Design and construction of composite cut-off system at Grand Ethiopian Renaissance Dam, Ethiopia

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ABSTRACT: The Grand Ethiopian Renaissance Dam (GERd) Project is located along the Blue Nile River in Ethiopia. This paper is focused on the main design and construction aspects of the composite cut-off system of the Saddle Dam (60 m high and 5 km long, 15 Mm^3 of embankment volume), executed all along the central portion of the dam founded on residual soils (about 4 km).

Composite cut-off, constituted by pressure grouting and plastic diaphragm panels, was conceived to address two different requirements: permeability and erosion control.

This paper covers the investigations carried out to assess the erodibility of foundation material and the design elements conceived to counteract the unlikely sequence of events that, if occurring in progression, would have the potential of evolving into a progressive erosion process. Moreover, the criteria adopted to define the extension of diaphragm panels and the continuous refinement process of diaphragm geometry following the construction progress and the acquisition of additional geotechnical information are discussed in details. Finally, the assessment of composite cut-off system is provided based on the data acquired during the implementation of the works.

1 GEOLOGICAL SETTING

The Saddle Dam of GERd Project is located in a contact zone where the meta-sediment (low metamorphic) collided with the basement rocks (high metamorphic). The compression stress is given by an orogenic cycle known as Mozambique Belt. The boundaries between the gneissic and volcano-sedimentary sequences are typically of tectonic origin. The geomorphology indicates that between the two dam shoulders, constituted of schist on the left side and metagranite on the right, the foundation material derives from the highly decomposed base rock.

At site scale the geological setting of the Saddle dam foundations is composed of five main geological units characterized by metamorphism at different grades of both volcanic, igneous and sedimentary rocks. The identified units are stacked by a pre-cambrian compression regime also witnessed by the presence of folds, faults and boudinage structures.

The Figure 1 outlines a schematic geological plan reporting the main geological formations. In particular, the Saddle dam is founded on rock (weathered, suffix “w” and fresh) in left and right abutments, and on residual soils (i.e. decomposed rock, suffix “d”) of variable depth in the central part.

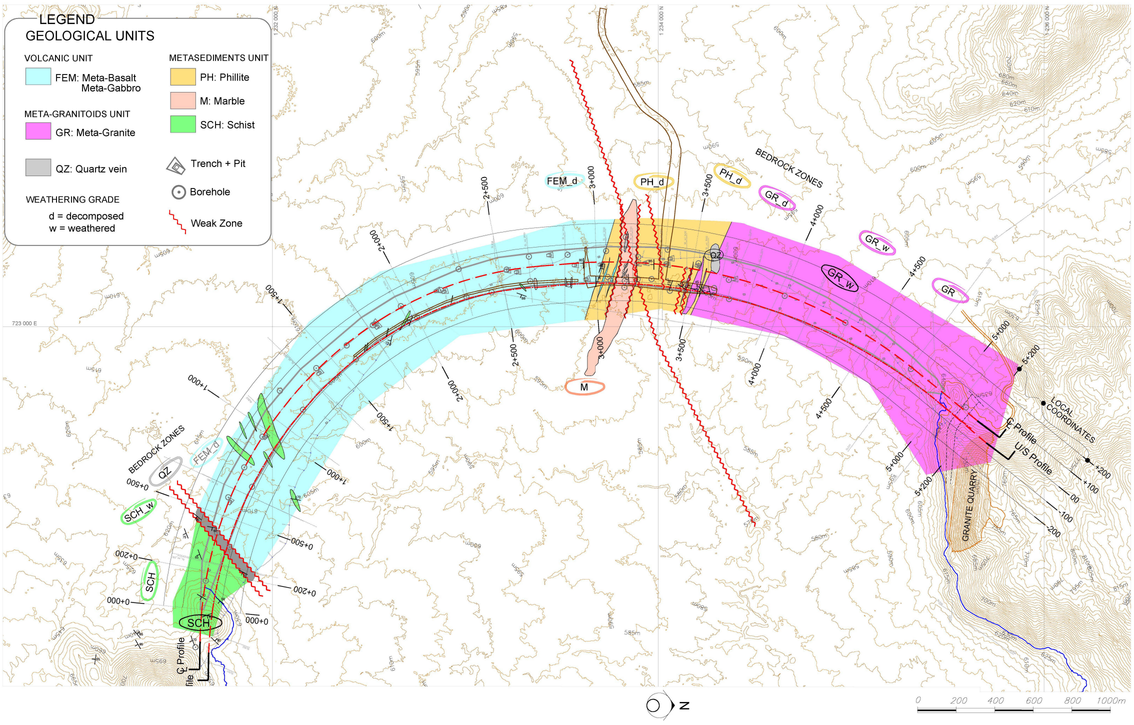

Figure 1. Saddle Dam. Schematic Geological Plan.

