Chapter

Geotechnical Engineering Applied on Earth and Rock-Fill Dams

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Abstract

This chapter presents the importance of geotechnical engineering on the site selection, design, construction, operation, and maintenance of earth-rock dams and earth structures; it emphasizes the geotechnical engineering work related to dam safety during the operation stage. Preliminary geological studies required to select the best dam site are described first. Next, the field and laboratory studies related to the curtain design and dam foundation treatment, as well as geotechnical studies required for the construction, operation, and maintenance of the dam, are discussed. Recent developments in the following three areas are also included: (a) seismic considerations for the design, construction, and maintenance of earth dams; (b) importance of water flow control through the dam embankment and dam foundation, required to avoid internal soil erosion and excessive pore pressure; and (c) dam safety in Mexico and around the world. A case history of a recent failure is used for illustration purposes. In this example, design and construction shortcomings resulted in serious damages on an earth dam. Conclusions and recommendations related to this topic are presented at the end of this chapter.

Keywords: earth-rock dams, dam safety, geotechnical engineering, hydraulic works, soil erosion

1. Background

As is well known, the construction of earth dams dates back many centuries, whose main objective has been the storage of water and flood control.

Due to many reasons, mainly social and environmental, the construction of new dams has led to the operation and conservation of existing structures. This fact has caused geotechnical engineering to be involved in the dam safety management; therefore, it is essential to know the principles of analysis and design with which they were constructed.

There are multiple factors that intervene in the selection of the type of dams; but the topography, regional geology, the availability of construction materials, seismicity of the area, the hydrology of river basin, the environment and geotechnical conditions of the reservoir, and the curtain site are the most important [1]. Thus, the type and classification of the dam dictate the magnitude of the previous and definitive studies to execute the work [2, 3].

2. Geotechnical engineering in preliminary studies

Geological studies play a key role in the early stages of analysis. Its objective is to know the quality and characteristics of the materials, mainly of the areas where the dam is to be constructed. However, these studies must continue at the preliminary stage, project, and throughout the construction of the work.

Some examples of geological investigations can be geological and geotechnical cartography, exploratory excavations (trenches, galleries, or tunnels), and identification of rock mass discontinuities and their geomechanical classification (e.g., [4–6]).

In the case of soil mechanics studies, it is advisable to include the following activities:

- Collection of information: geologic maps, previous studies, aerial photographs and satellite images, etc.

- Recognition visit: preliminary identification and classification of soils and, in particular, its geological origin, visual classification, and soil site characterization.

- Programming of geotechnical boreholes: depth of the explorations, number and type of boreholes, sampling method, etc.

- Measurement of in situ properties: shear strength, permeability, shear modulus, and instrumentation

- Laboratory tests: index properties, mechanical properties, and compaction tests

Regarding rock mechanics analysis, it is advisable to carry out studies of the rock mass, for example, origin and degree of weathering of the rocks, rock quality, classification, characteristics of the joints, location of faults or old landslides, permeability, compressibility, deformability, shear strength, and susceptibility of the rock to the change of its properties due to wetting.

3. Geotechnical engineering in design

At the design stage, there are two conditions to keep in mind: safety and economy. However, the selection of the type of dam depends on geotechnical aspects such as (a) type, quality, characteristics, and location of the materials for its construction; (b) characteristics of the foundation at the dam site; and (c) stability of slopes in the reservoir and embankments of the dam. In addition, the dam axis depends on the characteristics and geotechnical properties of the foundation.

Concerning the characteristics of the materials for the construction of earth dams, those that are dispersive, collapsible, or susceptible to piping should not be used. In addition, for the design of this type of dams, the mechanical properties of earth materials must be taken into account, for example, shear strength, compressibility, and permeability. If the dam is located in a seismic zone, the dynamic shear modulus and damping of the materials must also be obtained.

Regarding the compressibility and shear strength of the foundation materials, the short- and long-term settlements of the dam have to be analyzed. As for the volume of water that passes through the foundation, the type of treatment and alternatives to reduce the flow will be defined by the permeability of the materials. Similarly, when the dam is located in a seismic zone or an area susceptible to vibrations (e.g., near borrow areas where explosives or related works are used), the susceptibility to the liquefaction phenomenon must be evaluated.

The compacted layers thickness, the inclination angle, the materials, and construction procedures of the dam embankments are governing by the upstream and downstream slope stability analyses. These analyses must consider different loading conditions: full dam, empty dam, rapid filling, rapid drawdown, seismic effect, and so on. Additionally, the susceptibility to piping must be analyzed, which is why it is important to consider the design and installation of filters and transition zones.

Finally, in the economic aspect, transportation and the treatment processes for the materials directly influence the total cost of the work.

