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**Impact of waterproofing and drainage systems failures on safety criteria of dams**

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## DEDICATION

We would like to dedicate this thesis to all those who supported us throughout this journey, with love, patience, and encouragement.

### HADJER BENYOUUCI

I dedicate this work to the memory of my beloved father Mr. BENYOUUCI Mohammed, my dear mother Mrs. ZAIR Fatima and my sisters whose endless love and sacrifices have shaped who I am today.

I also dedicate it to my dear husband Mr. MELLOUK Aziz, whose unwavering support, patience, and encouragement gave me the strength to keep going. I truly couldn't have done it without you. To my little son my sun shine Sami. Thank you for always believing in me

### KIWASI JESLINA WAKI

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## **Abstract**

Waterproofing and drainage systems are essential to the structural safety and hydraulic performance of embankment dams. When poorly designed or inadequately maintained, these systems can lead to uncontrolled seepage, internal erosion (piping), and eventual dam failure. This study evaluates the effectiveness of various waterproofing and drainage configurations using the Boughrara dam as a reference model. Through numerical simulations conducted with GeoStudio software, several scenarios were analyzed involving different grout curtain depths, drainage system placements, and core base lengths.

The results identified the most effective configuration as a grout curtain 60 meters deep, placed centrally beneath the clay core, paired with a drainage system extending 60 meters downstream of the core. Additionally, a core base length of 43 to 50 meters proved optimal for reducing seepage and improving structural stability. This combination provided the best results in terms of minimizing hydraulic gradient, pore water pressure, and flow rate. These findings highlight the critical role of integrated waterproofing and drainage design in enhancing dam reliability and preventing failure.

Key words: Embankment dam, Boughrara dam, hydraulic behaviour, waterproofing, drainage system, Geostudio.

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## Résumé

Les systèmes d'étanchéité et de drainage jouent un rôle fondamental dans la sécurité structurelle et le comportement hydraulique des barrages en remblai. Lorsqu'ils sont mal conçus ou mal entretenus, ils peuvent entraîner des infiltrations incontrôlées, des phénomènes d'érosion interne (phénomène de renard), voire un effondrement total du barrage. Cette étude vise à évaluer l'efficacité de différentes configurations d'étanchéité et de drainage en prenant le barrage de Boughrara comme cas d'étude. Des simulations numériques ont été réalisées avec le logiciel GeoStudio pour analyser plusieurs scénarios incluant diverses profondeurs de rideaux injectés, positions de drains et longueurs de base de noyau.

Les résultats ont montré que la configuration la plus performante consiste en un rideau d'injection de 60 mètres de profondeur, positionné au centre sous le noyau en argile, combiné à un système de drainage de 60 mètres en aval du noyau. De plus, une longueur de base du noyau comprise entre 43 et 50 mètres a donné les meilleurs résultats en termes de réduction des infiltrations et d'amélioration de la stabilité. Ce montage a permis de minimiser le gradient hydraulique, la pression interstitielle et le débit, confirmant l'importance d'une conception intégrée de l'étanchéité et du drainage pour garantir la stabilité et la durabilité des barrages.

Mots-clés : Barrage en remblai, Barrage de Boughrara, comportement hydraulique, étanchéité, système de drainage, Geostudio.

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## المخلص

تُعد أنظمة العزل المائي والتصريف من العناصر الأساسية في سلامة السدود الترابية وأدائها الهيدروليكي. فعند تصميمها بشكل غير مناسب أو عند ضعف صيانتها، قد تؤدي إلى تسرب غير مراقب، ونشوء تآكل داخلي، مما قد يتسبب في فشل هيكلي كارثي. تهدف هذه الدراسة إلى تقييم فعالية تكوينات مختلفة للعزل المائي والتصريف باستخدام سد بوغرارة كنموذج مرجعي. ومن خلال المحاكاة العددية باستخدام برنامج جيوستيديو، تم تحليل سيناريوهات مختلفة تشمل أعماق ستائر الحقن، مواضع أنظمة التصريف، وأطوال قواعد النواة الطينية.

