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Super-Deep Cut-Offs to Improve Inadequate Foundation and to Repair High Dams

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Abstract: Many damsites have not been harnessed because of unfavorable foundation conditions like deep alluvial deposits or pervious rocks or karst. Recently the technology of milled concrete cut-offs has made a major step forward pushing way back the limit of impracticable projects. The paper describes a new hydromill capable of cutting, using stabilizing fluids, panels to a depth of 250 m and the operations related to cutting and casting of a super-deep panel. The paper also describes super-deep milled cut-offs obtained with the alternate technology of large diameter, secant piles to depths > 250 m. The paper will describe preliminary and ancillary activities necessary to create such a cut-off. Finally the paper proposes examples of applications of the super-deep cut-offs to new dams and to repair existing dams (and their abutments) where emptying the reservoir is impracticable and the depth of repair must include a large part or the whole of the embankment.

1 Introduction

Today a super-deep cut-off to 250 m depth is a reality. This would change the perspectives of dam engineering.

The majority of dam accidents derives from foundation flaws. Most foundation inadequacies are in excessive permeability, insufficient foundation strength being much less frequent. Dam owners, more and more confronted with the need to improve the foundations of their dams, need to test and develop methods and technologies responding to such an issue. The rapid growth of dams heights and the pressure to build on most any foundation, often required more than yesterday technologies could offer.

This paper focuses on reduction of permeability at very large depths with technologies other than grouting or jet-grouting. Conventional cut-offs will just be mentioned while recent progress in equipments and construction of super-deep cut-offs will be presented in detail.

2 EVOLUTION OF CONCRETE CUT-OFFS

2.1 Clamshell cut-offs

Up to the early fifties of last century, only relatively shallow cut-offs where possible. They were built with open strutted cuts or slurry trenches or sunk caissons in special cases. The turning point arrived when I. C. O. S. of Milan developed the bentonite mud supported excavation and started the era of modern concrete cut-offs. The paper by C. Veder [1] published in 1953, set the bases of the new technology. The early applications, with 0. 6 m diameter secant piles at 0. [illegible] m spacing, were done at Maria al Lago dam followed by Venafro dam on river Volturno, both in Italy.

Soon after the pioneering applications, the concrete cut-off excavated in bentonite mud had a booming success and their depths increased in a few years from the 39 m of Maria al Lago ([illegible]) to the 88 m of La Villita (1968) to the record 130. 7 m of Manic 3 (1973).

Equipments and working methods went through a similarly rapid evolution as [illegible] specialized contractors (RODIO, SOLETANCHE, TREVI) joined in the endeavor. The [illegible] clamshell was complemented by the framed clamshell and the cable lifting system by the [illegible] Kelly boom. Control and de-sanding of the bentonite mud was introduced. Plastic [illegible] self-hardening mud were offered as alternatives to rigid conventional concrete. [illegible] reinforcements and post-tensioning cables were introduced to extend the unsupported panel [illegible] in case of exposed walls. Formed, semi-circular joints between panels were complemented [illegible] and scraped contact joints.

Limitations to the excavation in bentonite mud were represented by highly pervious [illegible] cavities producing mud losses and by large boulders exceeding the size of the clamshell. [illegible] limitation was the inadequacy of the excavating tools to penetrate hard rocks this requiring [illegible] to improve the contact panel-foundation rock. Another limitation remained: possible [illegible] from the vertical which could be on the order of 1% up to 40 ~ 60 m, then increasing [illegible] depth. This could cause windows between adjacent panels.

2.2 Milled cut-offs

The substitution of the clamshell with milling cutter wheels represented a [illegible] the introduction of the bentonite mud. In early eighties of the last century RODIO ([illegible] in Trevi Group in 2005) in Italy, and SOLETANCHE in France developed the [illegible] technology. In 1986 a 100 m depth test panel was performed by Rodio in [illegible]. The first hydromill was applied to install the twin cut-offs at Piano della Rocca dam [illegible] (1989) where the senior Author was in charge of the detailed design of the dam. [illegible] offs maximum depth was a merely 15 m including 2 m in hard flysch [illegible] application of this novel technology multiplied in view of faster advance [illegible] bottom contact.