4. Geotechnical engineering in construction

The participation of the geotechnical engineer is indispensable in the different stages of the construction of dams, in particular, to verify that the materials and activities correspond to the design and planning of the work.

Special care should be taken in the construction of structures that cross the dam, for example, the spillways and intake structure, among others. The inadequate control of the compaction and characteristics of the materials in the periphery of these elements can cause the phenomenon of internal erosion and piping. In fact, it is in these areas that erosion and piping processes begin. Both situations have caused the failure of numerous earth dams. A particular case is the Teton Dam that [7] described.

It is also important to control the grain-size distribution specifications of the filter and drainage areas, especially when they are placed on the site. There are experiences of plugging and malfunctioning of filters, precisely because of the segregation of soil particles or because of the lack of compliance in their characteristic grain-size.

Likewise, in the construction process, it is important to implement the dam to evaluate its behavior as the construction progresses. The above will allow taking corrective measures before any eventuality, for example, reduce the speed of construction and build berms on the slopes to reduce the stresses acting at the bottom of them, among others.

5. Geotechnical engineering in operation and maintenance

The presence of the geotechnical engineer in the operation and maintenance of a dam helps to solve any eventuality. In addition, its presence supports quick decision-making to avoid damage or failure in the behavior of the dam and the foundation.

According to the life of the dams, the aging of the materials is an important aspect of their safety. This effect causes the earth materials to undergo a change in their structure, composition, and properties, which are due to the microbiological activity of chemical or mechanical processes that have during the useful life of the work. As a result, these changes cause the softening, loss or gain of rigidity or strength of the material, alteration of its hydraulic conductivity, and so on. Aging of the materials can also cause the clogging of drains and filters. Mitchell [8] described an example of a dam affected by age.

It is vital to establish a dam security system that evaluates and prioritizes those that require immediate attention. In this sense, geotechnical engineering can contribute significantly to the design of mechanisms to assess their condition and define the hazard level for their repair or rehabilitation. In this regard, several countries have developed techniques for this essential part of the life of dams [9, 10].

6. Seismic considerations in dams

The damage or effect of an earthquake on earth and rock-fill dams depends on the geology of the site, soil conditions, stability of the foundation, characteristics of the slopes, and slopes in the reservoir, as well as the seismo-dynamic considerations that are taken into account in the analysis of complementary structures (spillways, intake structures, etc.).

The seismic effects on dams usually result in dam settlement, landslides in the area of the reservoir, or embankments. Such effects also appear as cracks in the structures that complement the dam, which can cause excessive water seepage through the dam and soil erosion. In addition, the earthquake can cause soil liquefaction if dam is constructed on low density or uncompacted soil layers [11, 12].

6.1 Analysis methods

There are several methods of analysis for the evaluation of seismic effects in dams; however, they can be summarized in two stages of main interest:

1. Establish the seismic environment under which the dam does not fail. In this case, the ICOLD [13] in its Bulletin 72 recommends considering the design earthquake for two levels of severity: maximum credible earthquake and operating basis earthquake.

2. Define the analysis methodology according to the magnitude and relevance of the dam, as well as the design stage (preliminary or final) and the risk involved in the failure of the dam.

Some traditional methods of analysis for seismic design in dams can be pseudostatic [14, 15] and finite element. **Table 1** summarizes the general aspects of each of them.

The information required by the above methods is summarized in the following points:

a. *Seismicity of the area*. Acceleration and maximum velocity of the terrain, spectral acceleration, magnitude, epicentral distance, seismic sources, return period, and accelerogram representative of the area.

b. *Geological aspects*. The occurrence of superficial faults, induction of seismicity due to the effect of the first filling of the reservoir, and liquefaction of sands in the foundation and/or body of the dam must be foreseen, in addition to the existence of landslides in the area of the reservoir or the dam.

c. *Material properties*. The G modulus (obtained from the dynamic shear stress-strain curve) and hysteretic damping, D.

d. In the case of clays, the dynamic effect of the shear strength with respect to the resistance in static conditions must be taken into account.

e. In the case of sands, susceptibility to liquefaction should be considered according to their relative density.

6.2 Inspection after an earthquake occurred

In dams located in seismic zones, there must be a guide to carry out immediate and subsequent inspections. Both inspections should focus on the dam, the

Generalities	Method			
	(1)	(2)	(3)	(4)
Consider a rigid sliding wedge	X	X		
Consider a single dynamic pulse	X			
The resistance of the soil is assumed constant during the occurrence of the earthquake	X	X	X	
The coefficient of kinetic friction remains constant and equal to static friction	X	X	X	X
The creep acceleration is constant throughout the sliding surface	X	X	X	X
It assumes a single fault surface	X	X	X	
Does not take into account superior vibration modes	X	X	X	
Does not consider the three components of the earthquake	X	X	X	X

Note: (1) Pseudostatic, (2) [15]; (3) [14]; (4) 2D finite element

Table 1.
Overview of traditional methods for seismic analysis of dams.

embedments, the foundation, the area of the reservoir, and the auxiliary works (inlet and outlet channels, spillways, intake structures, tunnels, and electromechanical equipment, among others).