أظهرت النتائج أن أفضل تكوين يتمثل في ستارة حقن بعمق 60 مترًا موضوعة تحت النواة الطينية في موقع مركزي، إلى كما أن طول قاعدة النواة بين 43 إلى 50 مترًا أظهر كفاءة عالية في جانب نظام تصريف بطول 60 مترًا خلف النواة تقليل التسرب وتحسين الاستقرار الهيكلي. وقد أظهر هذا التكوين أفضل النتائج من حيث تقليل التدرج الهيدروليكي، ضغط الماء المسامي، ومعدل التدفق، مما يؤكد على الأهمية الكبيرة لتكامل تصميم العزل المائي والتصريف في تعزيز سلامة السدود ومنع انهيارها.

الكلمات المفتاحية: سد ترابي، سد بوغرارة، السلوك الهيدروليكي، العزل المائي، نظام التصريف، جيوستوديو.

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## General introduction

Dam failures are among the most catastrophic events in civil engineering, often resulting in devastating human, environmental, and economic consequences. This research presents a comprehensive study of dam failures by analyzing statistical trends, failure mechanisms, and preventive strategies. The study begins with an in-depth statistical overview of dam failures worldwide, identifying key factors such as dam age, height, storage capacity, and geographical distribution. It then explores the underlying causes of failures in both embankment and concrete dams, drawing from notable historical case studies to highlight recurring patterns and risks presenting real-world case studies to ground theoretical insights in practice.

A central focus of the study is on structural and hydraulic safety systems, particularly the roles of waterproofing and drainage systems. Detailed attention is given to internal and external waterproofing techniques, including core-based membranes, diaphragm walls, and foundation treatments like injection curtains. The research further investigates the influence of hydraulic parameters and drainage system design on dam stability. Poor drainage system is a leading cause of seepage-induced failures. Different configurations of drainage systems such as chimney drains, toe drains, and prismatic drain..., It further highlights maintenance practices that ensure long-term functionality of these systems.

Using the Boughrara dam in Algeria as a case study, this thesis models the interactions between waterproofing systems, drainage layouts, and dam integrity. The modeling study to assess the influence of these systems depths and positioning on dam behavior. By altering simulation parameters such as depth, length, position, and interaction among them. This reveals how design decisions directly impact hydraulic safety and performance under different operational scenarios. This practical application reinforces the importance of proper engineering design and maintenance in ensuring dam safety and its structural performance, offering actionable insights for future dam design and rehabilitation.

In terms of the structure of the thesis, and in order to ensure both coherence between its various sections and alignment with its well-defined objectives, the writing has followed, in chronological order, the chapters listed below:

Chapter I: Dam failure statistics

Chapter II: Importance of the waterproofing system for the safety of dams

Chapter III: Importance of drainage system for dam safety

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Chapter IV: Analysis of hydraulic behavior in a dam using GeoStudio: the effect of waterproofing on seepage and stability, case of Boughrara dam

Chapter V: Analysis of drainage systems influence on dam's behaviour

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## **Chapter I: Dam failure statistics**

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### I.1. Introduction

Historical dam failures have significant implications for safety, environmental health, and engineering practices. An analysis of various studies reveals that these failures often stem from a combination of natural and human-induced factors, including seismic activity, design flaws, and operational mismanagement. Understanding these failures is crucial for improving future dam safety and management practices.

### I.2. Definition of dam failure

A dam failure is the collapse or movement of part of a dam or its foundation, such that the dam cannot retain water. In general, a failure results in a release of large quantities of water imposing risks on the people or property downstream. (ICOLD, 2015)

It is a catastrophic type of structural failure characterized by the sudden, rapid, and uncontrolled release of impounded water. A very rare but not impossible risk, it refers to the partial or total destruction of the structure as a result of:

- A natural hazard: for example, an earthquake, an exceptional flood, or a landslide.
- A technical issue: such as a malfunction or structural defect.
- Human error or a malicious act.

