THE IMPORTANCE OF GEOLOGICAL AND GEOPHYSICAL EXPLORATION COSTS IN THE CONSTRUCTION OF HYDROELECTRIC DAMS COMPARATIVE EXAMPLES IN MEXICO

Adolfo Vázquez Contreras[1], Moisés Dávila Serrano[1], Rafael Acosta Quevedo[2] & Juan Sánchez Pérez[2]
[1]Oficina De Geofísica GEIC-CFE
[2]Subgerencia De Estudios Geológicos GEIC-CFE

ABSTRACT
Geological and geophysical exploration activities ofHydropower dams' are analyzed in a qualitative and semi-quantitative basis. Information about an under-construction hydro dam is included as well. Considered activities are those from feasibility and design support stages. Mexico biggest dams geological exploration works and their associated costs are reviewed and their impact on their construction and safety. Big dams finance underpinning depends on good hydroenergetic assessment besides an accurate geological model obtained before construction activities begin.

1. HYDROPOWER IN MEXICO
Hydropower is a very important part in the total volume of the electricitygenerated worldwide and the greater share of renewable energy. Worldwide, represents approximately 24% of energy production; in Mexico in 2008, the share of hydroelectric installed capacity for power generation reached 22.19% with a total of 11.343 MW[1]. Geothermal is the other most developed renewable energy in the country. Until today, the hydropower development has been through large dams in Chiapas as Chicoasén (the largest with 2,400 MW installed capacity) and more recently Aguamilpa and El Cajon, both in Nayarit, in the western part of the country.However, there is still great potential to develop especially at small dams, the latter being estimated at 3.200 MWto be implemented in the states of Chiapas, Veracruz, Puebla and Tabasco [2].The Mexican Secretariat of Energy (SENER, by its Spanish acronym) estimated an investment of 2.908 million dollars in hydropower for the period 2006-2015, so its importance will not wane in the coming years [3]. It is in this context that the geological-geophysical exploration acquires great importance.
In Mexico there are 64 hydropower plants, of which 20 are considered large dams by its size and 44 are small power plants [4].According to the records fromComisión Federal de Electricidad (CFE, Mexico's national electricity company), the oldest hydropower plantsin the country are PanindicuaroBotello, Michoacán(13MW) and Colotlipa in Chultenango, Gro. (8MW) both came into operation en 1910.The most important hydroelectric plants, Grijalva River Basin in Chiapas developed in the 1980s and since the 1990s Santiago River Basin in the west part of the country have generated more electricity today than any other plant constructed.
This work only concerns the information from six large dams (table 1), these being the most documented in regard of direct and indirect exploration of the site.Chicoasen, Aguamilpaand La Yesca, are thosethat generate more electricity in Mexico[3].

3References used in this paper come from CFE and their value stands for the relative costs of applied geology exploration which is why it is considered appropriate to include them even thought the information comes from the decade of the seventies due to lack of information on the subject in international literature.

Table 1. - Six major hydroelectric dams in Mexico

Name of the Dam	Number of turbines	Entryintooperation	Effectivecapacityinstalled (MW)	Location
Chicoasén	8	29-May-1981	2,400	Chicoasén, Chiapas
Zimapán	2	27-Sep-1996	292	Zimapán, Hidalgo
Peñitas	4	15-Sep-1987	420	Ostuacán, Chiapas
Aguamilpa	3	15-Sep-1994	960	Tepic, Nayarit
El Cajón	2	1-Mar-2007	750	Sta. María del Oro, Nayarit
La Yesca	2	2011-2012	750	Hostotipaquillo,Jalisco

2. STAGES OF STUDY IN HYDROPOWER PROJECTS

Once that has been done the hydropower balance of a river basin and has been selected segments of the river accurate to build hydroelectric dams (stages of great vision and identification), takes place the second phase of studies needed to build a hydropowerplant.These are divided into four stages: 1) Pre-feasibility 2) Feasibility 3) Preconstruction or design support and 4) Construction.Surveying, geological and geophysical exploration are carried out mainly in the first three stages, while in the construction phase, Geotechnical is responsible for the solution to the geological problems found mainly at the local level.The ultimate purpose of the basic engineering research is to ensure that the proposed hydro project is built on time at less cost, but also reunite a number of standard safety conditions (stability, strength to expected earthquakes, minimum induced seismicity, etc) as well as profitability (storage levels to ensure the generation provided by the design) and a service life which for purposes of economic calculation must be at least 30 years, although is expected to continue in operation for much longer. As mentioned in the stage of construction, geology and geotechnicshave to monitor and control the work in order to propose a solution to the problems encountered, mainly during the excavation of underground and surface, while is defined the geological model, the lithology, geological structure and the geomechanicalproperties of the rock mass.

The feasibility studies will show the best economic cost and based on them the budget and the planning can be made in order to monitor the progress of the work. Generally the design stage lasts a year while the construction usually takes on average four years.