In the case of immediate inspections, it is necessary to report any damage such as landslides, settlements, cracks, and groundwater seepage that did not exist before the earthquake. Similarly, it will be relevant to analyze the information recorded by the instrumentation, mainly to know the condition and behavior of the elements of the dam. The immediate inspection must be maintained for a period of not less than 48 hours. Thus, those responsible may establish emergency strategies if there is a potential risk of failure.

On the other hand, in the subsequent inspections, groups of engineers who are familiar with the project and the construction of the dam must be involved. In this way, the magnitude of the damage and the risk that the work represents are evaluated. Unquestionably, the purpose of the subsequent inspection will be to determine the forms and possible causes of failure. In particular, the inspection should focus on the condition of the foundation, for example, differential settlements, landslides, excessive pore water pressures, groundwater seepage, etc.

It should be added that the North American Great Dams Committee 1986 proposes a format for the inspection of these works. Likewise, [16] mention some recommendations for the inspection of these structures.

7. Relevance of seepage control

There are three main causes related to dam failure due to groundwater movement: (1) soil piping, (2) uplift, and (3) excessive water seepage through the dam.

Some typical measures to solve these problems are (a) adequate selection of materials for construction. (b) reduction of water seepage through a design that considers the geological conditions of the site and the permeability of the materials, (c) control of the compaction of the material and other construction procedures, (d) definition of transition zones between materials of different granulometries (filters), and (e) construction of relief wells that reduce and control pore water pressures.

7.1 Soil piping

Piping is a consequence of the seepage forces caused by the groundwater movement. This phenomenon is produced by the removal and dragging of soil solid particles. Piping occurs when the resistant forces of the soil are less than seepage forces. Resistant forces depend on several factors, but the cohesion, binding, and weight of the solid particles are the most important. Thus, for example, in earth dams, the filters located upstream and downstream of the dam help to combat the piping phenomenon [17]. **Table 2** relates the resistance to piping for different types of soil. In summary, the soils most susceptible to piping are the fine sands that are poorly compacted, whereas the soils with greater resistance are the clays of high plasticity.

The problem of piping can start in any crack caused by differential settlements of the dam, earthquakes, tension cracks, holes left by roots and rotten tree trunks, and, even, by holes or burrows excavated by animals. Frequently, soil piping occurs between contacts of rigid structural members of the dam and loose or poorly compacted materials.

7.2 Seepage forces

The seepage forces intervene in the stability of the slopes of the dam. Among the most critical conditions to which a dam may be subject during its useful life are (a) rapid filling of the reservoir, (b) steady-state groundwater flow with the normal water level, and (c) rapid drawdown of the reservoir. Before this, whatever the condition of analysis, it is necessary to draw a flownet or establish some analytical or numerical procedure to determine the pore water pressures and seepage forces on the failure surface of the slope of the dam.

7.3 Seepage control measures

The reduction of groundwater flow and exit hydraulic gradients is achieved with several procedures. Some examples are cutoff walls, grout curtains, waterproofing membranes or full face waterproofing to the face upstream of the dam, construction of impermeable cores at the dam, partial or total penetration trenches located in permeable zones, etc. Usually, these measures are complemented with the installation of filters and drains [6]. The latter serve as an additional line of defense against water seepage problems. However, filters must meet certain granulometric requirements, which can be found in the methods proposed by Terzaghi [18–23], among others.

7.4 Numerical modeling in groundwater flow analyses

Currently, the increasing development of computers allows the numerical solution of different seepage problems, which, by graphics or analytical methods, are

Resistance	Type of material
High	• Clay with high plasticity, well compacted • Clay with high plasticity, poorly compacted • Well-graded sand-gravel or sand-gravel mixtures packed in the clay of medium plasticity, well compacted
Media	• Fine-graded sand or mixtures of sand-gravel packed in the clay of medium plasticity, poorly compacted • Well-graduated gravel-sand-silt mixtures without cohesion (IP < 6), well compacted
Low	• Gravel-sand-silt mixtures well graduated without cohesion (IP < 6), badly compacted • Fine sands, without very uniform cohesion, well compacted • Fine sands, without very uniform cohesion, poorly compacted

Table 2.
Empirical relationship between the resistance to piping and the type of material [24].

usually difficult to solve [25]. However, numerical modeling makes it easier to study different cases of analysis, for example, heterogeneous and anisotropic groundwater flow, steady-state and transient state flows, as well as the groundwater flow in saturated and unsaturated media. In this area, the methods of finite differences (**Figure 1**) and finite elements (**Figure 2**) are usually the best known. Different publications show the facilities provided by these procedures [26–28].