Depending on the specific characteristics of each dam, the failure can be:

- Gradual: Earthen dams, for instance, may experience erosion after an extreme flood or due to a leak, leading to breaches and eventually the collapse of the structure.
- Sudden: The abrupt failure of part of a dam can generate a wave similar to a tsunami.

The consequences can be severe:

- For populations: drowning, burial under debris.
- For property: destruction and damage to buildings, infrastructure, and engineering structures (bridges, roads).
- For the environment: destruction of flora and fauna, loss of arable land, various forms of pollution, etc. (Ministère de la Transition écologique, 2023)

### I.3. Types of dam failure

According to Costa 1987, types of dam failures can be classified into 3 parts

- Group G – global failures leading to complete dam collapse.
- Group L – local failures leading to local defects.
- Group P – failures leading to loss of serviceability.

Global failures represent the worst-case scenario. Both local failures and loss of serviceability mainly involved operational restrictions. Failure from both groups L and P may lead to global failure if they are not dealt with.

#### I.3.1. Concrete dam failures

The list of failures of concrete dams were assembled including the historical documented cases. Basic types of failure correspond with both ultimate limit states and serviceability limit states. (Hariri, 2014)

#### I.3.2. Collapse of dam blocks

Collapse of dam blocks belongs to the group of global failures and is caused by block sliding, block uplifting or block overturning. These failures can be described as sudden and entire failure of structure. (Nahyan, 2022)

#### I.3.3. Foundation failures

The foundation failure belongs into group of global failure. The progress of foundation failure depends on both strength and resistance of foundation material and also on hydraulic gradient. Piping occurrence is necessarily precedent by local exceeding of bearing capacity of foundation. The progress of the piping is indicated by both pressure and seepage regime changes. (Lemos, 2011)

### I.4. Analysis of dam failures

#### I.4.1. Overview of dam failures in the 21st century

A comprehensive analysis identified 53 operational dam failures in the 21st century, with most incidents occurring in intermediate, non-aging dams. Human-related factors were identified as the primary causes. (Nasser et al, 2024)

### I.4.2. Landslide dam failures

A study analyzing 1267 landslide dam failures revealed that 91.8% failed due to overtopping. The failure rate was highest shortly after formation, with 87% failing within one year and 51% failing within a single day. (Limin, 2024)

### I.5. Statistics analysis of dam failures

#### I.5.1. Total failures

Dam failures, though relatively rare, can have catastrophic consequences. Between January 2005 and June 2013, the United States recorded 173 dam failures and 587 incidents that could have led to failures without intervention. (Association de la sécurité des barrages, 2019)

Globally, approximately 15% of dams face damage, failure, or emergency situations annually, with earth dams accounting for about 70-75% of these cases. (Al-Ansari et al, 2020)

As of 2024, many of the world's 70,000+ dams are aging and increasingly vulnerable to failure due to the rising frequency and severity of extreme weather events linked to climate change. (Micha and Yassir, 2024)

While 15% of dams worldwide face damage or emergency conditions annually, historical records indicate that at least 1600 dams have failed over time, with earth dams comprising 70% comprising of these. (Zhang, 2007)

The causes of these failures are multifaceted, often linked to human error, design flaws, and environmental factors exacerbated by climate change.

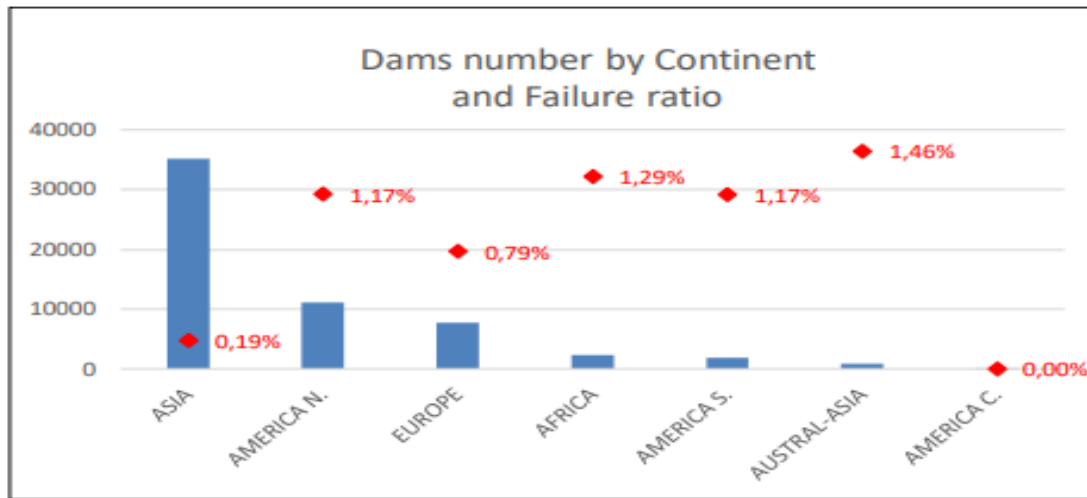
#### I.5.2. Dam failures across continents