The technology spread rapidly and milled depths progressively increased [illegible] 5 m of Mud Mountain dam (SOLETANCHE 1988). Differently from clamshell [illegible] the early hydromill equipment, special devices to check and correct deviations in real time were included. Hydromill became the preferred technology whenever dee Ppanels had to be cut or soil/rock interfaces were present. For 4 decades the limit depth substantially remained unchanged, and the 130 m record of Manic 3 (1973) and the 124,5 m of Mud Mountain (1988) unchallenged.

3 SUPER-DEEP CUT-OFFS

The industry has recently shown that for hydromills this is not the limit. The 250 m record depth has been attained and the good quality of the panel assessed.

Hydromilling can be done either milling a rectangular space (panel) by twin, teethed cutter wheels with horizontal axis, or milling a *cylindrical* shaft (pile) by a rotary cutter head with vertical axis.

3.1 Milled Rectangular Shafts

As already mentioned, the possibility of steering the milling unit was introduced by the beginning from the Manufacturers (each one with different devices) thus reducing the deviations from the vertical to a few centimeters only. As corrections could be applied as the milling process proceeded, verticality deviations became unrelated to panel depth. This become a unique advantage of the milling heads, removing any depth limit imposed by deviation from the vertical.

Modern Hydromills can correct inclination in all the three axis. The position of the milling [illegible] can be modified in three ways, by moving flaps (hydraulic jacked plates, that can tilt and [illegible] the frame in all directions) by tilting the milling drums jointly or independently in opposite directions and by adjusting separately the direction and the rotation speed of the cutter wheels. [illegible] frame position is controlled with 2 inclinometers and a gyroscope on board. A sophisticate [illegible] (DMS Drilling Mate System) allows a real time control of all parameters. Inclinometer [illegible] gyroscope signals are processed and appear as offsets and angles on the operator's screen for [illegible] corrections. With the 3D overlap analysis it is possible to visualize at selected depths [illegible] the position of contiguous panels, highlighting the overla pand flashing alarms if specified [illegible] are exceeded.

There are other means of knowing the position of the frame: the shift of the ropes with respect [illegible] panel collar frame or ecosounding the distance of the shaft's walls from a given point on the [illegible] KODEN ecosounder).

A new generation of hydromills SC 200 designed and built by SOILMECH in 2011 is capable [illegible] [illegible]dented depths. The measured deviations from the vertical, at the bottom of the 250 m [illegible] panel, were 0.3 m across the panel long axis, and 0.25 m along the panel short axis say [illegible] and 0.10% of the panel depth.

[illegible] Drilled CircularShafts

[illegible] technology has been derived from oil drilling and the potential depth can exceed the 300 [illegible] Cylindrical heads however work without guidance. The necessary improvement, that [illegible] cylindrical shaft an acceptable element for a super-deep secant piles cut-off, is a closely controlled verticality. A solution was found with a direction-controlled, smart-drilled pilot hole.

Direction-controlled holes are typically 200 mm (8"). At the end of each 3 m long drill rod, the verticality is measured with a single shot survey probe providing the deviation from the vertical and the azimuth against the north. The necessary correction is then obtained with a drill string equipped with down-the-hole water hammer with inclined shoe. Using this set up, 200 mm diameter holes have been performed in hard rock with UCS up to 150 MPa. The directional hole, once completely drilled, becomes the guide to the cylindrical mill. An offset of 200 mm is still acceptable for 100 m deep piles, 1200 mm in diameter at 890 mm spacing. This corresponds to a deviation on the order of 0.25 %.

At Wolf Creek dam (Kentucky, USA) using a cylindrical head 1270 mm (50") in diameter and reverse circulation, to ppile rigs of TREVIICOS-SOLETANCHE drilled 1120 secant piles to a maximum depth of 84 m creating a continuous cut-off. Against a specified deviation of 0. [illegible] the actual deviation measured at the bottom of all piles did not exceed 100 mm say 0.12 % of the pile length.