Numerical techniques have wide advantages over any other analysis procedures. Two of the most relevant are coupled groundwater flow-slope stability analyses and groundwater flow deformation. In both cases the scope is to analyze the pore water pressure, with which more realistic results are obtained from the problem analyzed [29].

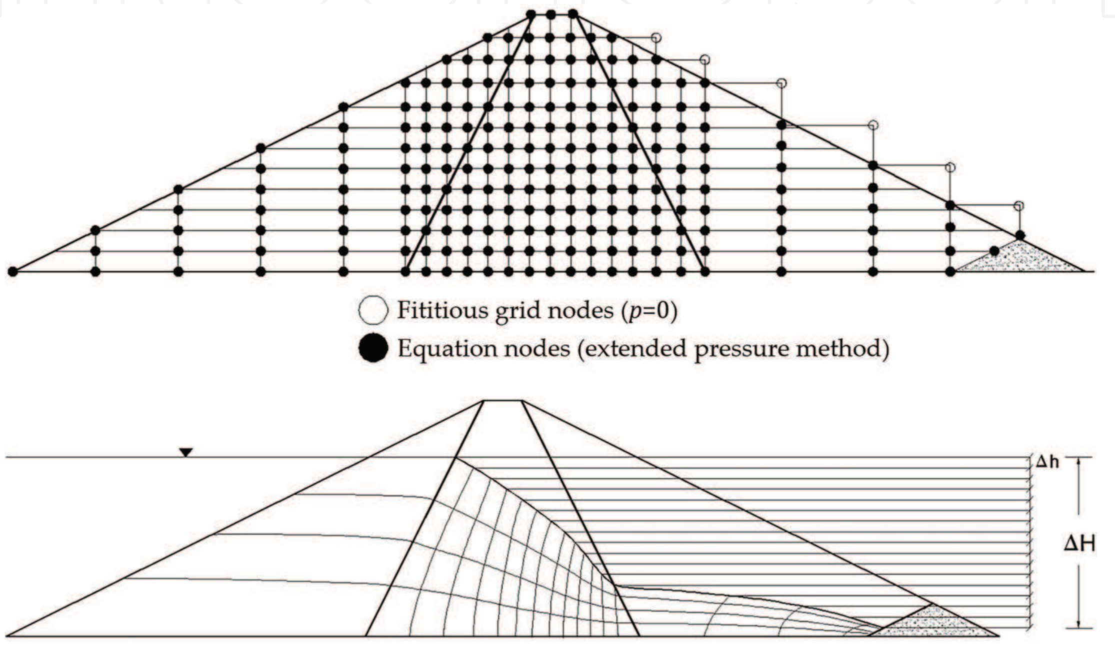

Figure 1.
Solution of a water flow problem by the finite difference method [30].