Dam failures have been documented across all continents, with varying frequencies relative to the number of existing dams in each region. According to data from the International Commission on Large Dams (ICOLD), the ratio of failed dams to existing dams by continent is as follows:

- Asia: 0.19%
- North America: 1.17%
- Europe: 0.79%
- Africa: 1.29%
- South America: 1.17%

- Australasia: 1.46%

Figure I.1 shows the number of dams by continent and failure ration.



**Figure 1.1:** Number of large dams by continent and failure ratio (ICOLD, 2019)

These statistics indicate that, despite having a large number of dams, Asia has a relatively lower failure ratio compared to other continents. In contrast, regions like Australasia and Africa exhibit higher failure ratios. It's important to note that these figures are based on available data, and actual numbers may vary due to underreporting or differences in data collection methods. (ICOLD, 2019)

A more recent study analyzing global dam failures in the 21st century compiled a dataset of 53 operational dam failures, highlighting that these incidents have occurred across all six continents. The study emphasizes that human-related factors are the predominant causes of these failures, underscoring the need for improved management and maintenance practices worldwide. (Nasser et al, 2024)

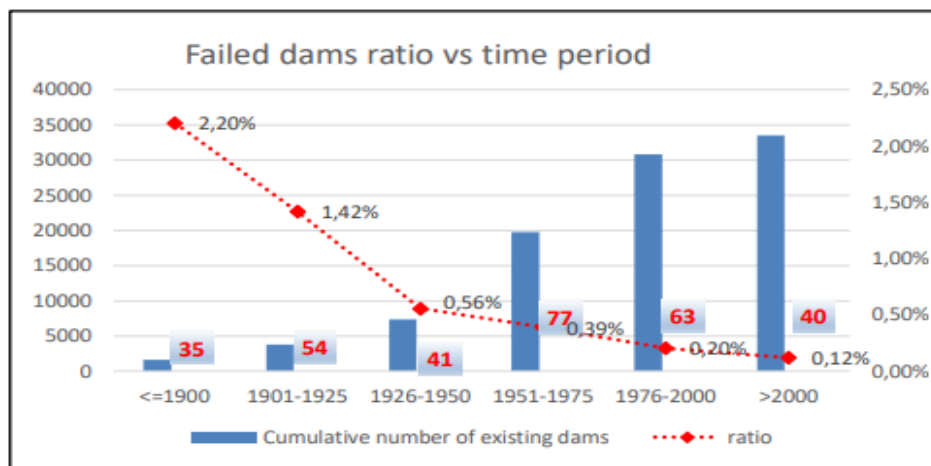
### I.5.3. Effect of time on the probability of the failure

The registered dam failures over 25-year periods are presented below. The data indicate a clear decreasing trend in the failure ratio over time. The accompanying table and figure provide a summary of these data, illustrating the relationship between the cumulative number of existing dams and the evolution of the failure rate as shown in table I.1.

**Table I.1:** Dam failures by time periods and ratio with existing dams (ICOLD, 2019)

Time Period	≤1900	1901-1925	1926-1950	1951-1975	1976-2000	>2000
Cumulative Number of Existing Dams	1588	3808	7375	19724	30829	33470
Failed Dams	35	54	41	77	63	40
Failure Ratio (%)	2.20%	1.42%	0.56%	0.39%	0.20%	0.12%

Figure I.2 shows the dam failures by time periods and ratio with the existing dams.



