17° Congresso Nacional de Geotecnia

10º Congresso Luso-Brasileiro de Geotecnia

11º Encontro de Jovens Geotécnicos

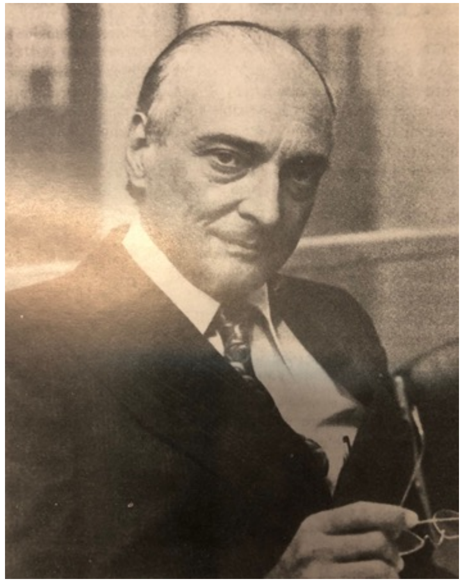
LABORATÓRIO NACIONAL DE ENGENHARIA CIVIL

Sociedade Portuguesa de Geotecnia

Associação Brasileira de Mecânica dos Solos e Engenharia Geotécnica

VII VICTOR DE MELLO LECTURE

LESSON LEARNED FROM DAM CONSTRUCTION IN PATAGONIA ARGENTINA



ING. OSCAR VARDÉ
Honorary President Argentinian National Academy of Engineering

17CNG
Lisboa • LNEC
14-17 • novembro • 2021

VICTOR DE MELLO

Victor brilliant personal qualities has been described by the De Mello previous lecturers:

- “Friend, Engineer and Philosopher”, John Burland;
- “De Mello Foundation Engineering Legacy”, Harry Poulos;
- “My mentor and my role model”, M. Jamiolkowski;
- “Giant of Geotechnics”, Jim Mitchel;
- “A visionary”, J.P. Giraud;
- “Victor devoted his life to the betterment of people not only of Brazil, but also the world at large”, N. Morgenstern

MY VISION ON VICTOR´S PERSONALITY

"His salient personality results in that in all areas in which he exercises activity, he achieves an outstandingly high level, as a consequence of the unusual compounding of natural gifts that are rarely encountered, developed to such a high degree in a single person. He has:

the indefatigable capacity of work of a Portuguese;

the stoicism, and patience and interior peace of an Hindu;

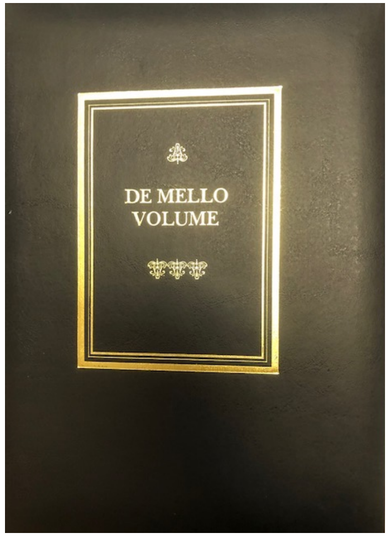
the preoccupation with perfectionism of a Swiss;

the method and systematism of a Britisher;

the pragmatism of an American;

and the eloquence and enthusiasm of a Brazilian"

Introduction to De Mello Volume, Rio de Janeiro, 1989



VICTOR IN ARGENTINA

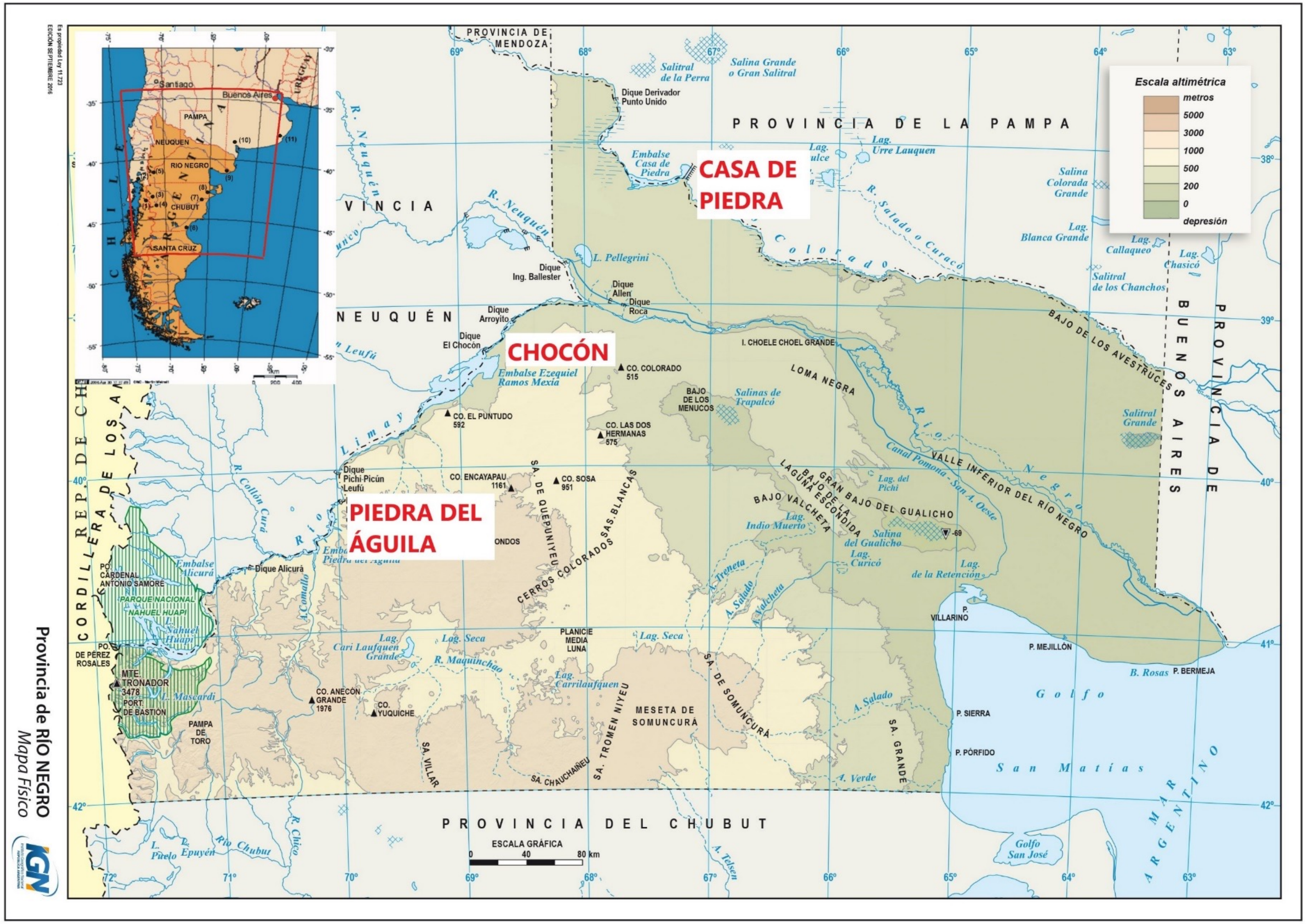
In Argentina Victor participated in the most important events since our first conference on Soil Mechanics in 1968.

In 1975 as Vice President of the ISMSFE for South America he contributed as author and final evaluator of the Pan American Soil Mechanics and Foundation Engineering Congress, in Buenos Aires.

He was Consultant and Expert in numerous large hydroelectrical projects in Argentina:

- Paraná Medio and Yacyretá as a Board Member;
- Potrerillos as a member of the Board with Giovanni Lombardi and myself;
- Casa de Piedra and Rio Hondo as an Independent Consultant.

CASA DE PIEDRA, ALICURA AND EL CHOCÓN



CASA DE PIEDRA DAM

CASA DE PIEDRA DAM

- Located on the Colorado river
- Owner: “Ente Casa de Piedra” (Provinces of La Pampa, Rio Negro and Buenos Aires).
- Designer: Consulting Group including Sir Alexander Gibbs and Partners from England, TAMS from U.S.A. and IATASA from Argentina.
- Contractor: Impregilo, from Italy

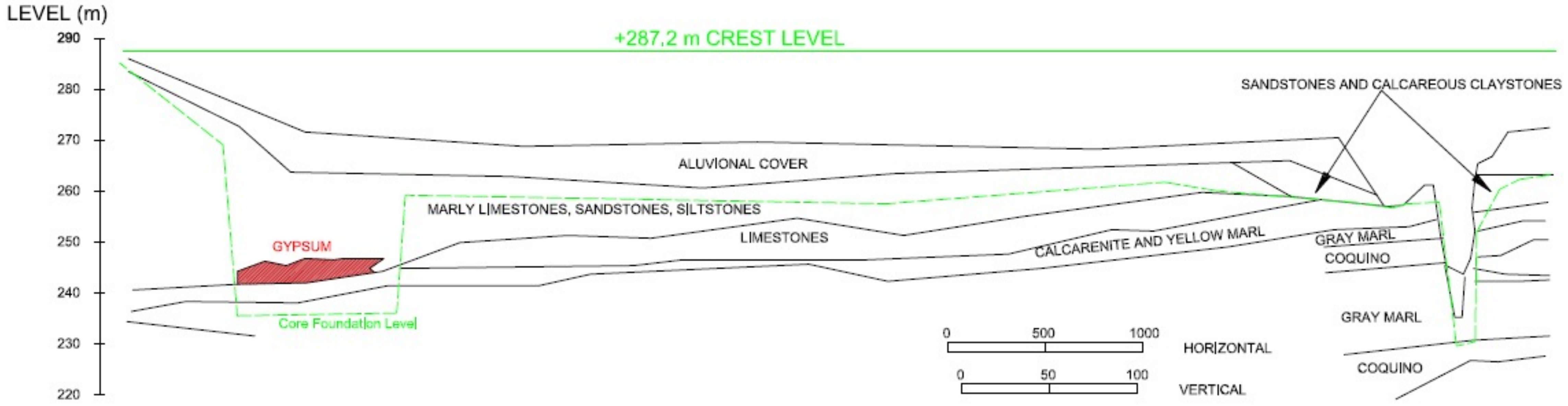
Total length of 11 km

Maximum height of 54 m in the 200 m river gorge, and an average height of 20 m founded on both banks on the river terraces.