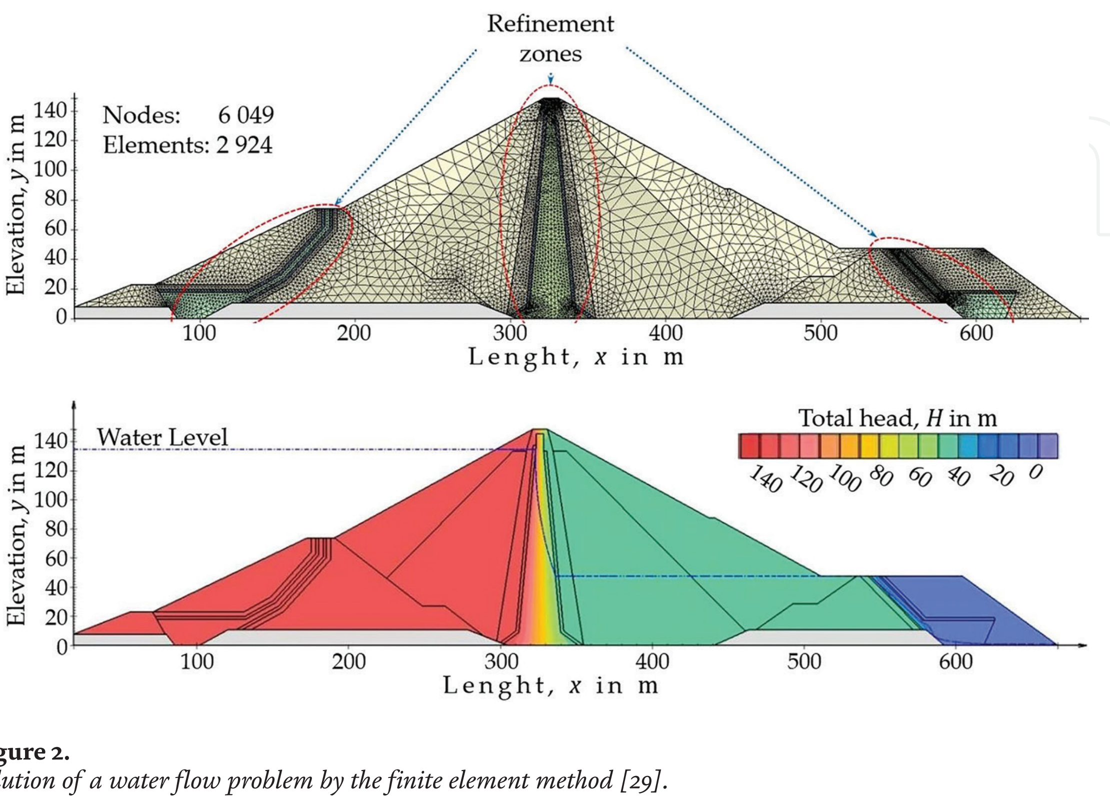

Figure 2.
Solution of a water flow problem by the finite element method [29].

8. The security of dams in Mexico

In Mexico, from 1926, when the National Irrigation Commission was created, the design and construction of several dams were undertaken in order to store water for agricultural irrigation, hydroelectric generation, water supply, flood control, aquaculture, and recreation. These works allowed dam engineering and soil mechanics in Mexico to become the two disciplines with international prestige for Mexican engineering.

The design, construction, and operation of dams in Mexico, especially earth and rock-fill dams, have had a high level of technological development, whose influence has transcended in the international arena. However, until recently, there was no official standard for the safety of dams that would specify in a theoretical and legal framework the minimum requirements to be met in the basic stages of the life of the dams, that is, design, construction, first filling, operation, maintenance, and abandonment.

Recently, the National Water Commission (formerly the National Irrigation Commission) established a multidisciplinary working group made up of experts from various government agencies and research institutions. Its objective was to establish a Mexican Standard, in addition to setting the minimum requirements that must be met in the different life stages of a dam and establishing the solution plans for different emergency scenarios, as well as the management and technical decisions that significantly affect the safety of existing dams in the national territory, and thus reduce risks to people, property, and the environment.

8.1 International context

In the last 30 years, the construction of new dams has decreased in developed countries [9]. Currently, the actions have been aimed at rehabilitation, prolonging the useful life and increasing safety and final closure of those that are not in operation. Therefore, dam safety management programs have focused on:

- Maintain and operate the dam at the security level considered in its design.
- Verify that the dam meets design expectations, and identify possible deviations from safety levels by monitoring its behavior and surveillance.
- Periodically review the design and performance of the dam to identify safety problems and formulate action or remediation measures.
- Establish action plans in case of any incident of the dam.
- Decide which safety issues or existing problems in the dam require immediate attention or can be handled within a framework of the dam safety improvement program.

8.2 Situation in Mexico

In Mexico, there are 5166 dams administered by different agencies. Of the slightly more than 5000 dams, 836 are classified as large dams [31]; most of them with earth and rock-fill curtains built in the middle of the last century. However, there are also a significant number of masonry and concrete curtains; several of them are from the nineteenth century or the beginning of the twentieth century.

A large part of the dams in the country is about to reach their useful life. Others are at an advanced age, that is, between 20 and 50 years old. Seventy-one percent of the dams exceed 20 years old, and on average, they are 36 years old. Therefore, in dams where there is no efficient maintenance, there will be a loss of capacity due to silts, contamination, and possible deterioration of the curtain and its elements.

Another situation that is observed is the change of use for which the dam was originally built. Dams initially intended for irrigation or hydropower generation are now adapted for human consumption. Similarly, projects that were developed for the storage of rainwater are now mixed with wastewater, which attacks normal concrete and reinforcing steels.

8.3 Safety assessment of dams

To know the security status of a dam, it is advisable to carry out annual inspections, every 5 years and whenever an extraordinary event occurs. Botero et al. [9] recommend that the annual inspections seek to know the behavior and operation of the dam in the short term. In inspections every 5 years, a detailed analysis of the condition of the dam must be made and possible corrective actions identified. Finally, in the case of inspections after an extraordinary incident, these should focus on the study of the effects that it could have on the dam. In any case, inspections should consider the following aspects:

- Collect all available information of the dam followed by a visual visit to the site.
- Know the behavior of the dam under normal and extraordinary conditions.
- Review hydrological safety.
- Update weather information.
- Evaluate the stability of the dam and the surrounding structures.
- Identify any problem or incident in the area of the dam and its foundation.
- Evaluate the seismic risk.
- Define the safety factors for the steady-state conditions, rapid drawdown, and earthquake for different reservoir water levels.
- Calculate the stress state and deformations, pore water pressures, groundwater discharge, and free board losses and identify landslides on the reservoir.