3. METHODS OF EXPLORATION

When selecting the construction site of a hydro dam, many factors are involved such as technical, social and environmental. In this paper we focus exclusively on the technical aspects that concern the pre-construction stages and the volume of direct and indirect exploration of the ground.The purpose of the exploration is to obtain a geological model as clear as possible that serve to characterize the geotechnical site and so theplanning, budgeting and perform the structural design of the works as well as obtain sufficient information to establish a safe and economic project[5] [6].Geological risk management and its economic consequences can lead to major losses beyond the physical repair of the work which rely on a good investigation of the site [7]. Referring to geotechnical instrumentation and monitoring works, Allen [8] mentions difficult conditions to detect (with exploration methods) the presence of lenses made of soft material, highly compressible areas and pockets of high pore pressure, which can cause faulting in the rock mass.From here, it is important to remark the need of the exploration as even for the location of the monitoring zones must follow criteria based on direct or indirect examination.

This work shall consider direct exploration of the site though drilling (exploratory boreholes), geotechnical testing of permeability in wells and excavations of galleries or tunnels. Drilling is a great support to define the stratigraphic and structural model for the site and to identify basic geotechnical parameters for design of the work, being carried out on both margins and the river bed, according to the location of the works. The objectives of the sampling site with exploratory drills with core recovery usually include the following: stratification on the site, vertical or lateral variations in subsurface geological conditions, sampling for laboratory testing, verification of the interpretation of geophysical measurements and placement of instruments *in situ* for geotechnical, geophysical and geohydrological testing. The interpretation of the evidence can be presented to anticipate areas of instability conditions. Geotechnical testing of permeability in the wells by injecting pressurized water constitute a substantial proportion of direct examination and focuses on the competition of the rock massand its ability to facilitate or prevent leakage of water from the dam.

Small diameter tunnels or galleries will be carried out mainly on the feasibility and preconstruction stages in order to define more precisely the local geologic context and in some areas on both margins where it is necessary to investigate key issues of the work as the possible continuity of fracture zones, mapping major fault systems on-site, research of geotechnical properties of rocks *in situ*, etc. For its size and cost, the location of such works is decided

based on information obtained prior the construction with drilling, topographic features, ditchesand geophysical surveys.
As for hydrogeologystudies, permeability tests and infiltration atsemiregional level arecrucial in the feasibility stage, given that water loss by infiltration should be minimum. The hydraulicseal of the dam and reservoir requires the certainty that the permeability of the rocksinvolved is low. Another important aspect is the determination of groundwater levels, fluctuations and surface flow or drainage. The installation of piezometers in exploratory boreholes allows the study of these variables.
The main task of geophysical research on the site for a dam is to contribute to the definition of contacts between geologic units in the location of fault zones covered by sediments and soil on the slopes through seismic velocities and dynamic elastic parameters of rocks on both marginswhere thedamwill take place. In this task, the seismic refraction method is the main tool and secondly the geoelectric method which helps to complement the geological model indicating the presence of fault zones, carst, mineralization and argillaceous zones. This method also helps to characterize the possible lithologies and materials on the site. Therefore, for the analysis of costs by geophysics indirect exploration, we consider only the seismic refraction method(SRM) and the vertical electrical sounding (VES) as the essential methods in the exploration of the subsurface. Among the geophysical techniques that eventually are used for indirect and semi-indirect exploration (in hole) can also mention the following: electric tomography, cross-hole, seismic tomography between wells, gravimetry and magnetometry and geophysical well logs. Electrical tomography method is one of the secondary techniques increasingly used in studies for dams and seismic tomography between wells [9].The indirect exploration of geophysical methods is very important because considerable savings can be made by identifying areas of weakness with risks of collapse in tunnels, which can interfere with the initial line of work and cause substantial changes to designs and therefore,higher costs. Likewise, determination of the quality of the rock by geophysical methods allows the choice of working with the most suitable machinery for excavation and guides the location of the points where the drilling should be performed.
Although direct and indirect exploration of a site involves other studies and support techniques such as surveying, photogrammetry, remote sensing, petrographic, mineralogical and chemical analysis, they were not included in the comparative information documented in this paper. Moreover for the seismic design of the dam is necessary the observations of local seismicity for at least two years prior to the construction in order to propose a design to ensure the competence of the structures. Another method that is not addressed in this paper is the regional seismic monitoring aid to the detection of active faults that could affect the project.