4 THE SUPER-DEEP PANELS OF GUALDO

TREVI tested new generation SOILMEC equipments at Gualdo di Roncofreddo [illegible] Gualdo panels, beside setting a new record for hydromilled cut-offs, highlighted the [illegible] hydromills to closely follow the vertical, irrespective of the depth travelled.

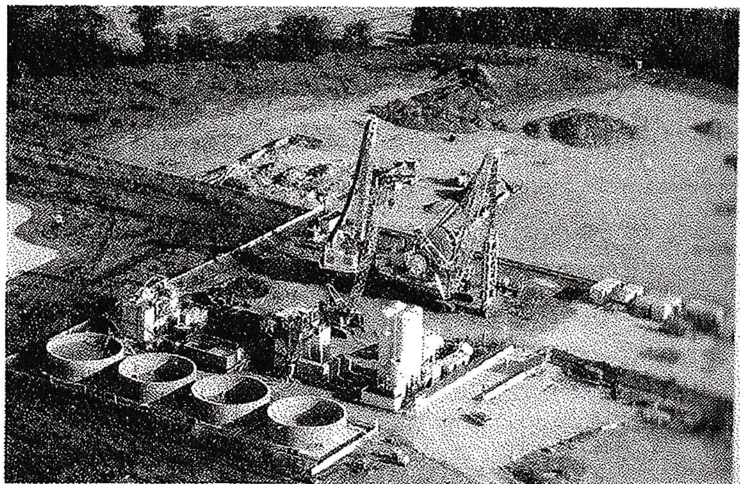

Figure 1 Gualdo test ground aerial view of with 2 hydromill carriers [illegible]

4.1 Ground Profile and Characteristics

The geologic profile of Gualdo testing ground, derived from a 250 m [illegible] are summarized in Table 1 and the Geomechanical characteristics of the [illegible] summarized in Table 2.

Table 1 **Gualdo test ground. Geological profile.**

Elevation [m]	Rock Description	Dip [°]	GSI	UCS [MPa]
g. l. to 6 m	silty and coarse gravel overburden			
6 to 27 m	claystone thinly bedded	12	53	
27 to 52 m	claystone, slightly bituminous, fractured, with gypsum veins. Inclusion of a chaotic mass (submarine slide)	25	53	
52 to 105 m	claystone with slickensides	25	53	43
105 to 129 m	chaotic mass with clay matrix and limestone inclusions			21
129 to 251 m	marl / sandstone alternating (flysch)	25	66	18 – 26

Table 2 **Gualdo test ground. Geomechanical characteristics of the rock**

Rock type	Unit mass [kg/m^3]	UCS [MPa]	Compress. Resistance(1) [MPa]	Traction Resistance(2) [MPa]	Carbonates Content [%]	Water Content [%]	RINH (3) [—]
Claystone	2340	10,8	5,6	0,6	1,5	15,2	2
	2426	20,1	16,2	2,0	2,0	34,0	31
	2480	29,7	25,2	2,6	2,7	45,9	44
Sandstone	2290	9,4	14,0	0,7	0,6	15,0	4
	2430	23,1	28,5	2,5	2,0	32,3	26
	2530	56,6	59,2	5,4	3,5	42,9	42

Notes: (1) Point Load Tests.
(2) Brazilian test.
(3) Rock Impact Hardness Number.

The to p 100 m of the rock were assigned strength parameters gradually shifting from $c' = 320$ kPa and $\varphi = 42°$ at shallow depths, to $c' = 790$ kPa and $\varphi = 29°$ at greater depth. The lowest ... were assigned strength parameters gradually shifting from $c' = 450$ kPa and $\varphi = 43°$ to $c' =$ ... MPa and $\varphi = 32°$ near the panel bottom.