From left to right bank the following five main geological units are present:

- Schist (SCH)
- Femic (FEM)
  - Meta-gabbro (mG)
  - Meta-basalt (mBa)
- Phyllite (PH)
- Marble (M)
- Metagranite (GR)

Minor quarzitic veins are found in the left and central portion of the foundation. Hence, the dam is founded on residual soil for a length of 3.6 km and on rock for the remaining portion of 1.4 km.

The boundaries between the above-mentioned geological units are often characterized by tectonic contacts giving rise to the following two weak zones (wz):

- wz_0+400 (Qz);
- wz 3+200 (M / PH_d) to wz 3+450 (deep PH_d).

These zones are continuous in the upstream to downstream direction crossing the entire dam foundation footprint and are characterized by high permeability and by the presence of potentially erodible material. The wz 0+400 is characterized by adjacent slivers of very strong quartz, marble and decomposed metagranite with a metric band of tremolite. In the central-right portion of the Saddle dam foundation, the area between wz 3+200 (M / PH_d) and wz 3+450 (deep PH_d) is characterized by sharp lithological contacts between phyllite and marble units and a more than 30 meters deep weathering profile where decomposed to highly weathered phyllite is found.

The excavation of the inspection gallery trench along the upstream toe outlined a complex geological setting made of sub-vertical slivers of material at different grades of weathering. A detailed geological mapping has been carried out along the plinth and the inspection gallery footprints following the progress of the excavation and concreting activities. At some place the excavation of the diaphragm panels in the upstream area has been inspected and mapped.

2 SCHEMATIC LAYOUT OF THE SADDLE DAM

The Saddle dam of the Grand Ethiopian Renaissance Project is a rockfill dam provided with upstream concrete facing (CFrd). Main features are resumed hereinafter:

– crest length	[m]	4865
– maximum height (H)	[m]	~ 65
– U/S slope	[h/v]	1.3:1
– D/S slope	[h/v]	1.3:1
– crest width	[m]	8

At Full Supply Level the overall reservoir volume of the Project, is about 80’000 Mm^3, 65’000 Mm^3 of which are stored above the minimum foundation level of the Saddle Dam.

As described in the previous paragraph, the dam is founded on rock in correspondence of the abutments and in residual soil in the central portion.

According to the local conditions of foundation, No. 2 main typical sections have been designed:

1. for the portion founded on rock, approximately 1’400 m long, the dam is provided with an upstream plinth and the seepage barrier is constituted by grout injections in correspondence of the U/S toe plinth.
2. for the portion founded on residual soil, approximately 3’600 m long, the dam is provided with an upstream inspection gallery and plinth, and the seepage barrier is constituted by composite cut-off (i.e. the combination of plastic diaphragm and grout injections)

No. 5 transversal galleries are provided to access from downstream the inspection gallery.

