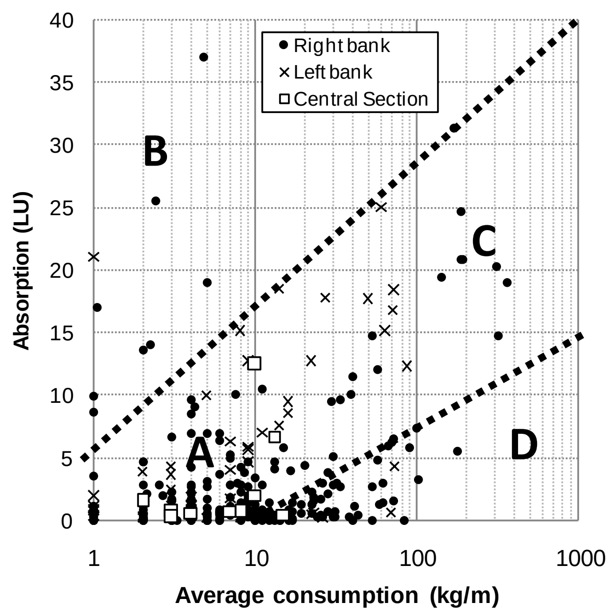


**Figure 9.** Grout consumption against absorption (adapted from Ewert, 1997).

"A" zone represents a low absorption and low consumption region, where the treatment efficiency is limited. The central section of the project presents this behaviour in great proportion, except for shallow areas (from surface to 10 m). To date 69% of grouted stages in whole project exhibits this behaviour.

"B" zone indicates the presence of tight fractures with high permeability and limited grout consumption due to the grout mix low penetrability; these cases were limited and are considered not representative of the rock mass general behaviour (3% of analyzed cases).

"C" zone of permeable and groutable rock features was mainly identified in project abutments below 400 m elevation. Grouting treatment in these areas was an effective measure to improve the rock conditions; which was confirmed through verification holes direct toward areas that showed average consumption over 100 l/m,

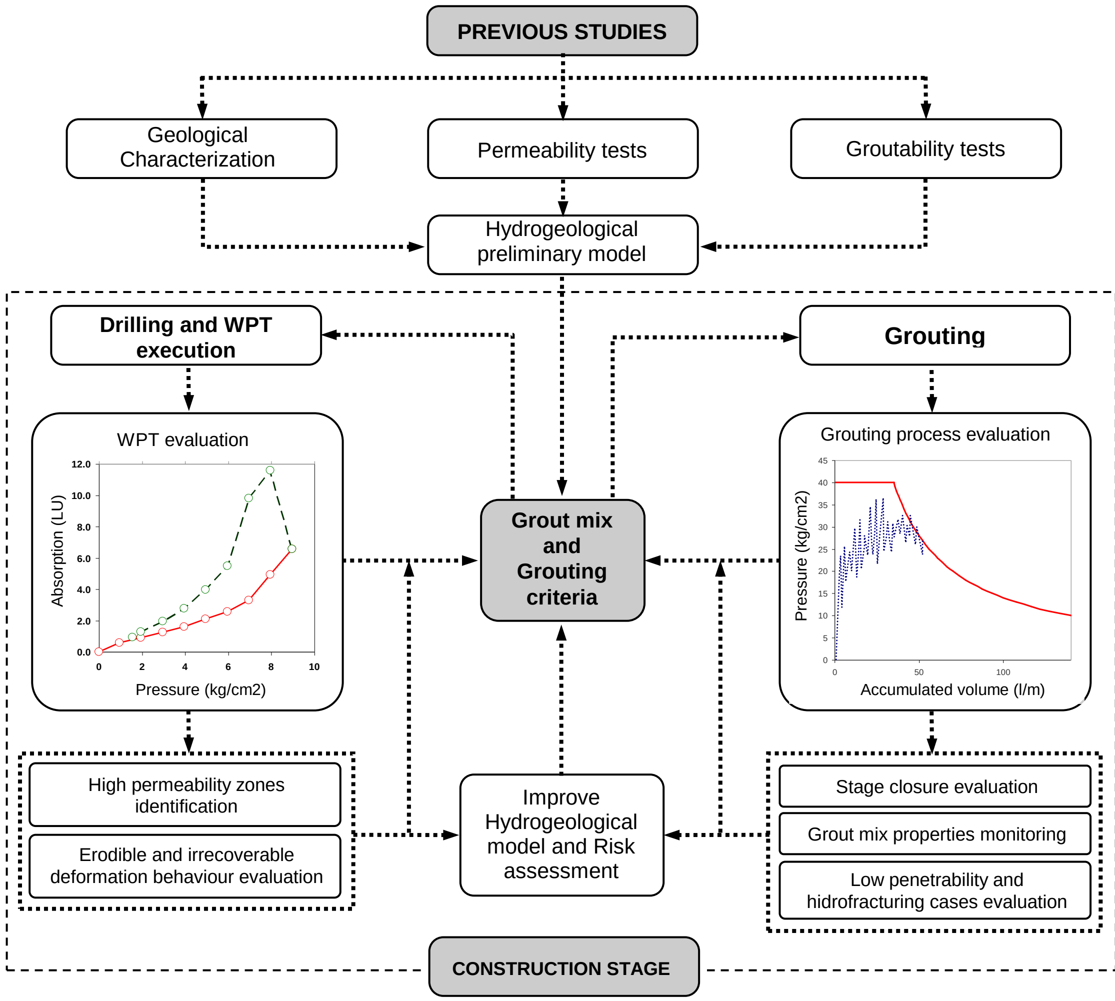


**Figure 10.** Grouting treatments design flowchart (adapted from Fransson *et al.*, 2008)

these verification holes showed grout takes, after quaternary holes, lesser than 20 l/m; nevertheless, sites with this behaviour represents only 8% of executed treatments.

"D" zone is represented by impermeable rock susceptible to hydrofracturing during grouting progress. Around 20% of treatment associated to hydrojacking phenomena have been identified, mainly in inferior galleries of left abutment, which did not cause excessive grout takes, however, reduction ratios between stages showed local anomalous results that have been solved with additional holes.

## 7 TREATMENT DESIGN METHODOLOGY

Based on previous experience related to grouting treatments in hydroelectric projects, the observational design methodology illustrated in Figure 10 is actually used in La Yesca dam.

The information generated during previous studies stage, provides the initial criteria and grout mix suitable properties; however, the evaluation of grouting and permeability results during construction stage, provide feedback to the geohydrological and geotechnical model, that together with experiences generated during the process, resulted in criteria modification for grouting procedures and grout mix properties.

During construction stage are evaluated: WPT results; behaviour of grouted segments and its correlation with geological conditions; behaviour of grout mix properties in different seasons and under different manufacturing conditions; grout consumption evolution between stages; evolution of maximum pressure reached; and eventualities related to hydrofracturing or hydrojacking phenomena that produce adverse results during grouting.

This iterative process lead to technical and economical optimization of grouting treatments, while its continued application may conduct to grouting behaviour predictions, risk assessment and appropriate mitigation measures.

## 8 CONCLUSIONS

The design of La Yesca grouting treatments is currently performed under an observational methodology. According to the results obtained, GIN method has been adequate for central section and low abutment areas of the project where low grout takes and hydraulic conductivities have been exhibited; however, other project areas that showed highly hydraulic heterogeneity during previous studies still in execution process, eventual results will lead to evaluate the applicability limits of actual grouting methodology, the necessary process modifications and current project optimization.

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