Seven kilometers are on the left bank

GEOTECHNICAL PROFILE

Foundations are mostly marine deposits of upper Cretaceous and Lower Tertiary, including marls, claystone, fossiliferous and coquina, and limestones



GYPSUM CAVERNS

Unfavorable geological features were detected during work dam foundations: caverns and dissolution channels through massive gypsum below a zone of the left bank, with a length of 800 m, between stations 700-1500 m.

The investigation of the problem was initiated as a result of a fortuitous event: The presence of a saline paleo layer prevented the setting of the concrete cast to build the cut-off in that sector. The presence of the cavities was brought up by the noticeable presence of gypsum, the loss of injection water in the boreholes and the fall of tools.

INVESTIGATION PROGRAM

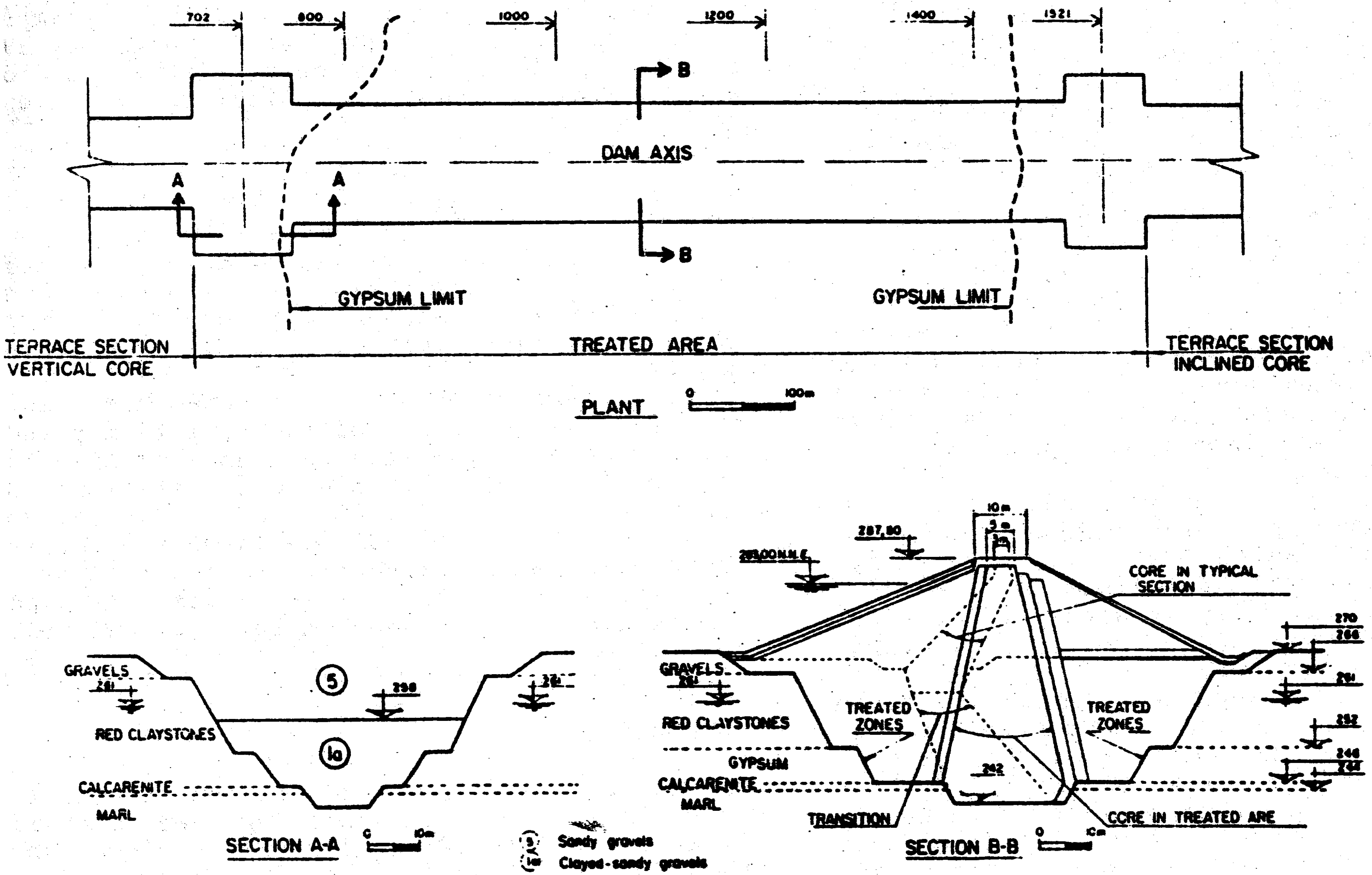
- The program allowed to determine the extension of the karstic gypsum bed, 20 m deep, 5 m thick, which lies over the pervious calcarenite and underneath the red claystones.
- The microgravity survey has been a major help to assess the occurrence and location of karstic cavities.
  The investigation in Casa de Piedra was carried out by the Compagnie de Prospection Geophysique Françoise under de supervision of Geoconseil of France. A total of 619 gravimetric stations were installed, using a gravimeter of high precision (0,5 cgal). The detection of negative anomalies, between -2 to -8 cgal in the zone of stations 700-1500 were in very good agreement with the location of cavities and gypsum dissolution phenomena, as was later verified during the excavations for dam construction.

ADOPTED SOLUTION

Several alternatives were considered for the foundation treatment of the affected zone.

Due to the associated uncertainties, a big excavation of about 2.000.000 m^3 was adopted to remove all the incompetent materials.

The central excavation was complemented by two symmetrical trenches, normal to dam axis, 86 meter long, founded in the gray marls and filled with core material.

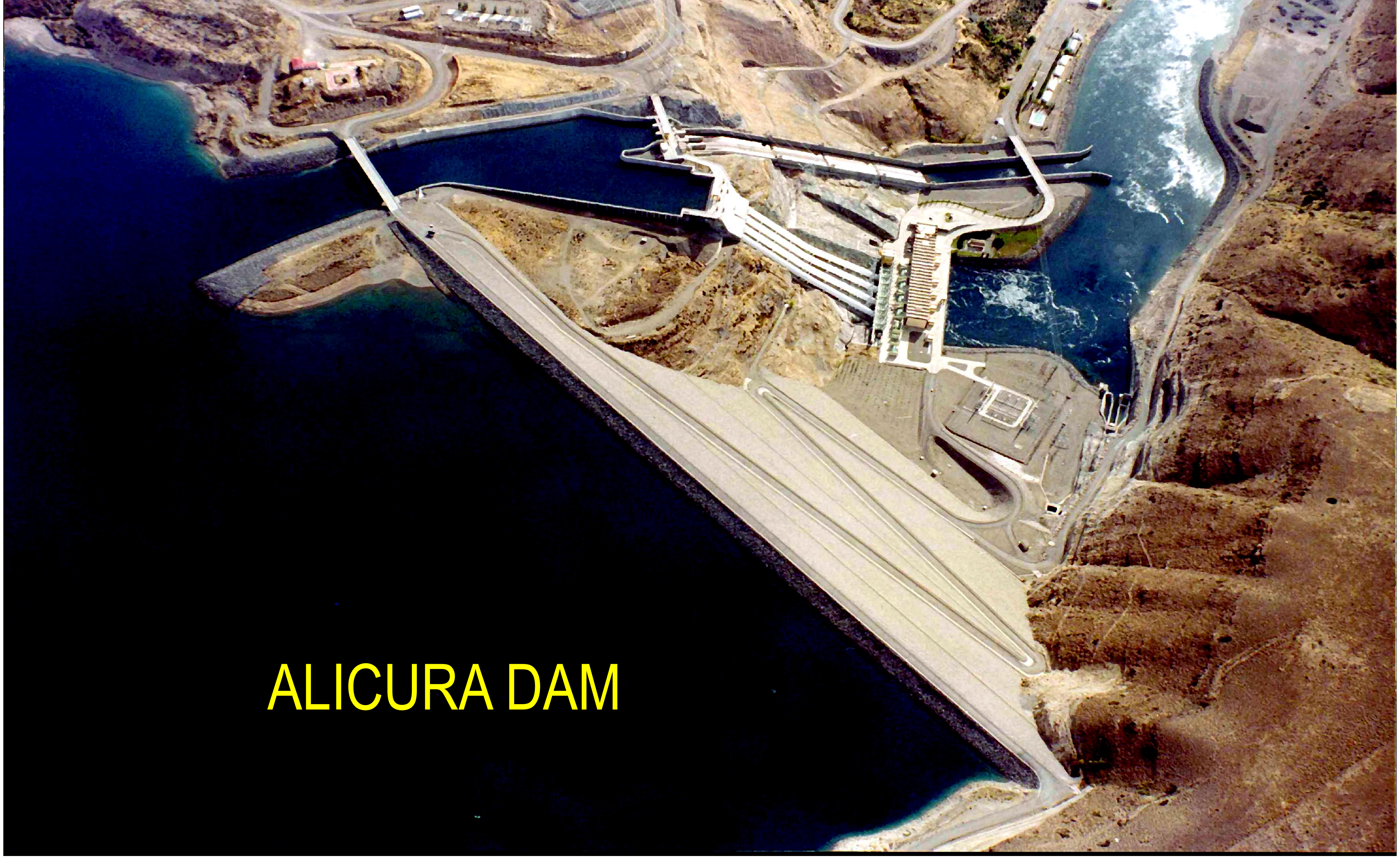


CASA DE PIEDRA-ADOPTED SOLUTION S700-S1500

VIEW OF THE EXCAVATION

LESSONS ACQUIRED AT CASA DE PIEDRA DAM

- There have been many records of dams affected by the dissolution of salts, causing the formation of caverns, and increasing the permeability in foundations by enlarging rock discontinuities. In the case of karstic foundations, like Casa de Piedra, where karsts were revealed during construction, although a very extensive conventional investigation had been carried out without detecting the abnormality, adequate techniques and early works were required.
- Proper and specific investigation techniques such as inspection adits and special geophysical methods, like gravimetry, are mandatory in order to achieve a successfully project of foundations on karstic formations.