**Figure I.2:** Dam failures by time periods and ratio with existing dams (ICOLD, 2019)

The highest number of dam failures was recorded between 1950 and 1975, with 77 failures. Since then, the number of failures has declined, though it remains notable, with 40 failures reported between 2000 and 2018. However, due to the increasing number of dams, the failure ratio has shown a continuous and encouraging decrease. Notably, 87% of recorded failures occurred in dams built before 1975, while only 13% involved dams constructed after this period. Despite the number of failures after 2000 still being significant, the overall trend indicates a steady decline in failures since the 1950-1975 period. (ICOLD, 2019)

#### I.5.4. Effect of the dam age on failure

The time span between a dam's construction year and its failure year (i.e., the dam's age at failure) is a crucial factor in assessing structural integrity. An analysis was conducted to compare dams that failed within the first five years of operation including failures during

## Chapter I: Dam failure statistics

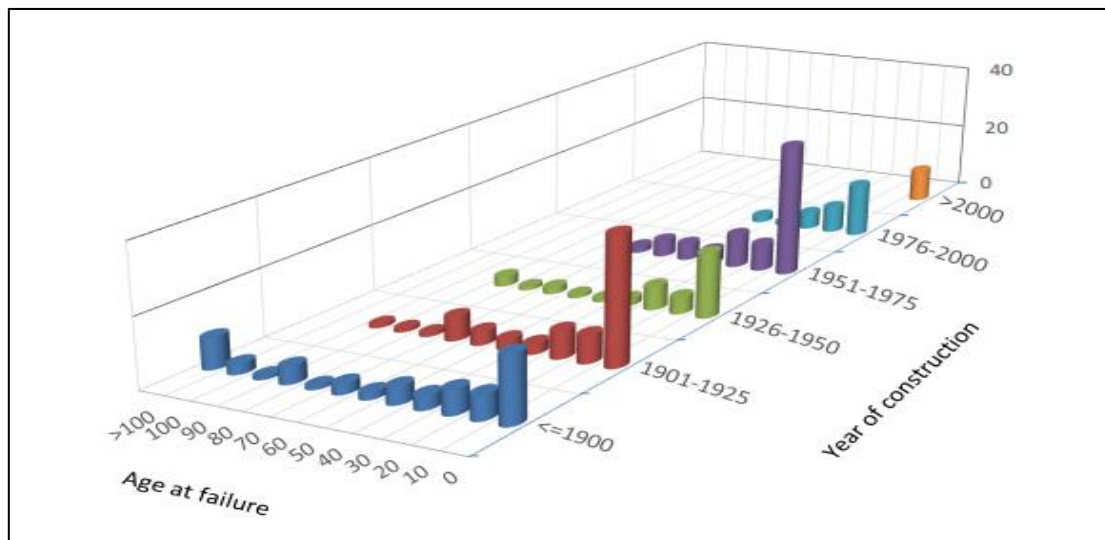
construction, initial impoundment, or early operational years with the total number of failed dams within the same time period. The findings are summarized in the following table I.2.

**Table I. 2 :**Ratio of failures occurring during the first 5 years versus total number of failures (ICOLD, 2019)

Year of Construction	≤1900	1901-1925	1926-1950	1951-1975	1976-2000	>2000
Ratio of Failures During First 5 Years of Operation vs. Total	30%	51%	46%	59%	59%	100%

With the exception of dams built before 1900, the ratio of failures occurring within the first five years of operation is consistently around 50%. This supports the commonly accepted observation that approximately half of all dam failures occur within this critical early period. Notably, all recorded failures of dams constructed after 2000 have occurred within their first five years of operation.

Figure I.3 provides a more detailed analysis by categorizing the age of failed dams in ten-year intervals, relative to their construction period. This refinement offers deeper insight into the relationship between a dam’s construction era and the timeframe in which failures occur.