Additionally, **Figure 3** shows a flowchart for decision-making in the evaluation of dam safety. In addition, **Table 3** indicates a classification of risk levels in dams.

8.4 Dam removal

With regard to dams that have ceased to operate or are abandoned, the concessionaire must prepare a project that defines the work for putting out of service and the conditions in which the area of influence will remain. In addition, the project must specify the necessary adaptations so that an incident does not occur due to the inappropriate behavior of the remnants of the dam. Therefore, in order to ensure that the removal is carried out correctly, it is necessary to verify that any danger to human lives or important properties has been eliminated.

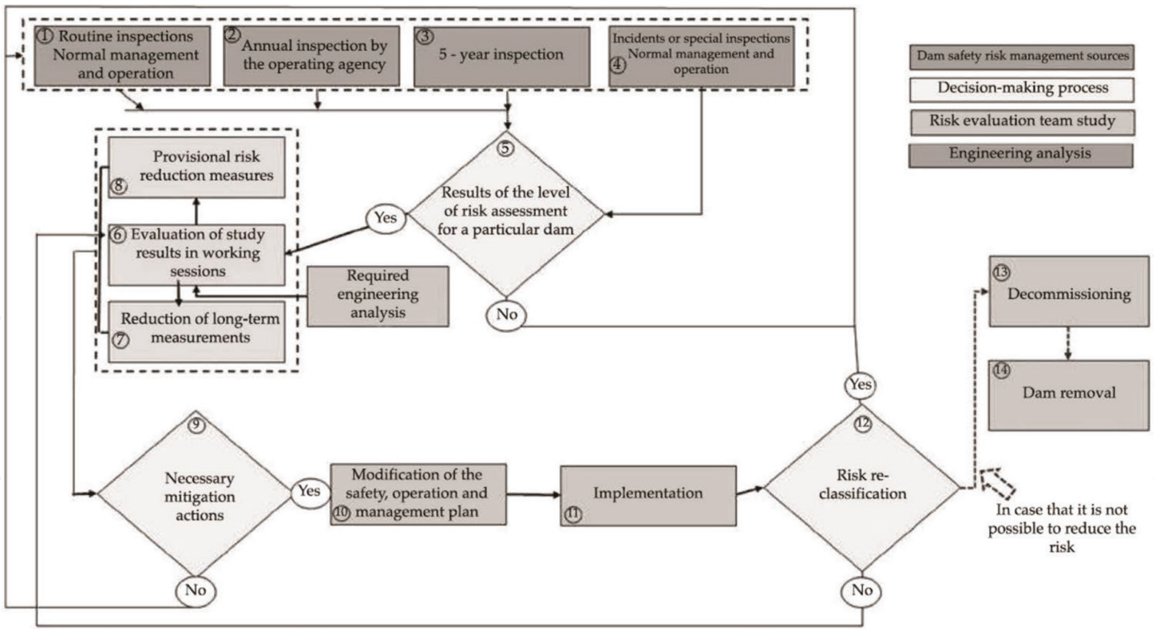

Figure 3.
Flowchart of the proposed method for structures higher than 15 m (modified from [32]).

Risk level	Description
Remote	The physical conditions for the development of a problem are nonexistent or unlikely to occur
Very low	The possibility cannot be taken into account, but there is no convincing evidence that it has ever happened or that there cannot be a situation that could lead to the development of that failure
Low	The causes of the defects are known. Indirect evidence suggests that it is feasible but indicates a low probability of failure
Moderate	The fundamental conditions or defects that can produce the fault are known, and the evidence suggests that it is directly possible
High	There is considerable evidence, direct or indirect, suggesting that such an event has occurred or is likely to happen
Very high	There is direct evidence that the problem is occurring actively or is very likely to happen

Table 3.
Risk levels in dams [9].

It should be noted that the problem of the removal of the dam does not end with the removal of the structures. The final phase consists of determining the impact of sediments on water quality and concentration of pollutants, flood potential, conservation of fish and wildlife, downstream infrastructure, cultural resources, and recreational activities that were carried out in the reservoir and determining if it is necessary to build new structures or mitigation measures.

9. An historical case of an earth dam failure

In this section, a historical case of the failure of a homogeneous earth dam is described. The dam was built in 2009 in San José Iturbide, Guanajuato. The objective of the dam was for the recharge of an aquifer and the supply of drinking troughs by capturing rainwater and runoff from the mountains. The height of the dam is 13.6 m, and the length is 98.5 m. The storage capacity of maximum water level (MWL) is 0.290 hm^3 (Elev. 2199.50 m.a.s.l). The material for the construction consisted of a sandy silt with some gravels and small boulders.