Rock permeability was in the range $(1.4 \sim 8) \times 10^{-8}$ m/s increasing to 10^{-7} m/s between ... and 141 m. The Hoek-Brown rock strength parameters are given in Table 3.

Table 3 **Gualdo test ground. Strength parameters for Claystone and Sandstone rocks**

Rock Type	σ_{ci} (MPa)	m_i (—)	GSI (—)
Claystone	20	7	50
Sandstone	15	12	65

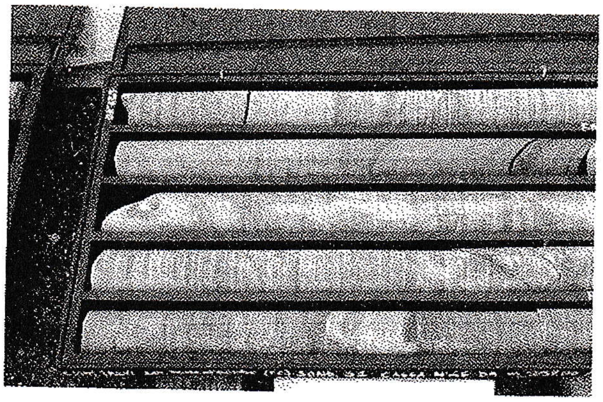

Figure 2 Gualdo test ground. Cores from the exploratory hole drilled prior to panel excavation

4.2 Testing Setup

At Gualdo, 2 panels 3.2 m × 1.5 m in cross section, 150 and 250 m dee pwere milled and concreted in 2012 (see Figure 3 and Figure 4). SOILMEC SC-135 hydromill was used for the first panel, SOILMEC SC - 200 for the second one. In 2013 control holes, checks and test followed. All activities have been monitored and certified by three Italian Universities; in detail Bologna University was involved in soil characterization, Ancona University in concrete design and control, Torino University in excavation accuracy and general survey.

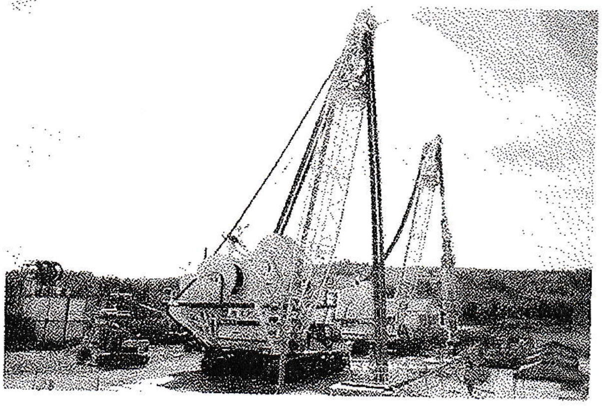

Figure 3 Gualdo test ground. View of hydromills SC-135 and SC-200 after completing a 150 m dee ppanel (background) and with the 250 m panel underway

The main data of the two hydromill units are shown in Table 4.

Table 4 Gualdo Test ground. Main characteristic of hydromills

Item	SC-135	[illegible]
Height of carrier crane (m)	26,5	[illegible]
Cutting depth (m)	130, -150	[illegible]
Power (kW)	450, +450	[illegible]
Milling cross section (mm)	2 000 × 3 200	[illegible]
Machine overall weight	230	[illegible]

The testing set up included a bentonite mud production mixer (SOILMEC BE12), 3 large bentonite mud reservoir (500 m^3 each), the innovative mud processing plant SOILMEC SMT-500 (nominal flow rate capacity of 500 m^3/h with a cut point to 20 μ) completed with the SDM detritus management folding (for directly loading the debris on trucks) and two SMD-90S mud decanter centrifuge (each one with a nominal flow rate of 60 m^3/h of thickened mud). The bentonite mud used to support the excavation was systematically controlled and corrected so as to maintain a unit weight of 1.2 ~ 1.3 t/m^3 and a Marsh viscosity between 32 s and 42 s.