ALICURA DAM

ALICURA DAM

Located on Limay River, 100 km NE of San Carlos de Bariloche city, Argentina.

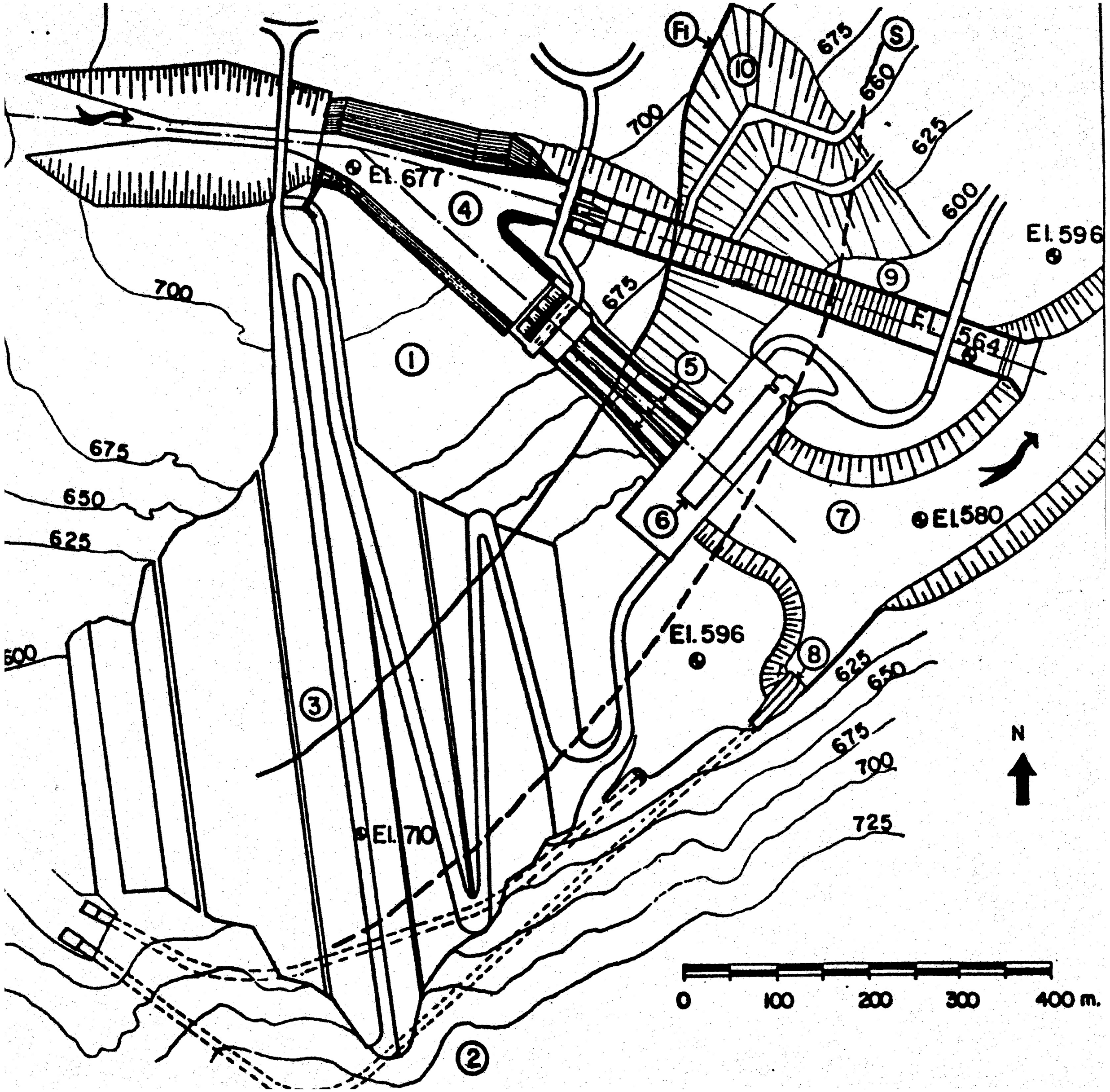
- Owner: Hidronor S.A., a public company.
- Design and supervision of construction: Consorcio Consultores Alicura, a joint venture of local consulting firms of Argentina, Electrowatt, and Sweco.
- Contractor: Impregilo from Italy.
- Board of International Experts: Don U. Deere (USA), Giovanni Lombardi (Switzerland), Jack Hilf (USA), Flavio Lyra (Brazil), and Bolton Seed (USA)

The project includes a 130 m high earth fill dam with the principal appurtenant structures located on the left bank, taking advantage of topographical features

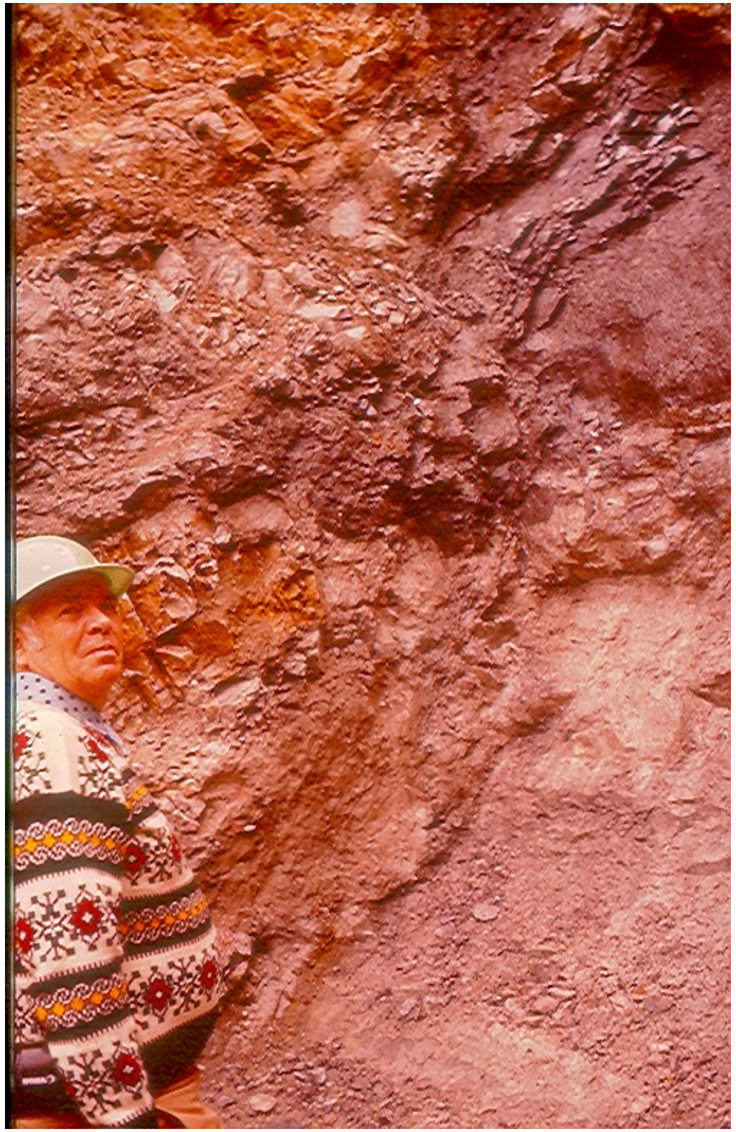
Total volume:13 millions of cubic meters, with a central core of morainic material founded on rock, while the shells rest directly on 10-15 m of alluvium.