4. PROBLEMS AND DAMAGE IN HYDROPOWERDAMS, MISTAKES IN THE STUDIES.

A collapse or crack in a hydro dam is a very important technical aspect because of the human and economic cost that should be avoided. In the operation stage, these faults can be potentially catastrophic for an insufficient toearthquakes, hurricanes, extraordinary rains and landslides. However, these failures may be due to errors in the early stages of planning and construction that did not allow a complete and detailed geological andhydrogeologicalframework at the site of the work and its interactions.
The errors in the pre-construction stage can be summarized mainly on an inadequate sampling, irregular and / or insufficient geological conditions of the site (lithology, presence of faults and zones of weakness, mechanical strength, hydrogeological variables, etc.) and associated geophysical parameters (seismic velocity and electric resistivity, elastic modules mainly) in the regional and local area considered for the project. During the construction stage of the project, unforeseen problems can occur for deficiencies during the exploration phase mentioned previously and if not corrected, can contribute to problems during the operational phase which in extreme cases could lead to failure.
To prevent problems that might occur in the operation stage should also be considered natural events that may affect the structures. Most often it involves the spatial and temporal occurrence of potentially destructive natural phenomena but estimation of its frequency is rarely accurate, so it is considered a risk factor and is designed with criteria based on economic profitability.
From earliest studies to determine the range of agents that a hydro dam will be exposed to, it is important to include aspects that are called Basic Engineering and relate to the regional framework in which the work will be developed, such as seismicity, geology, rainfall patterns and analysis of hydrological basins, providing the essential information to define the economic viability, social and environmental of the work.However, it is important to know in detail the its interaction with the Earth's crust and its processes modelers, as the study progresses to stages closer to construction (pre-feasibility, feasibility and design support), geological and hydrological studies must be improved, so unexpected events during construction are minimized and ensure that the work will last the time planned for operation and maintenance costs by external events are the least possible during its servicelifetime.

The quantity and quality of geological explorationare important variables that define the accurate of the construction program, its budget and safety deviations. The following three fragments were taken from the International Commission on Large Dams [10].
-Geological investigations should be as complete as possible to obtainfull knowledge of the site more accurately.
- In complex geological structures, in order to obtain an appropriate design prior to construction, it is advisable to dig the affected parts with the purpose to clarify possible doubts about the appropriate types of foundations.
- Designs must be based on real information, not theoretical data or those taken from limited research.

Table 2 summarizes the statistics of dam failures in the world until 1995 [11] and can be seen that the greater number of failures are due to overflows and leaks, which shows theinaccurately information that carried out the analysis of design and construction work.Other factors mentioned in Table 2 are related to the inadequacy investigation of the site leading to settlements and instabilities. Table 2 also illustratesthe importance of geological knowledge, mainly in sites with relevant geologic complexity in order to choose the best alternative sites for construction.

Table 2. -Occurrence of dam failures by type in XIX y XX (ICOLD, 1995)

Cause of failure	Cases
Overflow/Poor drainage	5
Landslides	4
Poor behavior spillwaystructures	6
Placement / compactiondammaterials	11
Lifting	4
Constructiondelay	4
Foundation failure / deformation and subsidence	11
Liquefaction	2
Anticipated rainfall / poor design or inadequate Research	8
Rupture of thedam	8
Earthquake	3
Leaks	14
Piping/regressiveinternalerosion	36
Insufficiencyspillway	7
Overflow	45
Internalerosion	9
Total	177

Regarding to large hydroelectric dams in Mexico, no accidents have occurred due to the failure of structures, but only problems in the design support stages during and after construction.Among the most important cases are the following in table 3, referring to six dams listed in table 1, classified according to the complexity of the geological conditions involved in its construction and also considered the topography and accessibility to the site.

Table 3.- Main problems of the five major hydroelectric dams in Mexico and problems in the construction stage of the dam “La Yesca”

Name	Construction Years	Altitude (m)	Type	Years Oper	Mainproblems
(1) Peñitas, Chiapas	1982-1986	53	Flexible curtain with core floated clay and graded materials	24	Foundations on alluvium. Landslide of 55 Mm3 in its pond during operation (2007).
(2) Zimapán, Hidalgo	1993-1996	203	Concretearc	14	Cracks in the arc. Detachment of blocks on the hillside. Cave onconductingtunnel.
(3) Aguamilpa, Nayarit	1991-1994	187	Rockfill dam with concrete face	16	Induced seismicity (magnitude 5). Settlements in the concrete face
(4) Chicoasén, Chiapas	1978-1981	261	Graded materials with impermeable clay core.	29	Leaks only 10 l/s or less. Deepening of the foundation more than planned in the river bed.
(5) El Cajón, Nayarit	2000-2004	181	Rockfill dam with concrete face	6	Settlements in the concrete face. Leaks at the bottom of the damup to 162 l/s
(6) La Yesca,Nayarit	2008-2011	210	Rockfill dam with concrete face	-	Failureof a large mass of left margin. Poor quality or rock mass in house power and intake and substation

	Low complexity		Medium complexity		High complexity

Some of the most important problems in reference dams and other considerations:

(1) Peñitas Dam is in an area of low hills near the Gulf of Mexico, characterized by shale, sandstone and conglomerate; failures are notable in the region and the presence of an active volcano El Chichonal just 25 km southeast [12]. The sitewhere the dam was built rises to 120m above the river and the works were constructed within a rocky massif of sandstones interbedded with thin layers of shale.This is the first system of dams on the Grijalva River, located just before it flowsthroughthe floodplain of Tabasco State. A landslidein the reservoir of this dam was verified as the largest recorded in Mexico; this was in November 2007 and was due to the failure of a clay layer triggered by a storm that precipitated more than 1000 mm of rain in just three days in the area.