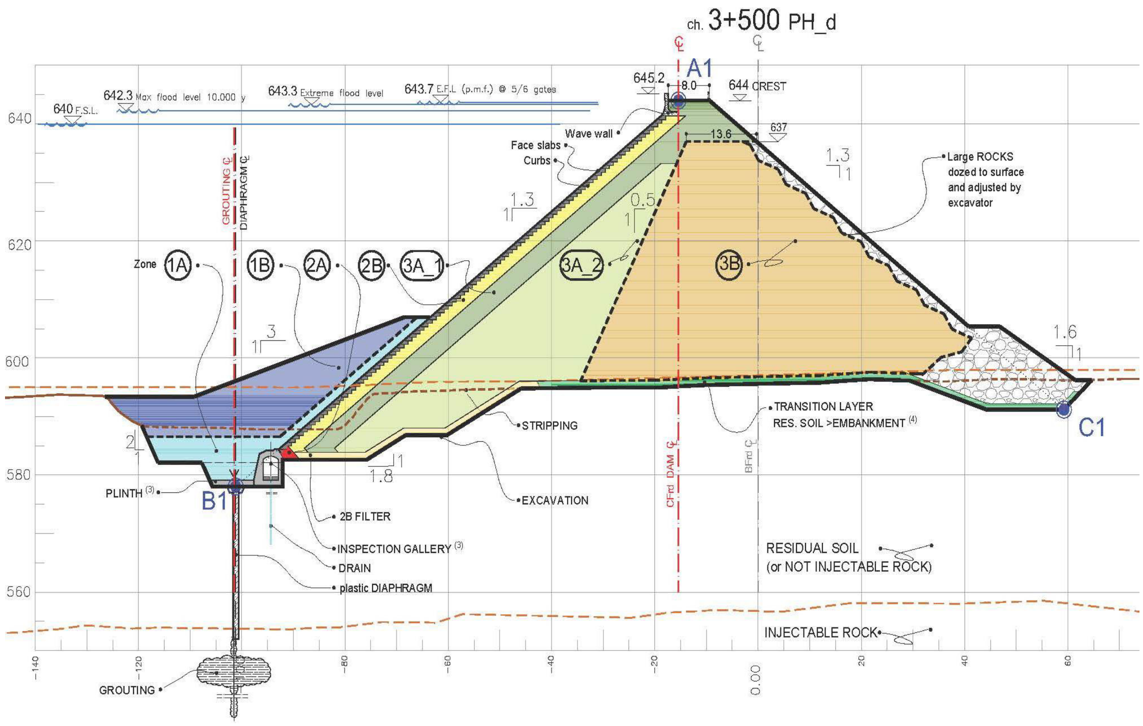

Figure 2. Saddle dam typical section on residual soil.

3 MAIN INVESTIGATIONS

3.1 *General*

An extensive investigation campaign has been carried out in order to characterized the foundation material of the Saddle Dam and ensure a safe design.

The different methods used during the first phase of the investigation campaign (carried out before the detailed design) are listed hereafter, grouped for different levels of detail:

- MACRO scale: approximately 12 km of geophysical lines processed with the tomographic approach allowed to identify the thickness of low velocity layers and the location of the main weak zones;
- MEDIUM scale: excavation of about 15 deep trenches (up to 17 m of depth) allowed to:
  - observe the structure and the mechanical characteristics of residual soils;
  - sample soil specimens;
  - estimate the minimum shear resistance of soil by back analysis of walls stability;
  - measure the residual shear resistance of the materials;
  - estimate the soil stiffness;
  - execute large scale permeability tests.
- SMALL scale: 45 boreholes drilled with core recovery and water tested; Marchetti Dilatometer tests (DMT) and Menard Pressuremeter (PMT), allowed to:
  - measure the thickness of residual soils;
  - evaluate the permeability of the foundation;
  - evaluate the stiffness and mechanical properties of foundation materials.
- MICRO scale: laboratory tests allowed to:
  - execute identification tests on the materials (grading and Atterberg Limits);
  - evaluate resistance and stiffness of residual soils in controlled boundary conditions;
  - evaluate variation in soil stiffness and resistance passing from unsaturated to saturated condition.
  - assess the swelling/shrinkage behaviour of the residual soils;
  - assess the behaviour of the residual soils with respect to still and flowing water (dispersivity and erodibility);

Moreover, before the excavation of the plastic diaphragm in the central part of the foundation where residual formations were encountered, borehole drilling for primary holes of curtain grouting were carried out with continuous core recovery every 12 m. This investigation provided detailed geotechnical information on the subsurface conditions, allowing to accurately define the characteristics of the foundation and the geometry of the diaphragm.

3.2 *HET*

In order to assess the risk connected to potential erodibility of the foundation material and design relevant countermeasures, Hole Erosion Tests (HET) were carried out on undisturbed samples collected at various depth from the excavated trenches.

Hole erosion test is a method for evaluating the erodibility of cohesive soils basing on the effects of water flowing through a hole predrilled in the specimen.