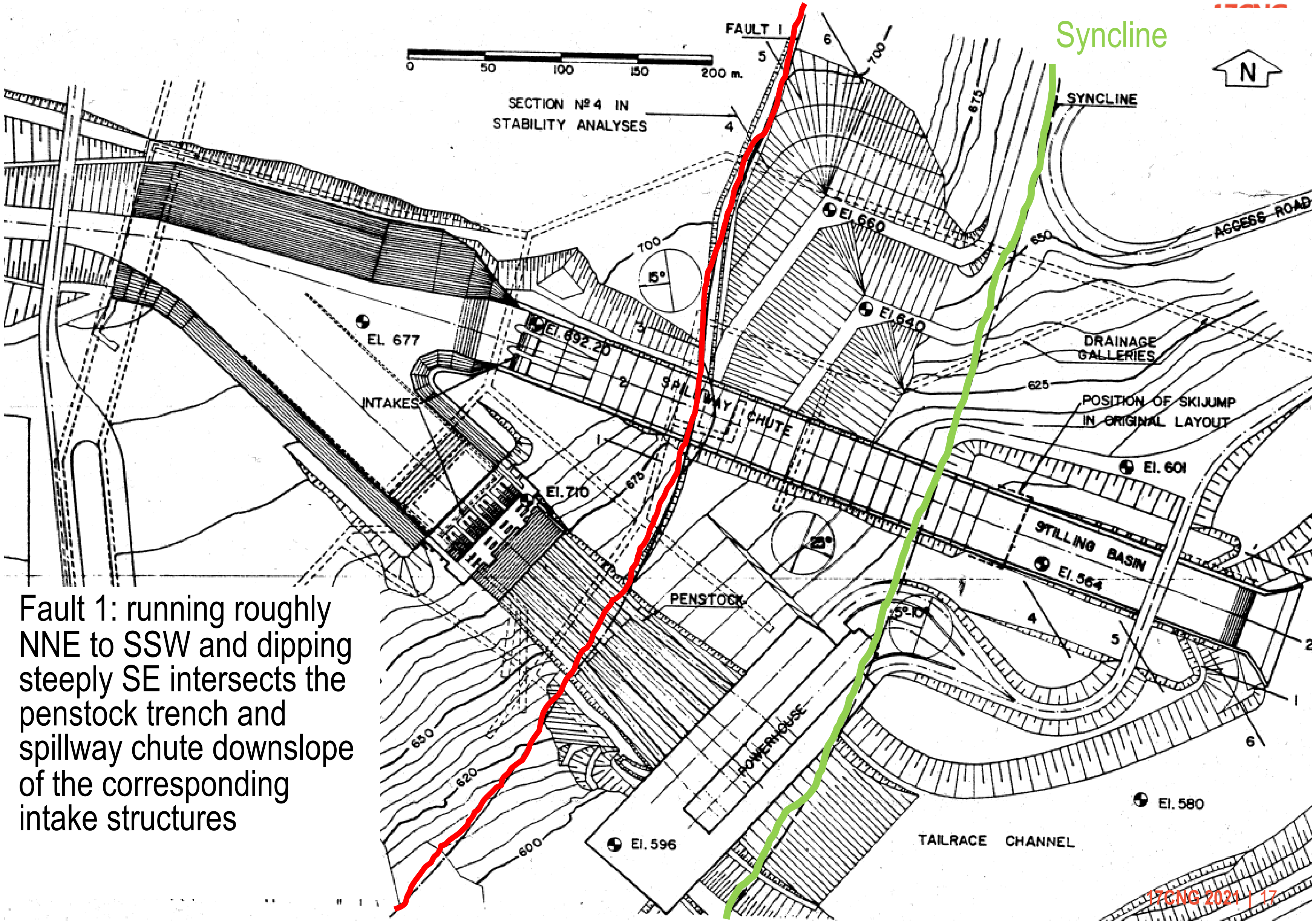
GENERAL LAYOUT

1.	Left abutment	F1: Fault 1
2.	Right abutment	S: Syncline
3.	Dam	
4.	Approach channel	
5.	Penstocks	
6.	Powerhouse	
7.	Tailrace channel	
8.	Bottom outlet	
9.	Spillway	
10.	Stabilization excavation	



ALICURA LEFT BANK



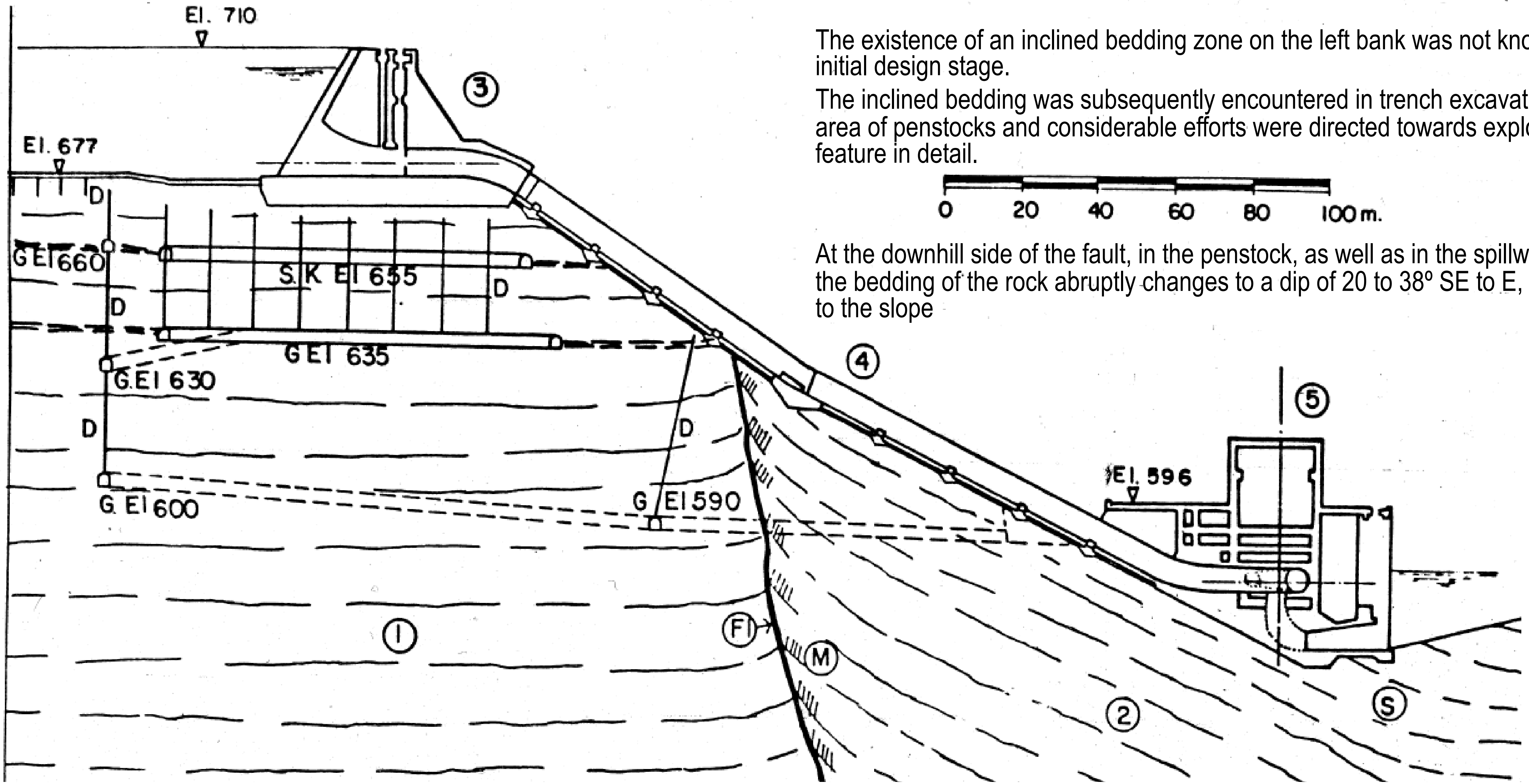


Fault 1: running roughly NNE to SSW and dipping steeply SE intersects the penstock trench and spillway chute downslope of the corresponding intake structures

LEFT BANK GEOLOGY

The existence of an inclined bedding zone on the left bank was not known at the initial design stage.

The inclined bedding was subsequently encountered in trench excavations in the area of penstocks and considerable efforts were directed towards exploring this feature in detail.



At the downhill side of the fault, in the penstock, as well as in the spillway area, the bedding of the rock abruptly changes to a dip of 20 to 38º SE to E, i.e. parallel to the slope

LEFT BANK GEOLOGICAL AND GEOTECHNICAL CONDITIONS

Real conditions of the massif were defined during the excavations in the first stage of construction. At the design stage they were not detected despite having carried out more than 4000 m of exploratory boreholes and an exploration gallery.

The gallery crossed fault identified as 1, which proved to consist of a zone of plastic mylonitized rock, 2 meters thick. Fault 1 appeared quite impervious.

A large number of pelitic interlayers are intensely sheared, predominantly along the upper contact with the sandstones.

The shearing produced slickensides parallel to the bedding planes. There were also thin 5 cm thick clay and silt bands of totally crushed material.

PELITES GEOTECHNICAL PROPERTIES

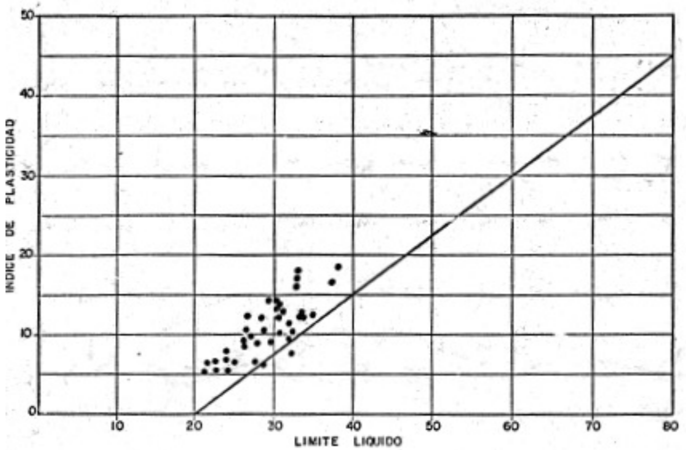
- PI = 5 to 20; ω_L = 20 to 40; clay content (minor to 2 microns) = 40 %; $\omega \leq \omega_P$; fully saturated
- γ_d = 1.8 to 1.9 g/cm^3 and; γ_s = 2.44 to 2.68 gr/cm^3

The drained strength parameters were determined by direct shear and triaxial tests mainly on remolded samples, that were reconsolidated to a density similar to the undisturbed ones.