(2) Zimapán Dam was built on a calcareouscanyon on anabruptmountainous area in central Mexico, characterized by massive limestone deposited in marine and reef shelf environment [13]. .During the construction stage occurred a fall on the right back downstream of the dam soa large concrete block (dimensions 15x4x60 m)was placed to replace the original form of the margin.Another major problem, although not in the area of the dambut in the long line of conduction tunnel (20 km), was the presence of a dissolution cave about 60m long and 30m high and 10 to 15m wide, in this case the solution was the design and building of an underground bridge, the use of seismic tomography was crucialto delimit the cave dimensions to save costs of excavation.

(3) Aguamilpa Dam, one of the highest of its kind worldwide, was built on igneous extrusive rhyodacite-daciticcomposition [14].The hydropower plantis located in a mountainous terrain in the Colima graven in western Mexico. During the filling of the reservoir, induced seismicity was caused by reactivation of a fault located about 5 km from the axis of the dam [15] generating earthquakes of up to 5 magnitude on the Richter scale; the activity stopped four years after filling, when equilibriumwas reached in the geological environment. From feasibility and pre-construction stages,alandslide was delimited and studied;a solution was to place drains, ditches and shot concrete. In 2002, the force of the water coming from the spillwayeroded rocks located after the ski jump, falling to the river causing partial obstruction of the flow at the powerhouse output; this was solved by removing material from the channel. Another problemwas the breezefrom the spillwaythat caused softening of the right marginslope, fallen on the road remaining partially obstructed.

(4) Chicoasén Dam is the second dam built upstream the Grijalva River, above a canyon platform in marine limestone. The major portion of the marginof the canyon consists of white sandy limestone layers with thicknesses up to 3m [16]. It is the most important dam for its generation capacity in the country and among the highest in the world. Turbines and generators are housed within a cave at 200m depth. During the construction of the dam deepened to 30m longer than planned because the canyon had large loose blocks misrepresenting information obtained during the exploration.

(5) El Cajón was built inthe Santiago River onigneous composition rhyodacitic ignimbrite that present a pseudo-stratified mass and compactness and hardness of a high value [17]. Although the dam is located on a seismically active region, locally in the narrowing of the canyonthere is no evidence of fault displacements. However, in 2007 there was a landslide on the access road to the powerhouse, which included partial solutions cuts into the hillside, anchors and gabion walls. Another issue was the carved wall at the control zone of the spillway,this by a combination of faults and dikes that reduced mass quality at the site. Also during the operation it has been noticed some cracks around the pondin the presence oflow compactnesspumicerocks.

(6) La Yesca is also located in the Santiago River. The construction site is in a very complex geological area mainly due to the presence of major discontinuities and hydrothermal alterations that complicated the early stages of construction, however, the site selected was restricted to the zone between the reservoir downstream of the El Cajon dam and sequence of volcano sedimentary rocks upstream.The main problem found was a macro block slipped a few centimeters when support was reduced by digging the deviation tunnels gates;similarlywas found a clump in the power house, oscillation chamber and intake zones, which treatments were applied further thanplanned originally.

Figure 1. - Overview and location of the dams Peñitas,Zimapan,Aguamilpa, Chicoasén,
El Cajon and La Yesca (under construction)

5. COSTS

A hydropower project should be a success from a financial and economic perspective. Dorcey[18] mentioned as the most important factors for success of large dam projects: probability of higher costs than the budgeted, delays during construction, availability and water value, water and/or powerdemand anddifficulties during the operation.
A geological investigation is critical to accomplish the cost-time program as expected, since it avoids additional expenses and saves on the remediation of situations that are out of the program, involving the extension of deadlines forconstruction implicating further exploration and additional treatments.
Design and construction phases, include costs such as type and quality of foundations, available construction materials, manpower costs, selected type of dam, the adopted design criteria, imposed regulations and environmental aspects [19]. Geological exploration is directly involved in the determination of the type of dam and also in the quality of the foundations (when verification is performed by a geophysical method, seismic or otherwise), because these effects depend largely on the geological environment.
According to experts,research of the construction site including geology and soil conditions, costsup to 2% or 3% of the total construction [20]. It is clear the importance of basic exploration of the site performed by the disciplinesof geology, geophysics, hydrogeology and geotechnical testing, representing a very small cost in total construction. It is worthy mention that the six Mexican cases used for this paper, relative costs of geological-geotechnical studies at feasibility and design support level ranged between 1% and 1, 5% according to the total cost of the projects.
Design costs of a dam are based on safety factors to hydrological, geological and mechanical uncertainties. As a substantial improvement in the technical report of exploration that are carried out at the design stage,is always appropriate to consider the elaboration of an integrated geological-geophysical summary of the site following the philosophy of so-called Geotechnical Baseline Report (or GBR) [21]. Such philosophy includes technical data, an analysis derived from significant geological features of the project establishing a base model as realistic as possible that can provide guidance to the responsible engineers and also when appropriate, the risks between contractors, designers and the owner of the work [22].