Concreting was made in two phases in December 2012 to test of two different mix designs already tuned upmonths before in Ancona University laboratories. The lower half of the panel was concreted with an high quality plastic concrete (PC), 10 mm maximum aggregate size, using a special cement based blend. Slump was set around 22 ~ 25 cm. The top half of the panel was concreted with conventional concrete with the addition of the excavation slurry (PC-S) (bentonite and fines) to obtain the same slump. The total volume of concrete poured was 1 280 m^3 say 9,3% more of the theoretical panel volume (1 171 m^3). Two different concrete mixing plants were used simultaneously; the average concrete delivery was 80 m^3/h. A special casting set was designed and constructed by SOILMEC (see Figure 4).

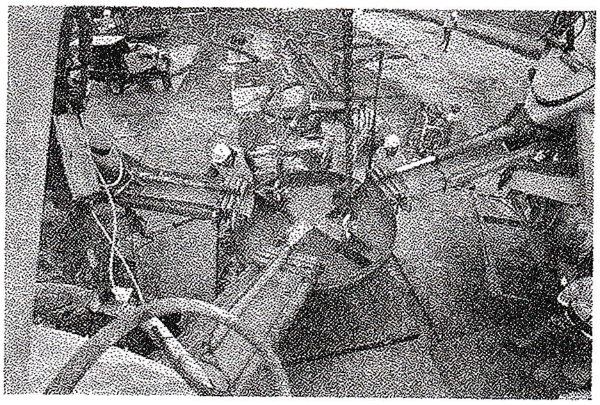

Figure 4 Gualdo test ground. Concreting the 250 m deep panel

Verticality Controls and Corrections

An offsite from the vertical of 0.75 m, normal to the panel long axis, was deliberately ...ed between 85 m and 115 m of depth to test the correction capability of the milling unit. ...fsite was corrected in the following 30 m of excavation. The maximum offset measured at ... attained 0.25 m along the short axis and 0.30 m along the long axis. The rotation along the ... axis was always less than 2°. Figure 5 provides the profile of the panel's walls along short (Y - Y') as recorded with the DSM system. The DMS system deviation data were confirmed ... using KODEN ecosounder (up to 100 m depth) and measuring the shift of the cables ...ing the frame.

In 2013 the actual panel profile and the concrete quality have been checked with a 251 m ...-drilled continuous coring hole, using a direction-controlled drilling technology ... by TREVI. The drilling has been directed to touch both long sides of the panel between

65 m and 85 m on North face and between 193 m and 205 m on South face (Figure 5).

The lowest 100 m of the bore-hole were successively grouted and a new direction-controlled hole drilled, forcing it to the side to cross the short West face of the panel 3 times at 175 m, 190 m and 225 m.