**Figure I.3:** Age of failure versus year of construction (ICOLD, 2019)

The first ten years represent the period with the highest number of failures. However, for dams built between 1900 and 2000, a significant number of failures continued to occur within the first 30 years of operation. Additionally, older dams remain susceptible to failure, as aging

infrastructure naturally deteriorates if not properly maintained and upgraded. For dams constructed after 2000, it is still too early to draw definitive conclusions regarding long-term failure trends. (ICOLD, 2019)

### I.5.5. Effect of dam height on the probability of failure

Dam height significantly influences failure probability due to structural stress, water pressure, and overtopping risks. Taller dams face greater hydrostatic pressure and a higher risk of overtopping during extreme inflows, especially if spillway capacity is insufficient. Since overtopping can lead to structural collapse, rigorous design, maintenance, and monitoring become increasingly critical as dam height increases. (Us army corps of engineers, 1972)

- The analysis is more meaningful when considering height ranges rather than absolute height values.

The following table I.3 defines the height ranges and presents the number of existing and failed dams within each category.

**Table I.3:** Failures versus dam height (ICOLD, 2019)

Height Range (m)	Existing Dams	Failed Dams	Failure Ratio (%)
< 15 m	6,984	45	0.64%
15 – 30 m	18,831	188	1.00%
30 – 50 m	5,570	52	0.93%
50 – 75 m	2,218	22	0.99%
75 – 100 m	866	3	0.35%
> 100 m	761	1 (*)	0.13%
Total	35,230	311	0.88%

Figure I.4 shows the number of dam existing and ratio of failed categorized by height classes.

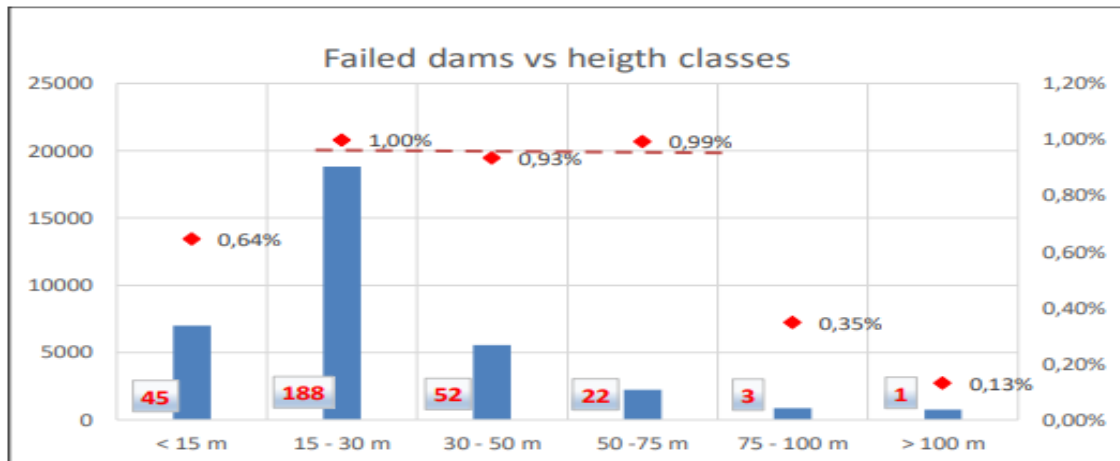


Figure I.4: Failures versus dam height (ICOLD, 2019)

The failure ratio remains around 1% for dams between 15 and 75 meters, while smaller dams (<15 m) may have underreported failures. For taller dams (>75 m), failure rates decrease significantly due to better design, construction, and maintenance. Failures are nearly nonexistent for dams over 100 meters, with the Vajont Dam being a unique case of external disaster rather than structural failure. Overall, failure risk declines sharply as dam height increases. (ICOLD, 2019)

### I.5.6. Failure distribution by containment capacity

Figure I.8 and table I.4 present the number of dam failures categorized by reservoir volume range, along with the failure ratio relative to the number of existing reservoirs within each volume range.