5.1 VOLUME OF EXPLORATION AND MAIN COSTS

As explained in chapter 3, significant aspects of exploration at local level of the site performed by geology and geotechnical are the subsurface drilling through boreholes, permeability testing and excavation of galleries , while geophysics execute surveys of seismic refraction profiles and resistivity across electrical soundings, constituting the most important aspect. Such studies require the highest economic cost in the feasibility and preconstruction phases (design support).
It is important to analyze and compare with other projects the volumes of direct and indirect exploration in dam sites as the quality and quantity of these studies affect construction costs, as well as in solving problems that may occur later (cracking, settlement, piping and leaks etc.).

The difference between one project and other regarding the studiesarea, can present complexities that involve increased exploration. A potential measure of semi-quantitative comparison between different projects is the amount of holes and tunnels (evaluated in meters of drilling or digging, respectively) performed per $km^2$and the amount of permeability tests per km^2,considering the area of the canyonimplying the area of the dam, spillways, deviation tunnelsand in most cases, the power house. Some projects have very long conductiontunnels and are not considered in the damarea.Likewise in the case of geophysical exploration the scanning volume can be calculated by taking into account the number of seismic refraction method (SRM) and the vertical electrical sounding (VES) for km^2, considering the approximate semiregional area covering profiles.For a comparison of the volume of geophysical exploration it should be considered the maximum openings of the current electrodes in the VESand the average lengths of the SRM. However in the cases analyzed it was found varying lengths of about 100, 200 and 300 m for the SRMand 100 to 400 m for maximum apertures of electrodes AB / 2.As a general rule, the depth of geophysical investigation for the site of a dam must be at least one third of the height of the dam, this condition was observed in each of the projects analyzed where the height of the dampredominant range is 180 to 250m and therefore is considered valid in the scope of projects involved.

Although dams have unique characteristics, some have a certain similarity in their topography, location and access. For comparison purposes it wasappropriate to sort them according the following classification based on the complexity for its construction, being more complex those areas where topography is rugged and more altered rock or important discontinuities are presented in the work zone:

Low complexity: (1) Peñitas

Medium complexity: (3) Aguamilpa (5) El Cajon

High complexity: (2) Zimapán (4) Chicoasén and (6) La Yesca

Table 4 makes a comparison of direct examination volume (geological) through boreholes, tunnels and permeability measurements in the area of the dam, whereas Table 5 performs the comparison of indirect examination volume (geophysical) in the semiregional influence area of each dam.

Name	**Studyperiod**[4]	**Area km^2**	**Drilling (m)**	**Drilling (m/km^2)**	**Tunnels (m)**	**Tunnels (m/ km^2)**	**Permeab tests**	**Permeab tests/km^2**
Peñitas, Chis.	1965-1986	2.62	14010	5347	870	332	570	219
Zimapán, Hgo.	1980-1989	0.5	6242	12484	743	1486	632	1264
Aguamilpa, Nay.	1960-1983	4	14300	3575	2632	658	960	240
Chicoasén, Chis.	1963-1975	1	6700	6700	1980	1980	650	650
El Cajón, Nay.	1962-1996	3.6	10352	2875	427	118.8	978	272
La Yesca, Jal.	1963-2006	1.7	2343	1378	905	523.3	127	75

Table 4.- Geological exploration by drilling (with core recovery), tunnels and permeability tests in 6 large dams in Mexico.

Name	**Study periods**[4]	**Area km^2**	**Total SRM**	**SRM/km^2**	**Total VES**	**VES/km^2**
Peñitas, Chis.	1965-1986	16	147	9.2	328	20.5
Zimapán, Hgo.	1980-1989	60	153	2.6	362	6
Aguamilpa, Nay.	1960-1983	14	260	18.6	325	23.2
Chicoasén, Chis.	1963-1975	5.1	60	11.76	325	63.72
El Cajón , Nay	1962-1996	33	1095	33.2	936	28.4
La Yesca, Jal.	1963-2006	59	366	6.2	450	7.6

Table 5. - Geophysical exploration at 6 large dams in Mexico.

[4]The years of study considered are non-continuous periods. It refers to all exploration campaigns in each case. Including the time spent on different alternatives to the axis finally chosen for construction.

Figures 2 and 3 show the comparison of the geological volume and geophysical exploration respectively. In these graphs the volume of exploration has been normalized to the maximum value of each aspect, whether is the total scan length, the number of trials or number of geophysical lines. As for direct examination, Figure 2 indicates that Chicoasen and Zimapan is where most direct examination wasperformed.