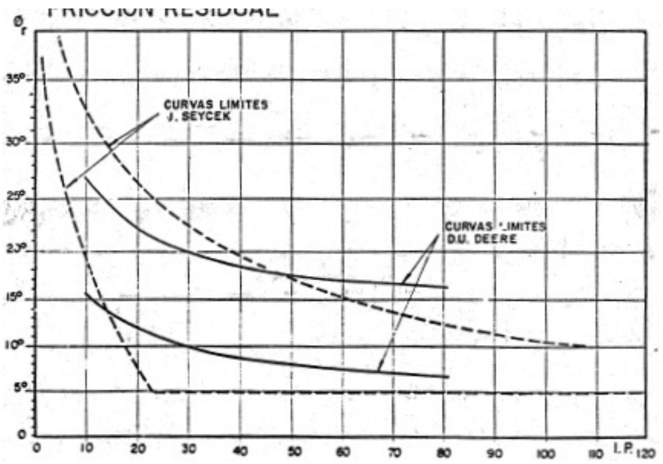
The values obtained by direct shear tests are lower than those by triaxial tests and rather close to the lower boundary. The direct shear test in this case is the most appropriate procedure.

Routine testing in the field laboratory of the Atterberg limits was then used so as to check that the plasticity indices fell in the known range.

Type of Test	Peak shear strength		Residual shear strength	
	c' (kg/cm^2)	φ' (°)	c' (kg/cm^2)	φ' (°)
Direct shear tests	0.0 - 0.3	22 – 31	0.0 – 0.1	17 - 21
Triaxial tests	0.0 – 0.3	22 - 30	0.0 – 0.1	21 – 24



Plasticity chart showing results from sheared pelite



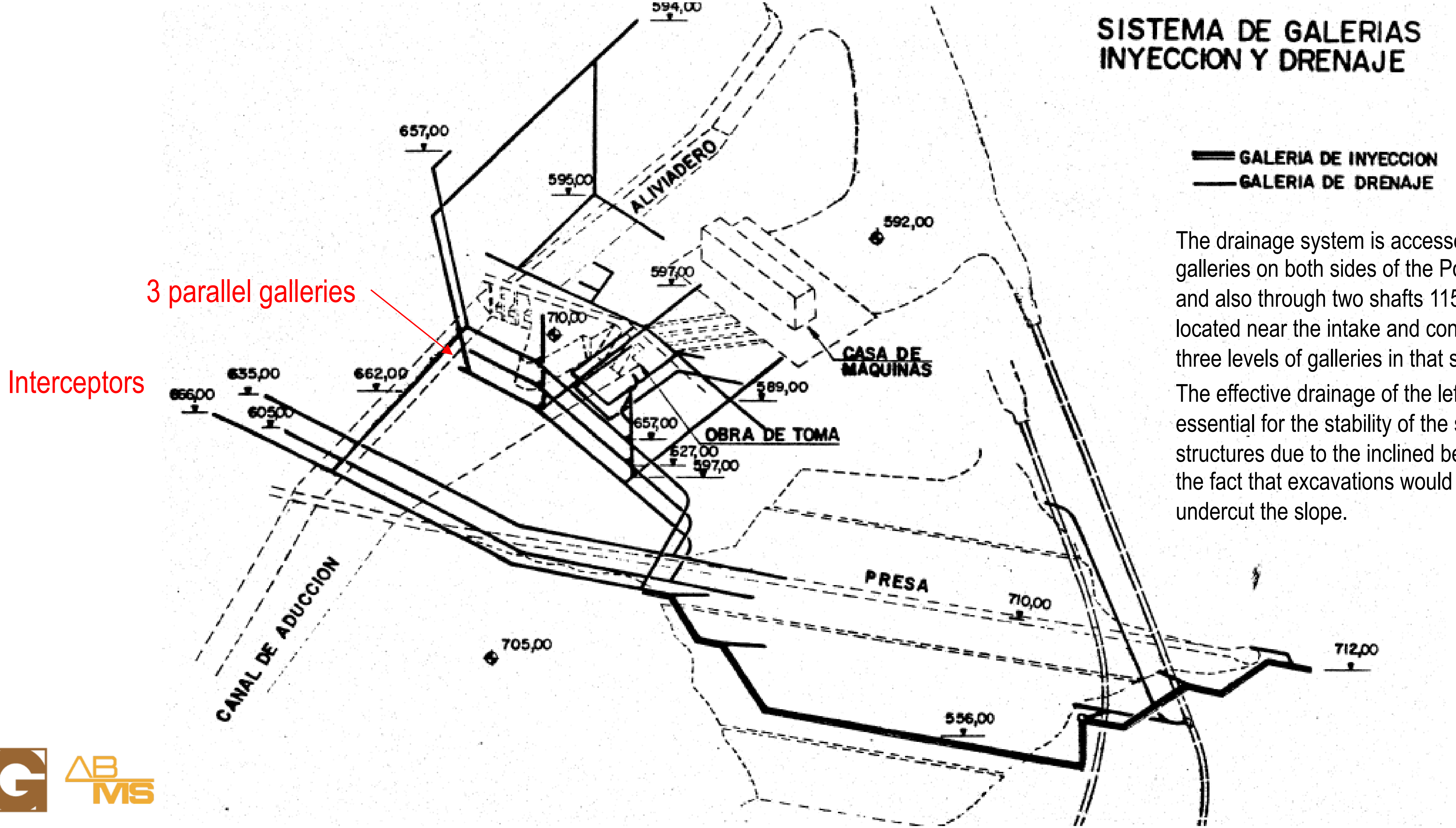
Deere and Seycek curves relating plasticity index and the residual friction angle

LEFT BANK TREATMENT AND DESIGN ADJUSTMENTS

- The geological and geotechnical characteristics of the left bank required design adjustments in order to guarantee the stability of the slopes and its structures in the penstock area and the spillway chute and energy dissipator.
- The intake for the penstock and spillway structures required also an extensive stability analyses to guarantee that sliding would not occur on the weak horizontal pelite layers.
- Drainage system: 5.500 m of drainage galleries with 35.000 m of drain holes to form 150.000 m^2 of drainage curtain
- 500 Post-tensioned rock anchors
- 1360 m long grouting gallery and 65.000 m^3 of grout curtain

SPILLWAY CHUTE AND ENERGY DISSIPATOR

DRAINAGE SYSTEM



The drainage system is accessed from galleries on both sides of the Power House and also through two shafts 115 m deep, located near the intake and connecting the three levels of galleries in that sector.

The effective drainage of the left bank was essential for the stability of the slope and the structures due to the inclined bedding and the fact that excavations would partly undercut the slope.

DRAINAGE GALLERIES

The drainage galleries section was rectangular, 2 m wide and 3 m high; the walls and roof were protected with sprayed concrete and have a concrete floor slab with a draining gutter

ALICURA LEFT BANK

LESSONS ACQUIRED AT ALICURA DAM

- The important conclusion obtained during the construction of the Alicura Project is that the adequate characterization of rock massifs affected by relatively small fault structures, but with shear planes between the strata, can only be achieved through a research plan that includes trench excavations, deep shafts and galleries. Conventional investigations through boreholes including special procedures do not adequately reveal the unfavorable features of thin sheared layers between more competent rocks, as in this case.
- In the case of Alicura, where concrete structures are located on a terrace due to topographic advantages, guaranteeing the stability of the slopes is a critical factor for the execution of the works. Its economic impact can also be very important.
- In thin sheared strata, where in-situ tests have no application, it is important to define the continuity of weak planes and their shear strength properties through systematic sampling and characterization tests.
- It is of the utmost importance the implementation of an efficient drainage system. The installation of drains from different gallery levels allows control of the system operation.

EL CHOCÓN DAM

EL CHOCÓN DAM

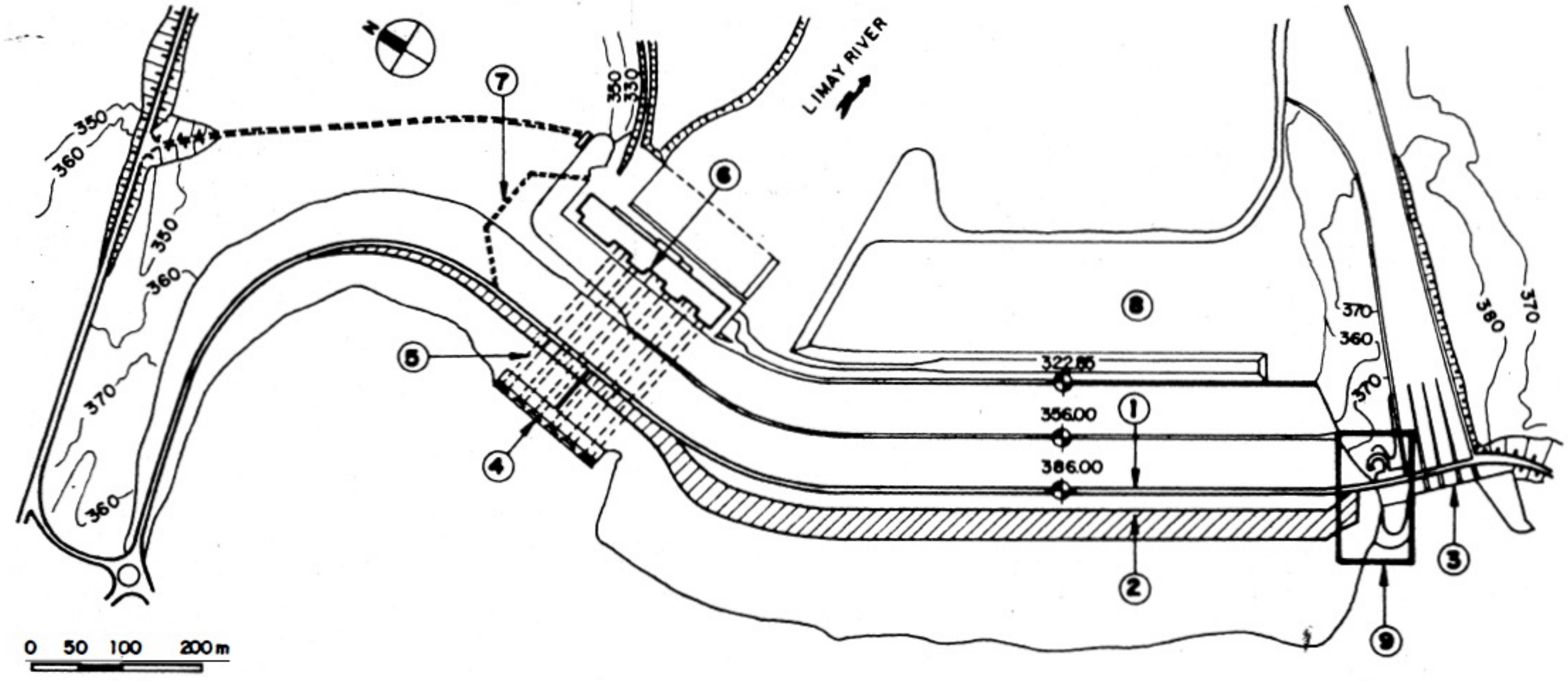
El Chocón Hydroelectrical 1200 MW installed capacity, is located across the Limay river