Downstream, approximately 3.7 km away, is the population called El Capulín, whose number of inhabitants exceeds 3300. In addition, it should be clarified that the dam was designed and built in a particular way without the consent of the National Water Commission.

In February 2010, the spillway collapsed during the first filling of the reservoir, for which more than 2000 people from El Capulín population were evacuated. **Figure 4** shows the failure of the dam. The technical visits after the failure showed that the material for the construction was highly erodible and was placed without any compaction procedure. On the other hand, evidence was found that there was no cleanliness in the contact of the dam with the basalt rock. In addition, water seepage was observed in the dam-rock basal contact, and several local type faults were identified on the upstream side of the dam.

9.1 Hydrological review

The results of the hydrological study for maximum avenues with different return periods (including 1 of 10,000 years) showed that, from a return period of 50, the maximum level of the dam was exceeded with hydraulic heads between 0.18 and 1.91 m. As a result, the safety of the structure due to overflow and erosion represented an imminent danger. In fact, the hydrological risk represented by the dam was high.

9.2 Geotechnical considerations

For the geotechnical investigation, six test pit excavations were carried out to obtain soil samples to determine the index and compaction properties of the material. In addition, in situ permeability tests were performed with the Matsuo Akai method. **Figure 5** shows the maximum section of the dam with the explorations made.

Figure 4.
Overflow and failure of the spillway of the La Salitrera dam, in 2010.

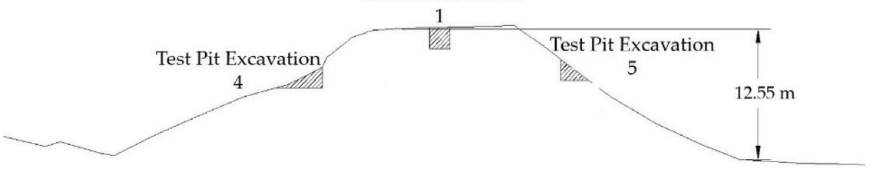

Figure 5.
Maximum section of the dam with the location of test pit excavations and material properties.

Slope stability analyses were carried out with two limit equilibrium methods: Morgenstern-Price and Bishop. Initially, the stability of the dam (upstream and downstream sides) focused on steady-state conditions for water reservoir levels: normal water level (NWL) and maximum water level (MWL). **Table 4** indicates the factors of safety for both conditions. In summary, it is observed that the factors of safety for the slopes of the dam do not satisfy the minimum factor of safety requested by CONAGUA (FoSmin = 1.5). **Figure 6** shows the minimum factor of safety and the failure surface for the downstream side.

On the other hand, the slope stability was analyzed, assuming a rapid drawdown of the reservoir. **Table 5** indicates that the dam slopes have a factor of safety less than 1.2. Therefore, both slopes of the dam are unstable and represent an imminent risk of failure.

Finally, the earthquake stability of the dam was determined. The water level was assumed at NWL, and a return period for the earthquake of 475 years was considered. As shown in **Table 6**, the safety factor for the analysis is greater than 1.0. Therefore, the stability of the dam under a seismic event is not critical. **Table 6** summarizes also the results for the three conditions of operation of the dam: normal, unusual, and extreme.

9.3 Delimitation of flood danger zones

The evaluation of the danger zones by the flood was determined taking into account two factors of main interest: (1) maximum depths and (2) maximum flow velocities. In this case, the hydraulic analyses showed that the channel has a capacity for an avenue with a return period of 10 years. In addition, the estimated maximum water velocities exceed 4 m/s, and the maximum depth of the avenue is greater than 1.5 m.

Flow condition	Slope	Factor of safety		Water level
		Morgenstern-Price	Bishop	
Steady-state	Upstream	3.105	3.108	MWL
Steady-state	Downstream	0.975	0.961	MWL
Steady-state	Upstream	1.815	1.820	NWL
Steady-state	Downstream	1.310	1.306	NWL

Note: MWL = maximum water level

Table 4.
Factors of safety determined with slope stability analysis under steady-state groundwater flow conditions.