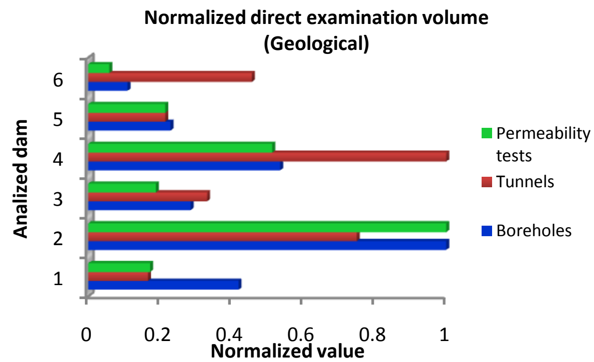

Figure 2. - Comparison of geological exploration on each method in 6 large dams.

As for indirect examination (Fig. 3), projects differ significantly in volume exploration. Projects on the Santiago River (Aguamilpa, El Cajon and La Yescathe most utilized method was SRM, while in the other projects used the method of VES, especially in Chicoasén.

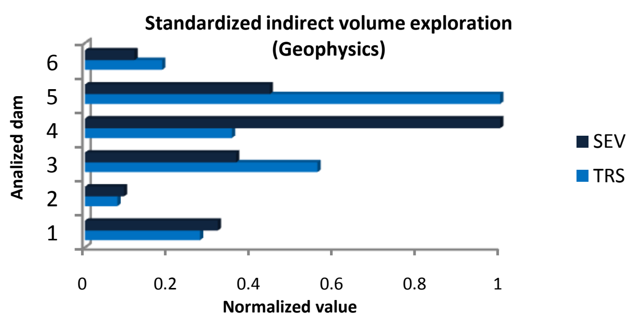

Figure 3.- Comparison of geophysical exploration on each method in 6 large dams

For each of the dams analyzed, the costs of drilling holes, tunnels and excavation permeability tests are indicated in thousands of dollars in Figure 4. The cost was estimated using current prices of these activities in Mexico.

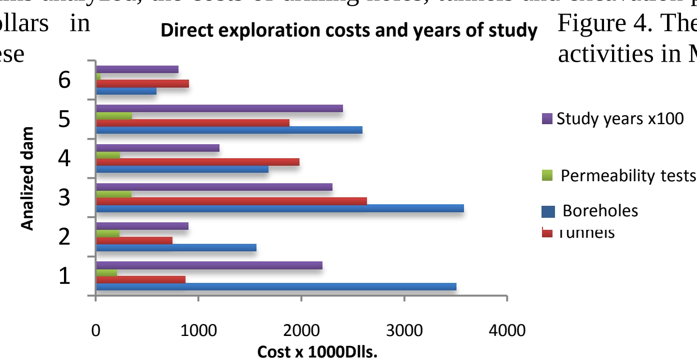

Figure 4.- Direct exploration costs and years of study in 6 large dams

The higher costs of direct exploration with drilling were in Peñitas (1) and Aguamilpa (3), while the higher costs for exploration tunnels were in Aguamilpa (3) and Chicoasén (4).Figure 5 shows the estimated costs of the geophysical exploration methods: seismic refraction method (SRM) and vertical electrical sounding (VES) in the 6 selected sites. The calculation is performed based on current prices of SRMand VESand the number of surveys or lines used in the semi regional area of the project.

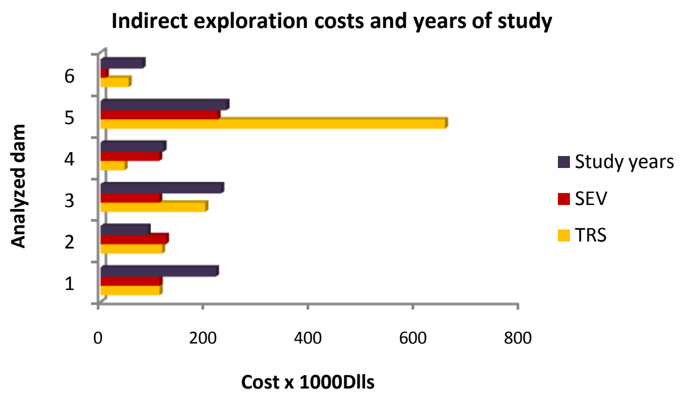

Figure 5. - Indirect exploration costs and years of study in 6 large dams

Figure 5 show that El Cajon dam had the higher costs of indirect exploration (5). The lower costs in terms ofSRMwere in La Yesca (6) and Chicoasén (4) and also La Yesca the lowestin total expenditures on exploration. In almost all projects, except for Chicoasén, the cost is almost equal for the SRM in comparison to the VES. It is noted that expenditures for the VESmethod were similar for most projects, while the SRMhad significant variations in costs.

Figures 6 and 7 show the total cost of direct and indirect exploration respectively for the 6 dams.