- Design: Italconsult, Sofrelec and Harza Engineering Co., between 1962 and 1965. The revision of the design and the construction supervision were carried out by Sir Alexander Gibb & Partners.
- The operation was assigned to Hidronor S.A. in 1968.
- Contractor: Impregilo, from Italy, and Sollazo, a local firm.

The first impounding of the reservoir took place in 1972.

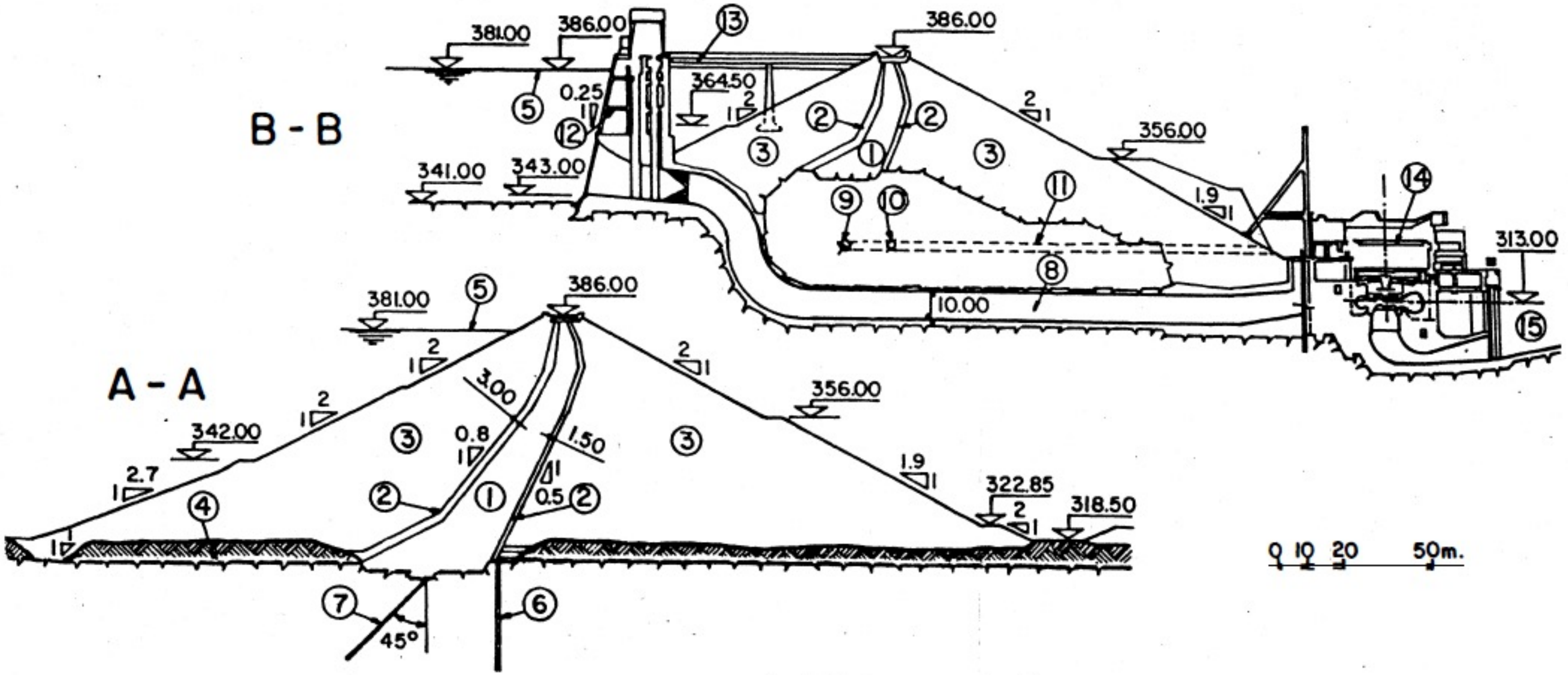
The earth dam is one of the largest in Argentina, 92 m maximum height, 13 millions of m3 and 2.245 m crest length. The lay out was based on the topography. The spillway is located on the right bank, about 100 m from the right abutment.

CHOCON DAM LAYOUT



(1)	Dam crest	*(1)*	*Couronnement du barrage*
(2)	Core-rock contact	*(2)*	*Zone de contact noyau-rocher*
(3)	Spillway	*(3)*	*Evacuateur de crue*
(4)	Intake	*(4)*	*Prise d'eau*
(5)	Penstocks	*(5)*	*Conduites forcées*
(6)	Power Station	*(6)*	*Centrale*
(7)	Access gallery	*(7)*	*Galerie d'accès*
(8)	Downstream fill	*(8)*	*Remblai aval*
(9)	Right abutment	*(9)*	*Appui rive droite*

EL CHOCON CROSS SECTION



1. Core.
2. Filter.
3. Gravel shells
4. Alluvium.
5. Normal reservoir level
6. Relief wells.
7. Grout curtain
8. Penstock.
9. Grouting gallery.
10. Drainage gallery.
11. Access gallery.
12. Intake.
13. Access bridge.
14. Power station.
15. Tailrace.

The dam cross section was designed using a thin sloping clay core. The top 14 m of the core were vertical.

Core material: clayed sands and silty sands, with a mean plasticity index of 23 %.