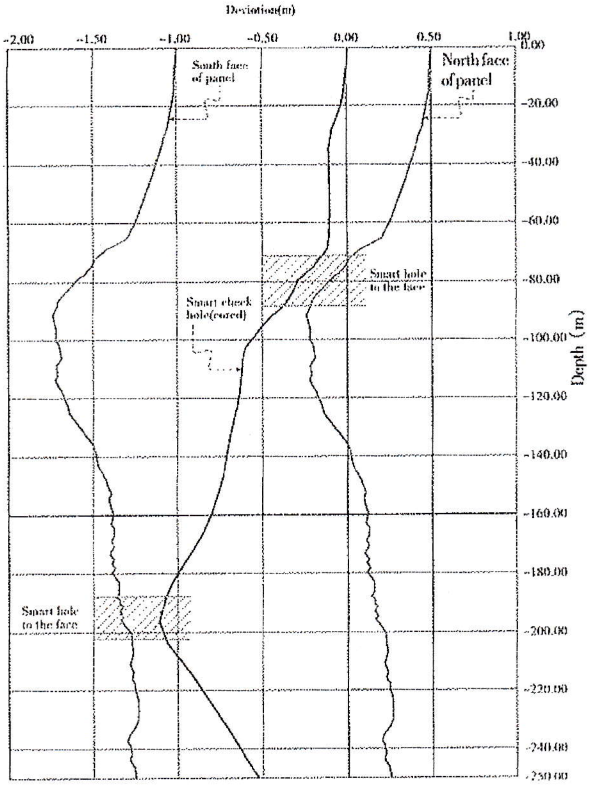

Figure 5　Gualdo test ground. The profile of the 250 m dee ppanel showing the imposed deviation at about 90 m and the recovery of verticality to end upwith an offset of only 0. 24 m. The red lines mark the panel profile [illegible] DMS system. The blue line shows the path of the smart-drilled direction-controlled hole intersecting the panel faces

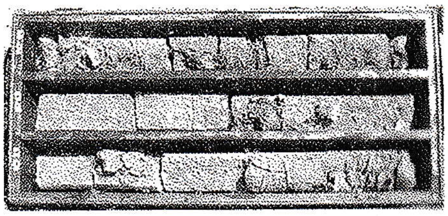

Figure 6　Gualdo test ground. The cores extracted from the [illegible] panel at 68 ~ 69 m depth. The flat face of the panel is [illegible] while half of the core is the local rock

4.4　Concrete quality

The 250 m of core were analyzed for concrete quality with [illegible]

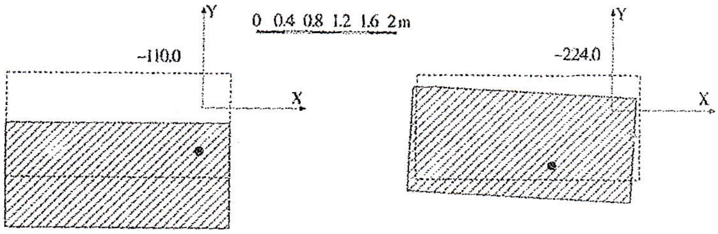

Figure 7 Gualdo test ground. Actual position of the panel with respect to the vertical (dotted line) at different depths. At-110 m the maximum imposed offset. The black dot is the smart-drilled check hole. The blue dot is the second smart0drilled check hole

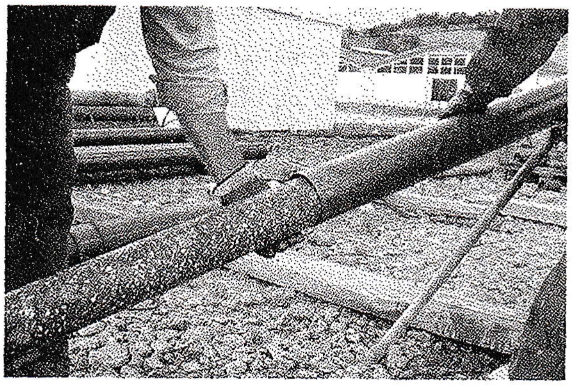

Figure 8 Gualdo test ground. An intact core showing the quality of the panel's concrete

[illegible]TV), with a 'sonic log' based on P waves velocity and with laboratory tests.

Laboratory tests were carried out on a discrete number of core specimens aged from 160 to [illegible] days. Results are summarized in Table 5.

Table 5 Gualdo Test Ground. Results of check tests on 250 m dee ppanel

[illegible]ition		Unit Mass (g/cm^3)	Strength (1) (MPa)	E_{50} (MPa)	Permeability (cm/s)
[illegible] half of [illegible] 125 m [illegible]	average	2,01	5,31	794	
	maximum	1,99	6,4		2×10^{-7}
	minimum	2,02	4,39		3×10^{-8}
[illegible] half of [illegible] 250 [illegible]	average	1,91	4,59	594	
	maximum	2,04	6,37		2×10^{-7}
	minimum	1,87	2,38		5×10^{-9}

[illegible] unconfined Compressive UNC.

[illegible] permeability coefficient decreases with time.

[illegible]W HORIZON

[illegible] possibility of excavating and concreting continuous concrete cut-offs to depths upto 250 m (or more with the secant piles technology), opens to designers and builders unprecedented opportunities.