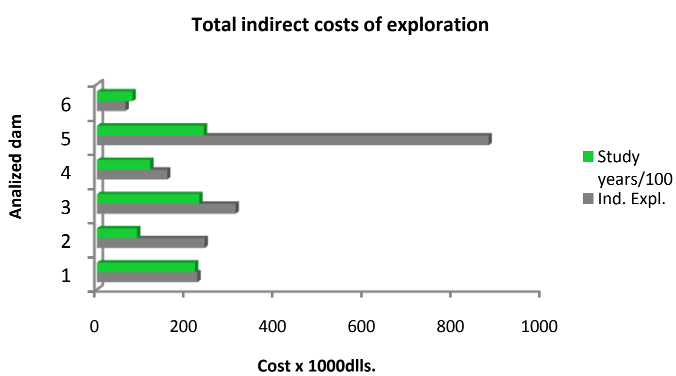

Figure 6.- Total costs of direct exploration and years of study in 6 large dams.

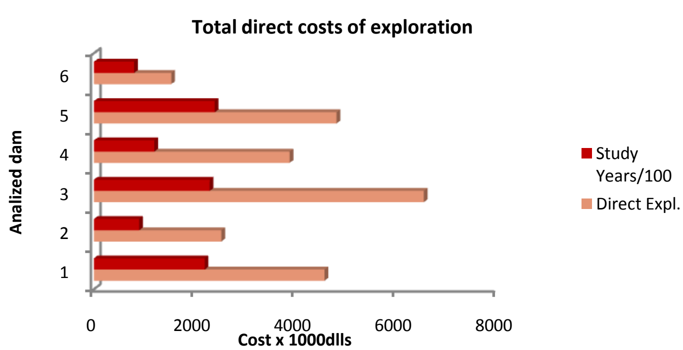

Figure 7.- Total costs of indirect exploration and years of study in 6 large dams

Aguamilpa had the highest direct exploration costs and El Cajon the highest indirect exploration costs.On the other hand, the lower expenses in direct and indirect exploration occurred in La Yesca (6).
Figure 8 compares the costs of direct and indirect exploration at the sixanalyzed hydropower dams and also the project study years and the years in operation until 2011. Direct / indirect exploration expenses are usually 20 times or more in the projects analyzed, except for the dams: (2) Zimapán (10.4) and (5) El Cajon (6.2). The average years of different periods of study are 16.3, but overall, the value is 20 or more. On the other hand the youngest dam in operation is El Cajon (4 years), while La Yesca (6) is not yet in operation.

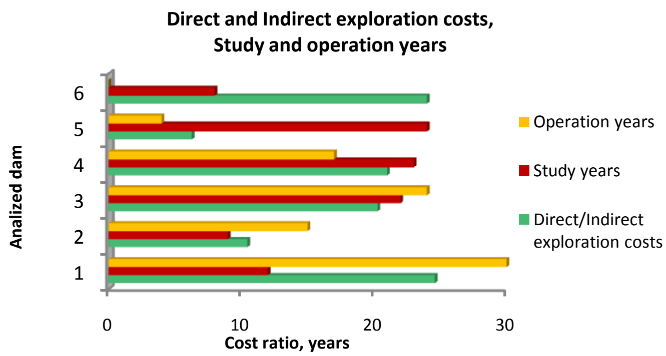

Figure 8.- Direct and Indirect exploration costs, years of study and years in operation in 6 large dams

The six dams studied in this text are the most important in Mexico and has been required between 10.5 and 18.1 million USD during the study phase. Finally figure 9 shows the total estimated cost (updated costs to 2011) of the investment in the study stage (only feasibility and design support) of the dams.It is important to remarkthat Chicoasendam (4) had the highest total cost assigned to studies (including the infrastructure for their development, geology, geophysics, seismology, topography, geotechnical and direct examination, etc.) while La Yesca (6) had the lowest investment. According to the total costs of the studies at least in the six cases analyzed, there was no consistency with the complexity of the site. Higher costs not always occurred in the most complex projects, except for Chicoasen, which in the decade of the seventies, when explored, did not have access to infrastructure, besides a complex geology. On the other hand La Yesca with a highly complex geology framework had lower exploration costs.

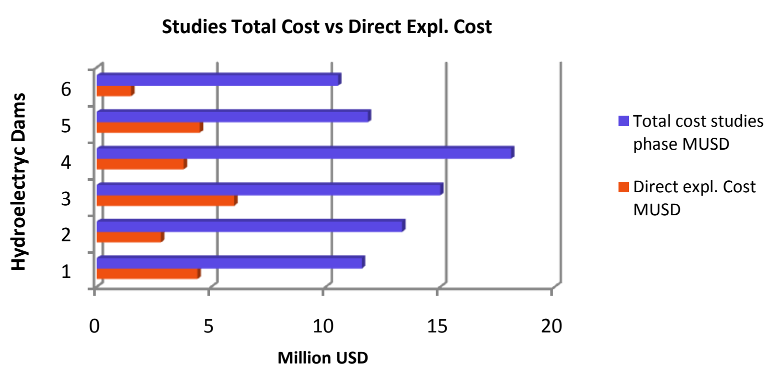

Figure 9. -Total estimated cost of investment in study stage

6. - CONCLUSIONS

- Financial certainty cost of construction of large dams and design efficiency is dependent on a proper stage of studies in which the discipline of geology is essential during the prefeasibility and feasibility phases as they are the basis for geotechnical activities during the stages of feasibility and design support.
- The analysis of the direct and indirect costs of exploration in the five major dams in operation and one under construction in Mexico, indicate considerable variability in the volumes of exploration and associated costs that are not directly relevant to the complexity of the area, but rather shows that such variables have been linked to the availability of time to study.