It is therefore conceived to investigate the erodibility of a cohesive soil subjected to concentrated leaks. Application to highly weathered rock formations, with large coarse grain fractions and residual structure is "stretched" and understandably problematic.

The HET is conducted in the laboratory using an undisturbed tube sample or a soil specimen compacted into a Standard Proctor mild. A 6-mm diameter hole is predrilled through the centreline axis, and the specimen is installed into the test apparatus in which water flows through the hole under a constant hydraulic head that is increased incrementally until progressive erosion is produced. Once erosion is observed, the test is continued at a constant hydraulic head for up to 45 minutes, or as long as flow can be maintained.

HET have been carried out on No. 21 undisturbed samples prepared by resizing blocks of residual soils sampled from the trenches excavated in the saddle dam foundation area (from 4.5 m to 11 m of depth).

Results of HET were quite scattered due to the anisotropy (orientation of the foliation of the parental rock with respect to the drilled hole) and inhomogeneity (weathering degree, local plane of weakness) of the residual soil at the scale of the sample. Therefore, the definition of critical gradient value for the different formations of the residual soil resulted problematic and scarcely significant.

Consequently, in order to protect the foundation from the potential risk of progressive erosion, it was adopted a "multiple lines of defence" approach, tailored for the different stretches of foundation depending on local geotechnical / geometrical / hydraulic characteristics and boundary conditions.

4 COMPOSITE CUT-OFF CONCEPT

Composite cut-off is constituted by pressure grouting and plastic concrete diaphragm panels. It has been executed all along the central portion of the dam founded on residual soil while on the left and right banks, characterized by the presence of schist and metagranite respectively, only pressure grouting has been carried out.

This system was conceived to address two different requirements:
- permeability correction;
- erosion control.

This last requirement was generally met by deepening the diaphragm down to a level of non-erodible rock or, in case of continuous at depth potential erodible material, down to a level where the corresponding seepage gradient at the U/S toe results lower than the critical gradient.

Construction of the diaphragm wall was preceded by the execution of the curtain grouting which allowed to acquire, together with the examination of U/S trench excavation slopes, detailed geotechnical information on the foundation materials. The bottom limit of the diaphragm (named as Objective Level or OL in the prosecution of this paper) was therefore defined in subsequent steps:
- tentative OL
  based on the analysis of primary grouting holes 12 m spaced and drilled with core recovery
- refined OL
  review of tentatively OL based on:
  - examination of U/S trench excavation slopes
  - analysis of grout takes and check holes results
- actual OL
  as-built of diaphragm wall.

In general, the excavation was carried out with a clamshell up to refusal conditions and then completed with the hydro-mill in order to socket the diaphragm into competent rock (the hydromel required a minimum pre-excavation depth of about 4 m). Positive or negative deviations between tentative and actual OL were observed along the foundation. Special cases, requiring specific evaluation, were constituted mainly by the following two categories:
- clamshell refusal above 4 m (with OL > 4 m). In such condition it was not possible to use the hydro-mill, being the pre-excavation trench too shallow;
- sharp lateral variation of panel depth (reflecting the geological structure of the foundation) which could result in a non-complete removal of portions of weak rock (overshadowed by sound rock).

These cases were duly recorded and analysed also by means of visual inspection of excavated panels, surface mapping of the trenches, and verification of hydro-mill digging parameters (recoded in continuous by the hydromill apparatus). In some cases, additional excavations were carried out by means of staggered panels or using heavy chisels. In other cases, special additional grouting injections were executed.

It is highlighted that, in addition to the composite cut-off system (diaphragm and pressure grouting), several active and passive design elements have been conceived to counteract the unlikely sequence of events that, if occurring in progression, would have the potential of evolving into a progressive erosion process:

- DEEP U/S TRENCH
  A deep trench (from 10 to 20 m) has been excavated in the U/S toe of the dam, where higher hydraulic gradients are expected, in order to found the plinth and the gallery on a material with better geotechnical characteristics and therefore less susceptible to erosion.
- PLINTH and GALLERY (with drains)
  Plinth and gallery, with an overall width of about 10 m, reduce themselves the gradient to values that are generally accepted for intensely weathered and fractured rocks. The gallery equipped with drains and piezometers will allow to monitor the efficiency of composite cut-off and, if necessary, execute additional corrective works.
- FILTER in the U/S trench
  A filter has been placed above the portion of residual soil foundation between the inspection gallery and the top of the upstream trench which would counteract continuation of erosion process.
- TRANSITION layer
  A transition layer has been placed in the remaining portion of the dam footprint on residual soil.
- U/S BACKFILL
  The upstream fine grained backfill, extended to about one third of the local height of the dam, will tend to clog potential pervious water conduits (flow-limiting and crack-filling actions).