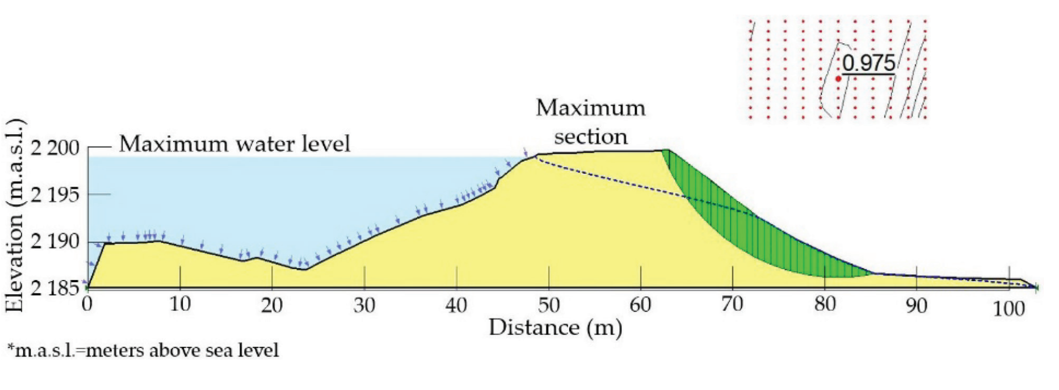

Figure 6.
Minimum factor of safety and critical failure surface in downstream side, steady-state groundwater flow (maximum water level).

9.4 Risk mitigation measures

Three alternative solutions are presented:

1. Construct a cylindrical type spillway (Creager) with a length of 16 m with a water head of 2.75 m and a capacity of 145 m^3/s. These characteristics correspond to a return period of 10,000 years.

2. Cut down the height of the dam by 3 m, and build a 3 m high channel wall from the left embankment; clean and excavate the ignimbrite rock 10 m long and up to the height of 2192 m above sea level, at the right bank, where the spillway was.

3. Remove the dam.

From these three alternatives, alternative 2 is considered the most feasible. As a result, a 10 m long wide crest spillway is proposed. The height of the dam must be reduced by 3 meters to reach a height of 2196.5 m.a.s.l. The modification of the NWL to the level 2192 m.a.s.l. restricts the water level so that it does not represent a risk to the dam. In addition, the modification of the MWL to the level 2195.7 m.a.s.l. will allow the transit of extreme events without affecting the security of the dam.

With regard to the mitigation of flood risk, cleanup work and release of the main channel are recommended. In addition, build the necessary structures such as bridges, culverts, etc. which will allow the free flow of water during extraordinary events.

Flow condition	Slope	Factor of safety		Reservoir water level
		Morgenstern-Price	Bishop	
Rapid drawdown	Upstream	0.838	0.803	MWL to NWL
Rapid drawdown	Downstream	0.976	0.962	MWL to NWL

Note: MWL = maximum water level; NWL = normal water level

Table 5.
Factor of safety determined with the slope stability analysis under rapid drawdown groundwater flow conditions (Section 1).

Operation	Slope	Factor of safety Morgenstern-Price	Flow condition	Reservoir water level
Normal	Upstream	3.11 > 1.50	Steady-state	MWL
	Downstream	0.98 < 1.50	Steady-state	MWL
Unusual	Upstream	0.86 < 1.20	Rapid drawdown	MWL to NWL
	Downstream	0.98 < 1.20	Rapid drawdown	MWL to NWL
Extreme	Upstream	1.72 > 1.00	Steady-state with an earthquake*	NWL

**Note: Earthquake with PGA = 0.45 g and Tr = 475 years.*
MWL = maximum water level; NWL = normal water level

Table 6.
Factors of safety obtained from slope stability analysis under normal, unusual, and extreme operating conditions.

9.5 Additional geotechnical considerations

As can be seen in **Tables 4** and **5**, the stability of the dam in steady-state and rapid drawdown groundwater flow conditions and the factors of safety are less than unity; therefore, the structure is unsafe. Also, taking into consideration the granulometric characteristics of the construction material of the dam, in addition to the photographic evidence of **Figure 4**, the material seems susceptible to internal erosion (piping); therefore, the safety of the dam is not adequate from this point of view.

10. Conclusions

The main conclusions of this work are:

- Geotechnics plays a fundamental role in the proper functioning of earth and rock-fill dams. For this reason, it is essential to perform geotechnical studies from the selection of the dam site and its intervention in the methodology of the design of the embankment and other elements that make up the dam and to monitor the behavior of the entire dam during its useful life.

- The failure of a dam can occur due to a deficient preliminary geotechnical study, a bad design of its embankment or foundation, a poor control in the quality of the construction, or a lack of maintenance in the instrumentation and operation of the dam.

- There are methods nowadays to adequately take into account the forces originated from earthquakes, the groundwater flow, and the problems of internal erosion (piping).

- The inspection visits to each dam should be carried out periodically and, especially, immediately after any extraordinary phenomenon, such as an extreme flood, an earthquake, or any other anomalies not contemplated in its design.

- It is convenient that the inspection visits are carried out by engineers with width experience and that they include the areas of hydraulics, hydrology, geotechnics, structures, and electromechanics.

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