- Proper planning stages of pre-construction studies should be linked to the geological complexity of the site. This will ensure that the geological model at the beginning of theconstruction is good enough to be the basis of geotechnical design of the work and have only minimal changes during the course of it. However, the process of refining the geological model is an endlessactivity but a small number of changes will be synonymous of efficient studies.

ACKNOWLEDGEMENTS

The authors especially wish to thank the valuable collaboration of Gustavo Arvizu and J. Luis Garrido for reviewing and enrichment the document with their extensive experience in the field of applied geology. We also gratefully acknowledge the assistance of the Federal Electricity Commission (CFE,by its Spanish acronym) for the access to the information that was considered in the elaboration of the article.

REFERENCES

[1] INEGI, 2010.- Sistema para la consulta de las Estadísticas históricas de México 2009.

[2] CONAE, 2002.- Desarrollo de las energías renovables en México: las perspectivas de la CONAE.

[3] SENER, 2006.-Estadísticas.

[4] http://www.hidroenergia.net/.

[5] Bonilla C. &Laporte G, 2006.- La investigación geológica y geotécnica y el diseño estructural de obras hidráulicas en proyectos hidroeléctricos de cogeneración, X Seminario Nacional de Geotecnia – IV Encuentro Centroamericano de Geotecnistas.

[6] AnandaSen, M.P.Singh, Vipul Nagar, NHPC Limited, 2010, Application of Geophysical Seismic.

[7] Head R.C., 2001. -Between a Rock and a Hard Place, at the turn of the runner, HRW, December 2001.

[8] Allen Marr W, 2001. - Why Monitor Geotechnical Performance?, 49th Geotechnical Conference in Minnesota 10.

[9] Serren S., Kleberger J., Simsek O., 2002.- Engineering Geological and Geophysical Investigation at the Dam Site Cine/Turkey.

[10] ICOLD, 1989. - Saving in dam constructions, Bulletin 73: 137.

[11] ICOLD, 1995. - Dam Failures, Statistical Analysis, Bulletin 99:74.

[12] González C. Carlos M, 1989.- Ingeniería Geológica del Proyecto Hidroeléctrico Peñitas, Chiapas, Superintendencia de Estudios Zona Sureste, Subdirección de Construcción, Unidad de Estudios de Ingeniería Civil, CFE.

[13] Arvízu L. G., Alcántara D. J., 1987.- Factibilidad Geológica del Proyecto Hidroeléctrico Zimapán, Hidalgo, CFE, Subdirección de Construcción, Unidad de Estudios de Ingeniería Civil, Superintendencia de Estudios Zona Golfo.

[14] Moreno Garnica S. y Soto Gutiérrez M. A., 1994.- Monografía Geológica Proyecto Hidroeléctrica Aguamilpa, Nayarit, CFE, Subdirección Técnica, Gerencia de Estudios de Ingeniería Civil, Subgerencia de Estudios Geológicos, Departamento de Geología.

[15] Delgado V., Vázquez R., Sánchez A., y Malagón M. 1999. Informe del enjambre sísmico del 28 de octubre de 1988, asociado a la C. H. Aguamilpa (Solidaridad). C. F. E. Inédito.

[16] CFE, 1976.- Proyecto Hidroeléctrico Chicoasén.

[17] Gómez Munguía D., Rodríguez Torres R. y Valdéz Guzmán R., 1986.- Factibilidad Geológica del P. H. El Cajón, Río Santiago, Nayarit, Comisión Federal de Electricidad, Unidad de Estudios de Ingeniería Civil, Superintendencia de Estudios Zona Pacífico Norte.

[18] Dorcey T., editor, 1997. - Large Dams, Learning from the past, looking at the future, Workshops Proceedings, Gland, Switzerland, April 11-12, 1997, The IUCN/World bankinitiative on Large Dams.

[19] ICOLD, 1997, Bulletin 110, Cost Impact of Rules, Criteria and Specifications.

[20] (http://www.bexley.gov.uk/index.aspx?articleid=5072).

[21] Smith E. Ronald, 2001. - Geotechnical Baseline Reports: State of the Practice, Proceedings 36 Annual Symposium on Engineering Geology and Geotechnical Engineering,Luke, Jacobson &Werle (ads) Univerity of Nevada, Las Vegas, March 28-30, 2001.

[22] http://hydropowerstation.com/.- Best Practices on Survey and Investigations of Hydro Electric Projects.