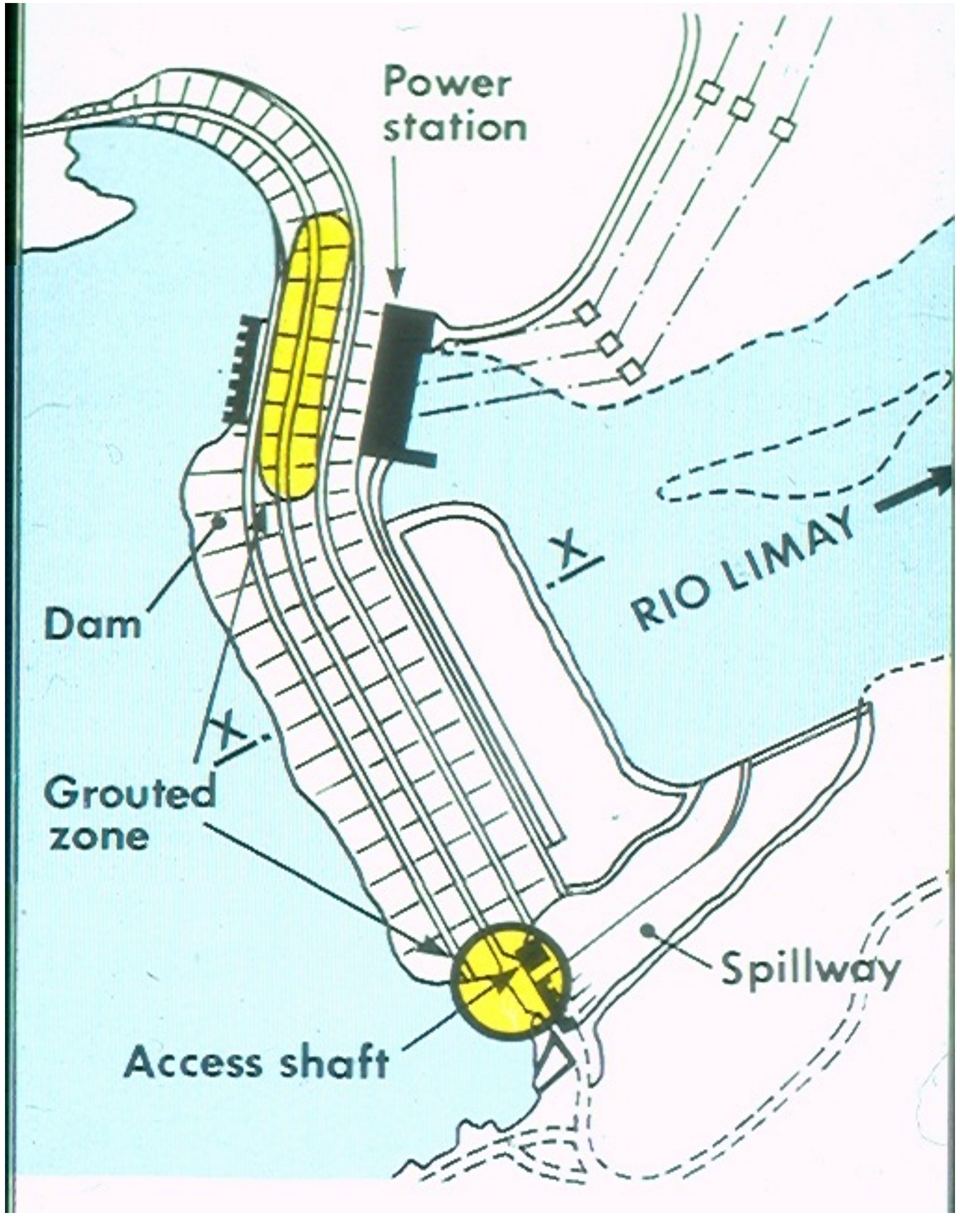
GEOLOGY

- The geology at the site is predominantly horizontally bedded sandstone of late Cretaceous age. The Upper sandstone is formed by alternating layers of lithic sandstones with lenses of wacky siltstones and claystones generally 3 to 5 cm in thickness. Discontinuous thin gypsum levels of secondary origin have been detected at the top and the base of the units.
- The sandstone forms the abutments as well as the left dam foundation.
- Gypsum infillings in the foundation rock discontinuities have been found in the river valley bottom and in both banks. These joint infillings are rather thin, ranging from several millimeters to 1 or 2 cm. Considerable evidence of gypsum infillings was present on both banks, mainly as horizontal layers.

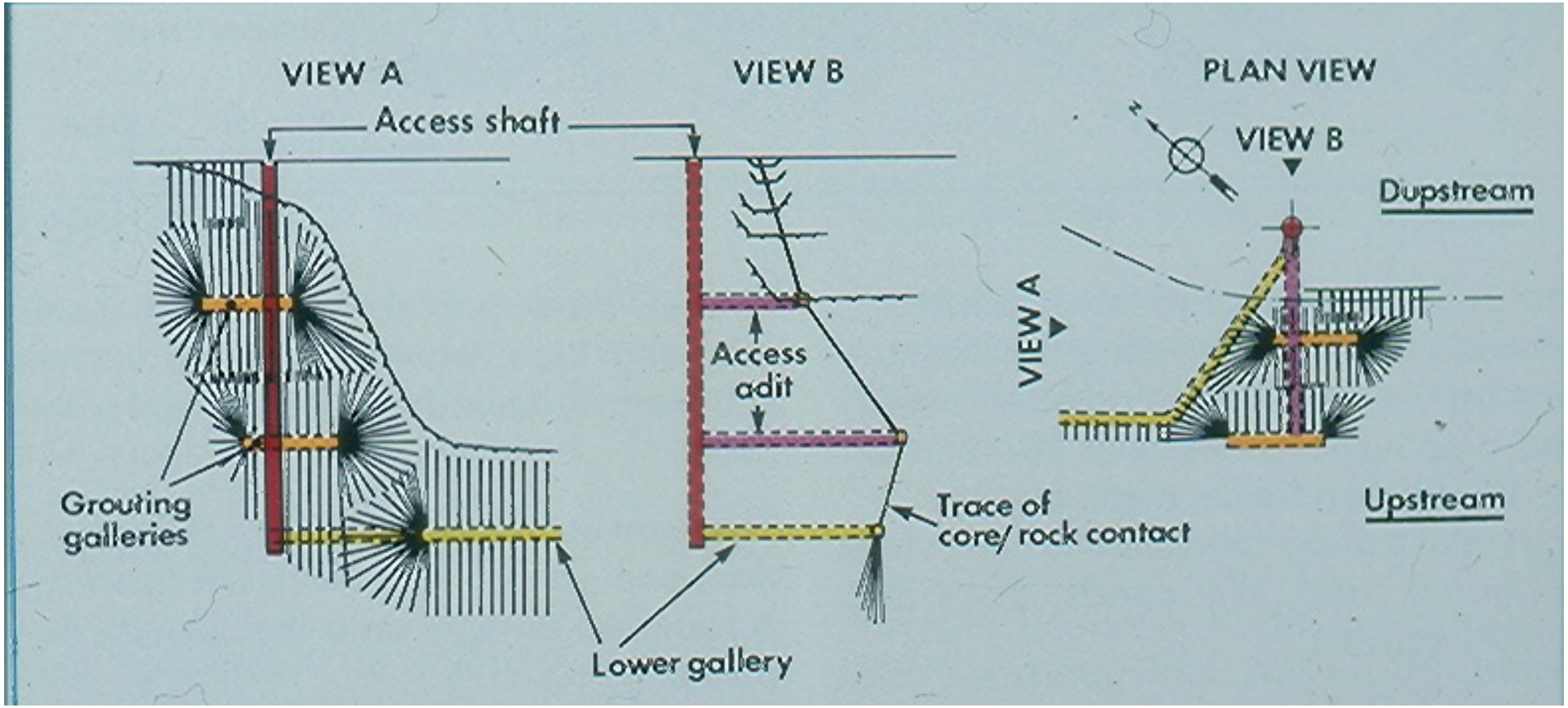
PROBLEMS ARISED DURING OPERATION OF EL CHOCÓN

- The performance of the dam and its foundation did not cause any particular concern from 1972 to 1982.
- In November 1982 the attention was focused on the evolution of high piezometric levels recorded in the core contact with the right abutment. An extensive program of studies and investigations was initiated by Hidronor to determine the causes of this behavior.
- Chemical analyses carried out on water samples from different drains showed that the measured seepage water of about 100 l/min contained an average of 2 g/l of soluble solids.
- An investigation was performed to identify some of the existing fissures and joints and the amount of water seeping through them to know the percolation pattern through the dam foundation.
- Field surveys have shown the presence of valley stress relief related joints, particularly on the right cliff between the dam and spillway area.

TREATMENT AREAS

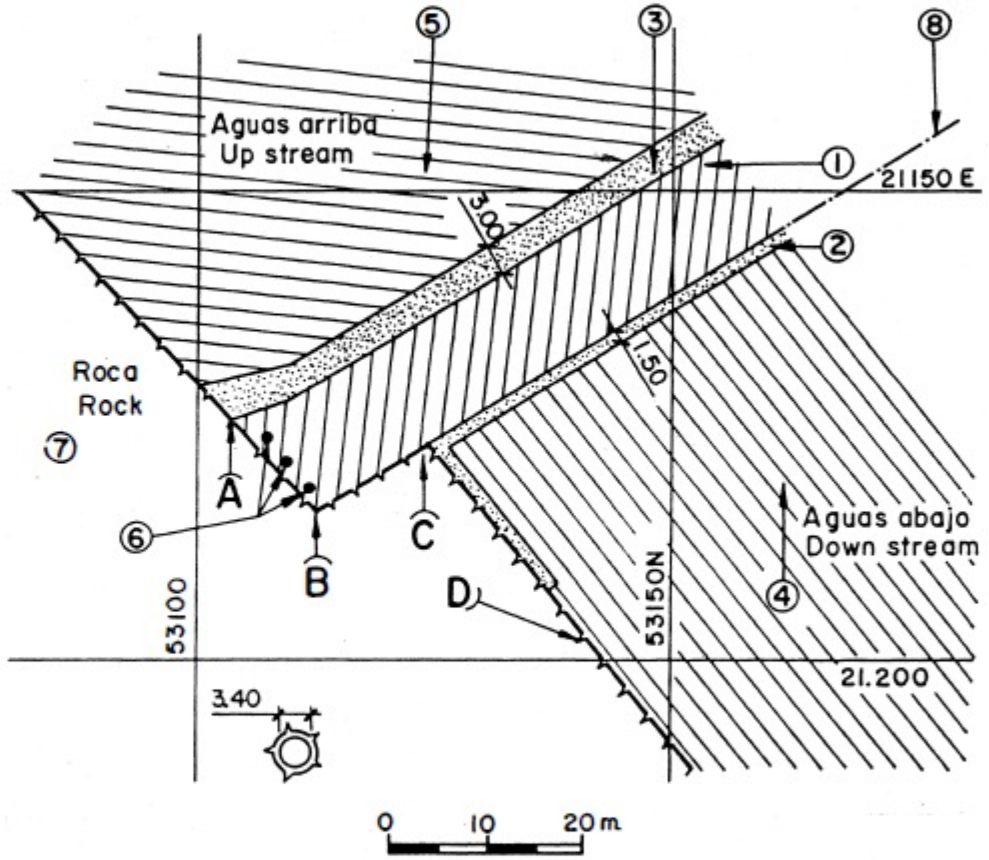


RIGHT ABUTMENT – ACCESS SHAFTS



RIGHT ABUTMENT TREATMENT

- A shaft in the rock, 107 m deep and three galleries at elevations 346, 308 and 282 m were then constructed to permit remedial grouting and drainage treatment of the rock abutment in the zone adjacent to the rock-core contact.
- The core is founded at the right bank in a cut off trench. A horizontal section of the abutment core-rock contact at El. 357 m
- The core against the rock, face AB, and downstream, face BC, bears directly against the rock, without any protective filter.



1. Core.
2. Downstream filter.
3. Upstream filter.
4. Downstream shell.
5. Upstream shell.
6. Hydraulic piezometers.
7. Right bank abutment.
8. Dam axis.