5 ASSESSMENT OF COMPOSITE CUT-OFF

5.1 *Foundation permeability before composite Cut-Off*

Permeability of Saddle dam foundation have been investigated at great detail by means of investigation holes generally spaced 36 m, drilled with core recovery along the cut-off axis and water tested (before the execution of grouting) with standard Lugeon methodology following the progress of drilling works (downward, with stage lengths of 5 m, 5 steps of ascending and descending pressure, each lasting 10 minutes, and a maximum pressure of 10 bars).

More than No. 120 investigation holes have been executed for an overall length of about 5’500 m. The graph in Figure 3 illustrates the distribution of Lugeon values below the invert level of gallery/plinth for the No. 4 main geological units (a fictitious value of 100 UL was assigned to the stages where it has been observed bypass, or water-absorption exceeding the pump capacity).

Main observations are the following:

- general distribution of Lugeon values with depth is similar in the different foundation stretches;
- foundation is impervious at large: 68% of the values is less than 5 UL;
- higher permeability is generally limited to the upper portion of foundation (i.e. from 0 to 20 m below plinth level). An exception is represented by the foundation stretch between ch. 3+050 and 3+500 characterized by the presence of deep-decomposed phyllite and marble.

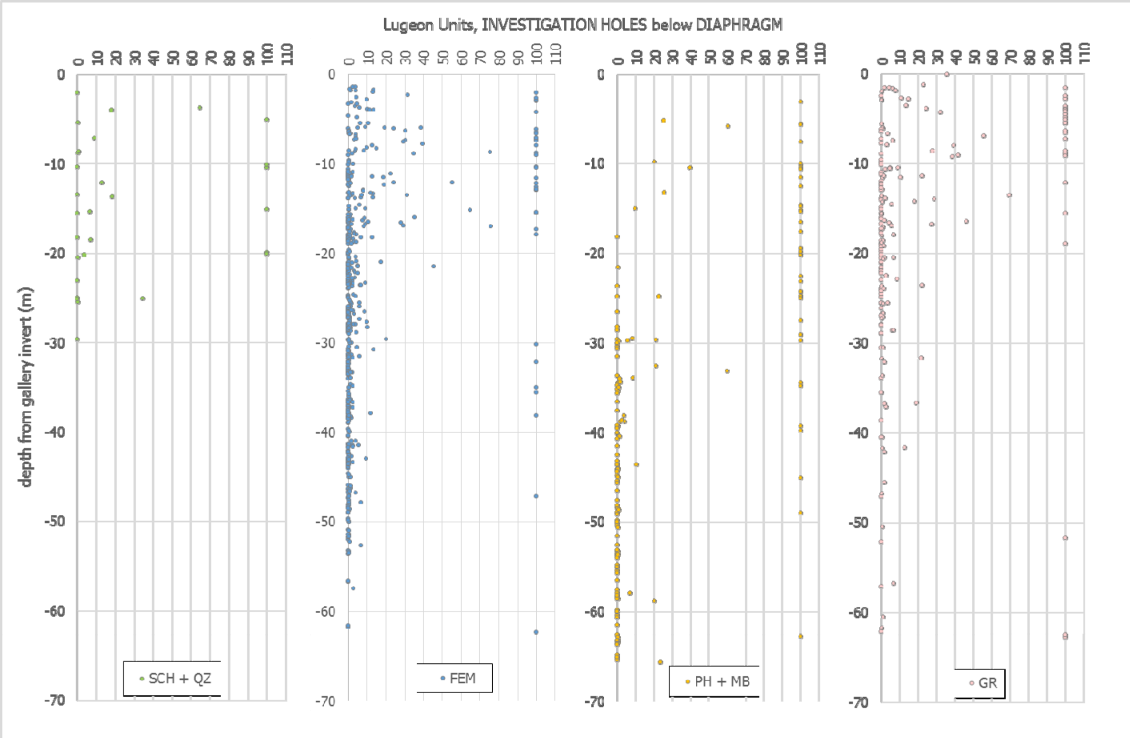

Figure 3: Investigation Holes, Lugeon Units VS depth below gallery/plinth invert.