In the first place, damsites which have not been considered so far, due to the excessive thickness of the alluvial deposits (anything in excess of 120 m or so), do become exploitable. Thick alluvial beds, boulderish formations where clamshell digging will not be practical, erodible rocks, karstified rocks too, can be sealed. Central core as well as upstream deck dams are the best suited schemes to be coupled to a deep cut-off intercepting foundation deposits of excessive permeability along the schemes of Figure 9.

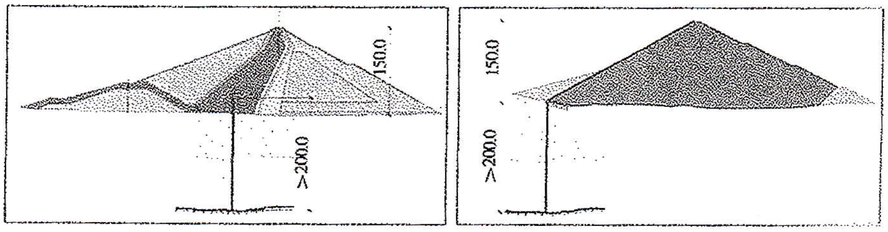

Figure 9 Super-deep cut-offs for central core or upstream deck dams until today unfeasible

Existing large embankment dams, considered to possess marginal safety against [illegible] (dams at risk), whose reservoir maximum water level has been limited to a fraction of the [illegible] capacity, can have their foundation restored and waterproofed and service life extended. A [illegible] deep cut-off can in fact be installed across the embankment and still enter substantial depths of the underlying pervious foundation along the scheme of Figure 10. Wolf Creek dam is a good [illegible] of this very type of refurbishment. With the proviso of a timely diagnosis, Teton dam [illegible] saved today with the installation across the embankment of a super-deep cut-off penetrating [illegible] sufficient distance the jointed foundation rock. An outstanding example of this category [illegible] Mosul dam in Iraq, 130 m high underlined by > 100 m of pervious, soluble and karstified [illegible]

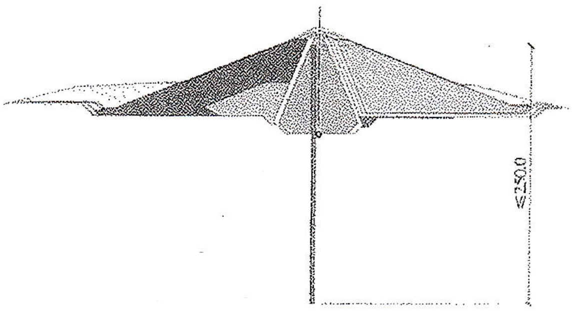

Figure 10 Super-deep cut-offs to improve problematic dations of existing dams working from crest or near-crest level

Finally existing dams of any height with inadequate central waterproofing [illegible] hydro fracturing of the core, can be refurbished by installing a new positive cut-off [illegible] plastic) along the scheme of Figure 11. High dams (> 150 m) with [illegible] concrete cores and other dams of similar conception fall in this group.

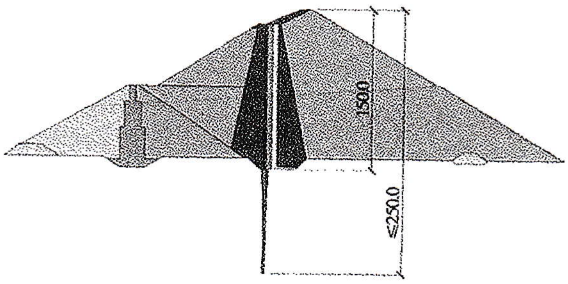

Figure 11 Super-deep cut-offs to improve the waterproofing zone of the dam

Modern design of high dams or of dams with large reservoir capacities (for which draw-down is not an option), from now on should include, as a dam safety provision, the space for a vicariate waterproofing (super-deep cut-off) to be inserted in a proper position, should any problem develo Pduring the life of the structure.

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