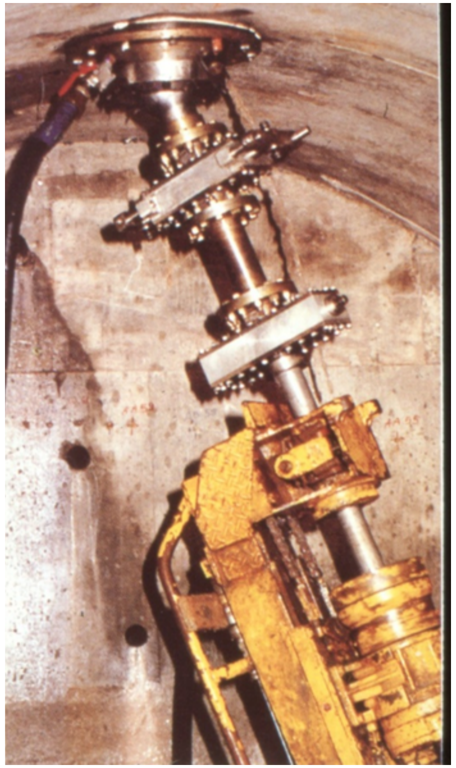
RIGHT ABUTMENT

RIGHT ABUTMENT TREATMENT

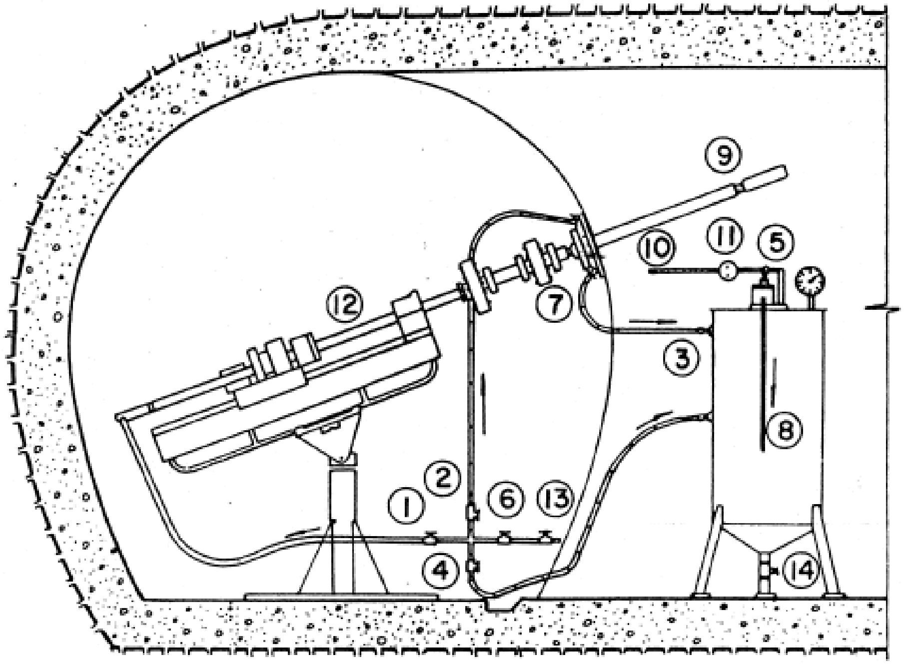
The first few holes drilled towards the contact face AB revealed worse conditions that had been anticipated. A number of rack joints near the contact were found to be open and full of water at hydraulic pressures near reservoir level. The core when contacted was found in some cases to be either in a near fluid state or with very low consistency. The samples were recovered using special procedures.

RIGHT ABUTMENT INVESTIGATION AND TREAMENT EQUIPMENT

All drilling and grouting done afterwards using a double gate system (SAS, Figure 22), and a pressure regulation device (PRD), mounted at each borehole mouth. This system allowed to maintain the pressure inside the hole equal or larger than the reservoir pressure in order to eliminate the danger of piping through the drillholes.



1. Valve for drill pipe.
2. Valve for pressure compensation pipe.
3. Return valve.
4. Filling valve.
5. Relief valve for pressure regulating device.
6. Relief valve.
7. Double gate valve (Sas).
8. Pressure vessel.
9. Check valve.
10. Lever arm.
11. Sliding weight.
12. Drilling rig.
13. Main water supply valve.
14. Drain valve.



RIGHT ABUTMENT CONDITIONS

- Rock near the contact was highly fractured due to stress relief and to blasting effects.
- At El 369 m there was zero effective stress at the rock-contact above El 357 m. These data confirm that a crack existed within the core close to the steep abutment, caused by differential settlement and arching between the core and the rock face. Exploratory holes showed the existence of open joints up to 2 cm wide.
- The fissures, subvertical and parallel to the river valley, are attributed to stress relief in the recent geological past due to valley erosion and possibly widened by blasting during construction.
- GIN method: stable mixes (water-cement 0.67/1.0 ratio by weight). Total volume injected was more than 100 m^3.

TREATMENTS FROM 1992 TO 1994

- In the left bank the treatment behind the Power Station was performed from the original grouting gallery and extensions excavated at both extremes during 1984 and 1985. A total amount of 460 ton of cement were injected through a drilled length of 6700 m.
- The potential problem of internal erosion of the core in contact with the rock in the foundation trench at the bottom of the valley led to the expansion of treatment work in successive stages. Between 1992 and 1994, the treated areas in both abutments extended to the valley.
- On the right bank, a gallery of 100 m in length with an internal diameter of 3 m, lined with concrete, was excavated. Three rows of injection holes and a drainage curtain, located downstream, were made from the gallery to reinforce the existing system.
- On the left bank a 622 m long gallery was built that descends from El 325 m to El 273, 25 m below the deepest foundation of the dam.

TREATMENTS IN 1995

- In February 1995, with the dam under the system of private concession it was decided to complete the treatment of foundations of the dam by building a section of central gallery joining both abutments. The gallery is 700 m long with a diameter of 3.4 m.
- The decision was based on having detected, through boreholes carried out from the galleries with double gate system and a pressure regulation device as mentioned hereinabove, areas of the core with a low degree of consistency, practically in the liquid limit.
- The excavation was carried out without the use of explosives, with a pilot advance drilling and a maximum unlined excavation length of 30 m. The three lines injection curtain was complemented by one line of drainage.

The serious conditions observed at El Chocón Dam are the result from the combination of

- Natural features
- Design features
- Construction features

NATURAL FEATURES

1. Flat-lying sedimentary weak sandstones and claystones beds having stress-relief joints in the bluffs and floor on the river valley;
2. Presence of subvertical and horizontal joints filled with salts, particularly gypsum, and
3. Relative clean and neutral reservoir water with high dissolution capacity.

DESIGN FEATURES

1. Rock nose between the spillway and the earth dam;
2. Steep right abutment face designed with a 2V:1H that was finally excavated to 4V:1H,
3. Core trench shape in the valley floor and the abutments that was difficult to blast in a weak rock;
4. Dispersive clay material used in the core;
5. Absence of a filter on the right abutment face B-C; and
6. Inclined core with a relatively thin section and several changes in a slope, including a vertical upper section that tended to increase local arching effects.

CONSTRUCTION FEATURES

1. Reactivation and widening of right abutment joint and fissures due to blasting effects;
2. Grout mixes depending on takes but generally unstable and very lean;
3. The single-line grout curtain not guided throughout the foundation by geological evidence uncovered during excavation. The vertical primary grout holes could not seal the subvertical joints and were probable ineffective in sealing these potential water passages.

CONSEQUENCES

1. Local arching effect and subsequent core cracking in right abutment.
2. Local piping of core in right abutment
3. Potential problem of core piping in the rock core-foundation trench in the valley bottom, specially in zones close to the abutments.

LESSONS ACQUIRED AT EL CHOCON DAM

- Drainage and grouting gallery: The construction of a drainage and grouting gallery under the foundation is very important for dams built on weak rocks with relatively low permeability and joints that, in some cases, are filled with soluble salts. Such a gallery allows monitoring the performance of grouting and drainage works during and after the first reservoir filling.
- Grouting program and grout mixes: The remedial grouting program was guided by knowledge of the joint system gained through borehole investigations as well as gallery construction. It was very successful in sealing all the rock as evidenced by a small amount of grout takes in the core-rock contact zone in the final stage of grouting. Such grouting program has stopped an accelerated ageing process of El Chocón Dam and improved its safety.

CONCLUSIONS

Project, construction and operation of large dams require high levels of competence in all the stages of the projects.

- Lessons from Casa de Piedra: with clear evidence of limestone and gypsum formations, the investigation should pay attention to the evidence of water leaks or anomalies that imply the presence of soluble rocks and cavities. The use of microgravimetry is appropriate for the detection of cavities or discontinuities that traditional survey research may not detect.
- Lessons from Alicura: it is important to increase knowledge through early interventions such as trenches, deep wells, exploration galleries. Due to their magnitude, these investigations may require the presence of the Contractor and are intended to investigate geological features of little importance due to their size, but significant due to their influence on the safety of the works. The design of a good drainage system and a thorough percolation control during operation through galleries and drains is fundamental.
- Lesson from El Chocón: where the situation becomes critical after ten years of normal operation, stresses the need for control and monitoring of the works throughout the useful life of the dam. The instrumentation system used and the permanent control carried out by the Owner made it possible to detect unfavorable conditions and plan an adequate corrective action in time.

Proper management of large dams in all stages allows controlling contingencies and occurrences of unforeseen events, avoiding the risk of failure in some catastrophic cases.

AKNOWLEDGEMENT

My deep recognition to the distinguished engineers who contributed to the professional and human development of my activity during 60 years, and who are no longer among us, very especially to Victor.

My gratitude to Luiz Guilherme de Mello and his family.