No. 58 wash-out stages over an overall number of No. 1070 tested stages have been recorded, which corresponds to about 5%. About 70% of these stages are concentrated in the first 15 m below the gallery/plinth invert level. These stages are distributed almost evenly among the different foundation stretches. Anomalous behaviours associated to high Lugeon Units and low grout take are found in about 10% of the tested stages.

5.2 *Grouting*

About 3'300 grouting holes, for an overall length of about 100 km have been executed along the Saddle dam foundation profile. The overall net quantity of cement injected in the sums to about 1'500 tons. The graph in Figure 4 reports the spatial distribution of net take of each grout hole series from primary (red area on the background) to quaternary (grey area on the foreground).

The main observations are the following:

– globally, the net average grout take reduces from 23 kg/m, recorded in the primary holes to less than 6 kg/m in quaternary holes;
– higher grout takes are observed in correspondence of most pervious areas (Quartz lineament at ch. 340; marble area and contact between PH / FEM and PH / GR between ch. 3+000 and 3+300);
– along the above areas the average grout take is considerably higher, reaching more than 100 kg/m;
– reduction of take from primary to quaternary hole series is generally observed along the entire foundation profile.

5.3 *Diaphragm*

The as-built profile of diaphragm panels was included in detailed analytic profiles reporting all the main information related to the composite cut-off system:

– Position of investigation holes (the ones water tested are highlighted with a blue hatch);

– Position of check holes executed after grouting;
– Tentative Objective Level;
– As-built diaphragm panels;
– Location of additional treatment areas and relevant check holes;
– Schematic geological profile, as surveyed on the foundation level of plinth and gallery;
– Excavation methodology of diaphragm panels (hydromill or clamshell);
– Difference between tentative Objective Level (OL) and Diaphragm bottom level (DL);
– Section type.

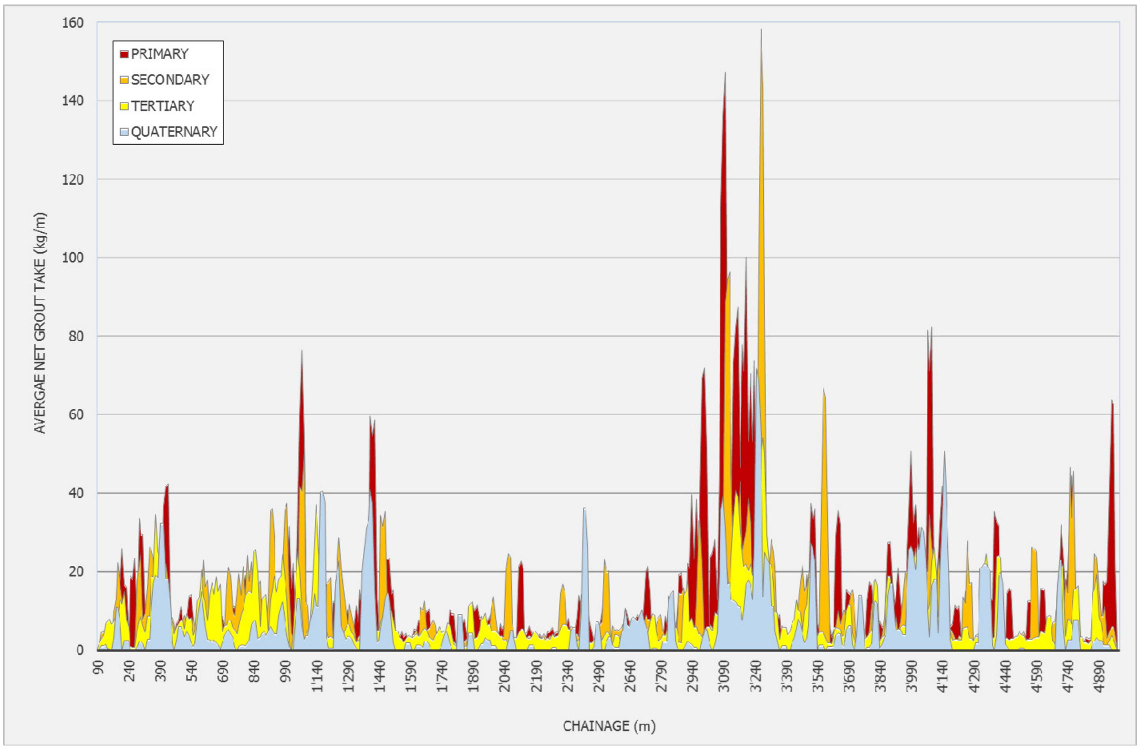

Figure 4: Distribution of average NET grout take (Primary to Quaternary holes).

As far as the diaphragm panels is concerned it is observed that:

– Diaphragm panels extend from ch. 0+200 to 3+650, with a max. depth of 30 m.
– The excavation of the panels has been completed always with the hydromill where the pre-excavation executed with the clamshell exceeded 3-4 m of depth (which is the minimum required to operate the hydromill). Few spot-points where this criterion was not respected, because of local conditions, were recorded.
– Hydromill excavation has been generally continued until a digging load higher than 200-250 kN (maintained for 10-15 minutes) or a drilling speed lower than 2.5 cm/min (for 10-15 minutes) have been reached. Excavation parameters have been carefully recorded continuously and in real time by the digital control apparatus of the hydromill.
– As built diaphragm resulted shallower than tentative OL along about 550 m over 3’450 m (i.e. 15%). The average deviation along this 550 m long stretches is just 3 m with a maximum of 30 m in correspondence of Quartz sliver at ch. 0+345.
– Specific inspections have been always carried out where diaphragm panels resulted shallower than the tentative Objective Level or if the excavation has been executed entirely with the clamshell.
– Sharp lateral variation of the weathering grade of the rock foundation are often reflected by the difference in depth of the adjacent diaphragm panels.
– Comparing the diaphragm profile with the results of water tests executed on along No. 90 check holes carried out after grouting it is observed that about 90% of the water-tested stages below the bottom of the diaphragm have less than 5 UL

5.4 *Foundation permeability after composite Cut-Off*

Permeability after grouting works have been investigated by means of check holes generally spaced 36 m, drilled and tested with the same methodology of the Investigation Holes.

More than No. 120 check holes have been executed for an overall length of about 4’200 m. Figure 5 illustrate the distribution of Lugeon values (below the bottom of the diaphragm) relevant to main geological units. Comparing the water test results before and after the execution of cut-off works it is observed that:

- the general distribution of Lugeon units shows reduced and less dispersed permeability values for the four different foundation stretches;
- the percentage of stages with permeability less than 5 UL results increased from 68% to 87%;
- higher permeability is generally limited to the upper portion of foundation (i.e. from 0 to 20 m below plinth level). Anomalous deep high-absorption stages are almost absent after cut-off works;
- the percentage of stages with wash-out behaviour is almost the same before and after cut-off works (i.e. about 5%) and are distributed almost evenly among the different foundation stretches;
- after cut-off works it is observed that the Lugeon values associated to wash-out behaviour are generally lower and that the shallower and most critical wash-out stages are almost disappeared.
- the anomalous stages with high Lugeon Units and low grout take are reduced from about 10 %, in the Investigation holes, to 5% in the Check holes.

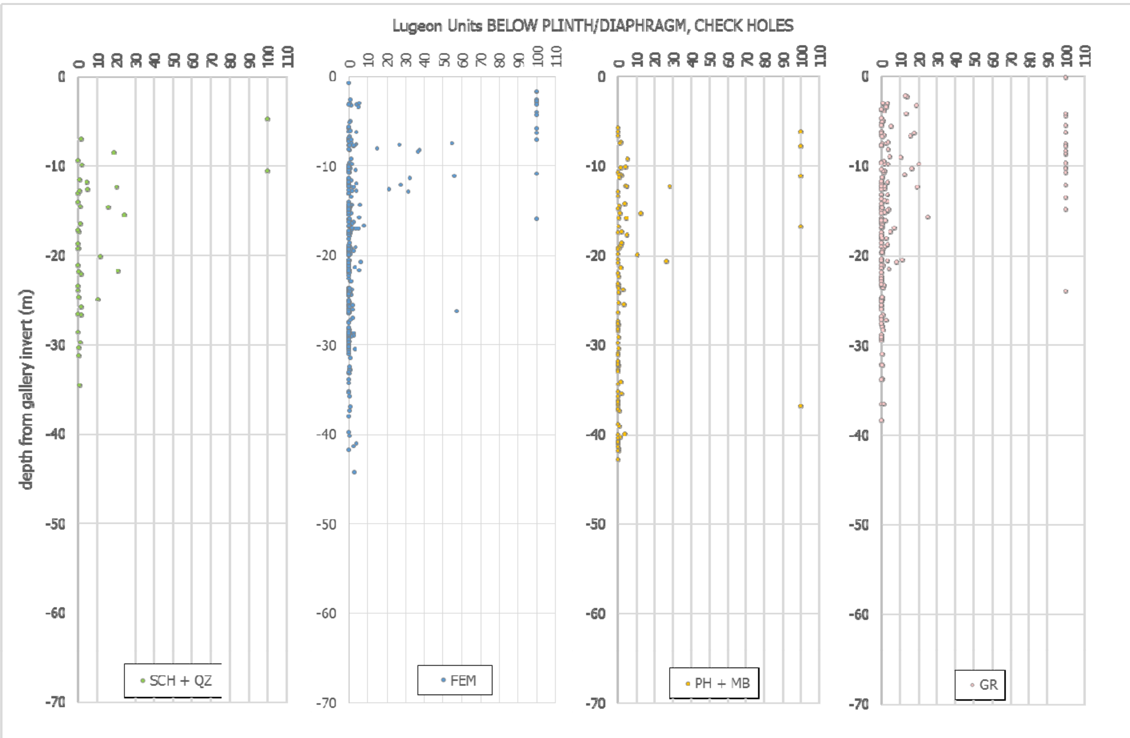

Figure 5: Check Holes, Lugeon Units VS depth below gallery/plinth invert.

5.5 *Additional Treatments*

Additional treatments have been prescribed in the portions of foundation below the plinth/diaphragm where it was observed:

- High Lugeon Units in the check holes;
- High Lugeon and low grout-take in the Investigation holes and in the adjacent grout holes;

- Diaphragm level shallower than tentative Objective Level;
- Extremely shallow diaphragm panels (excavated with clamshell only);
- Sharp lateral variation of diaphragm panels depth.

The additional grouting treatments have been generally carried out using the local available cement milled with the equipment available at site with the aim to improve the efficacy of grouting treatment by increasing of fineness of cement and reducing the size of larger particles diameter (that mainly control the penetration of the grout).

The overall length of the foundation stretches interested by additional grouting treatments summed to more than 1’500 m.

Moreover, in correspondence of the two main weak zones:
- wz_0+400 (Qz);
- wz 3+200 (M / PH_d) … wz 3+450 (deep PH_d).

continuous in U/S - D/S direction and characterized by high permeability and by the presence of potentially erodible material, the composite cut-off system has been integrated with a PVC blanket extending upstream for about 150 m in order to reduce the resulting D/S gradients to acceptable values.

6 CONCLUSIONS

Main results of composite cut-off works in terms of permeability correction are summarized in Figure 3 and 5. After composite cut-off works it is observed that:
- the Lugeon Values are generally reduced and less dispersed in all the foundation stretches;
- the percentage of stages with permeability less than 5 UL increased from 68 % to 87 %;
- the percentage of stages with wash-out behaviour is limited to about 5 % of the entire dataset. Shallower and most critical wash-out stages are almost disappeared.

Additional grouting treatments have been prescribed following the criteria reported in chapter 5.5 and included more than 1’500 m of foundation stretches.

In correspondence of the two most critical weak zones a PVC blanket extending about 150 m in the upstream direction have been introduced in order to limit the hydraulic gradients.

The analysis of composite cut-off system, together with the other defensive design elements (i.e. deep U/S trench, plinth and gallery, filter and layer, U/S backfill, horizontal blanket) allows to meet the Design’s requirements of permeability correction and erosion control.

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