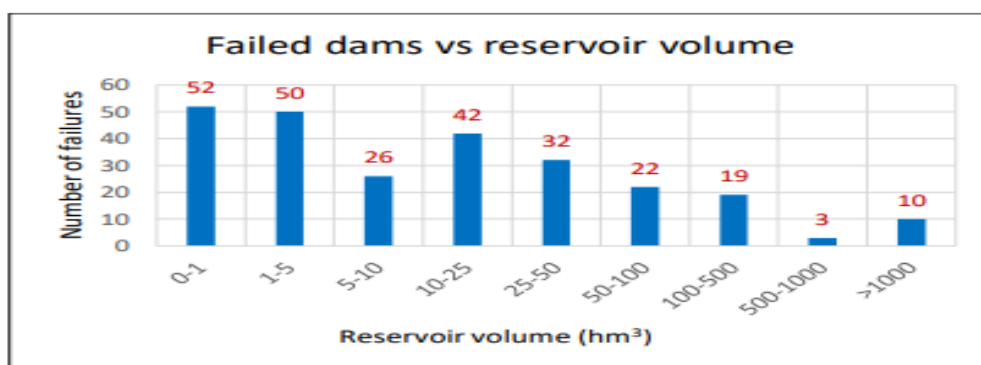


Figure I.5: Failure versus reservoir volume (ICOLD, 2019)

**Table I. 4:** Failures by reservoir volume range and failure ratio (ICOLD, 2019)

Reservoir Volume Range (hm <sup>3</sup> )	Existing Dams	Failed Dams	Failure Ratio (%)
0 – 1	9,474	52	0.55%
1 – 5	9,980	50	0.50%
5 – 10	3,527	26	0.74%
10 – 25	3,340	42	1.26%
25 – 50	1,836	32	1.74%
50 – 100	1,518	22	1.45%
100 – 500	2,291	19	0.83%
500 – 1000	551	3	0.54%
> 1000	1,143	10	0.87%

### I.6. Statistical analysis of causes of failure

#### I.6.1. Increase in dams and reduction in failures

- By 1950, there were approximately 5,000 large dams worldwide.
- By the end of the 20th century, this number increased to 45,000 dams.
- Advancements in technology and stricter safety regulations have reduced the failure rate from 2.2% (before 1995) to 0.5% today. (Al-Ansari et al, 2020)

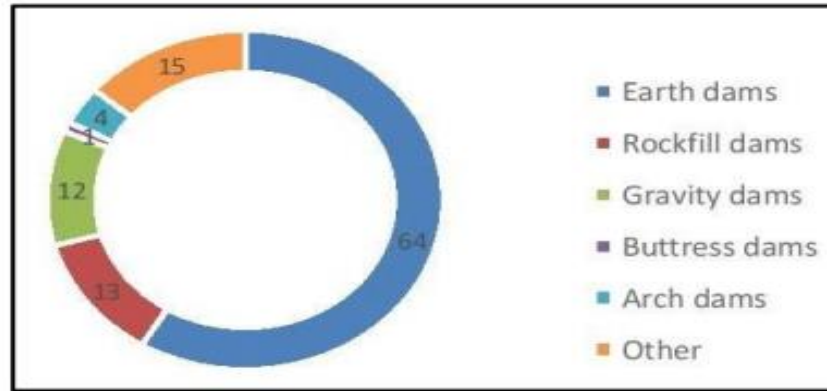
#### I.6.2. Types of dams and their failure rates

The figure I.6 below presents a pie chart showing the distribution of different dam types worldwide, excluding China. The proportions are as follows:

1. Earth dams: 64% represent the most common type in the world, indicating a preference for this design due to cost-effectiveness and adaptability.
2. Rockfill dams: 13% representing a significant portion, likely due to their resilience against seismic activity.
3. Gravity dams :12% are popular for their ability to resist water pressure through their own weight.
4. Buttress dams: 4% are less common, possibly due to higher construction costs.
5. Arch dams: 4% are used mainly in narrow, rocky valleys for structural efficiency.

## Chapter I: Dam failure statistics

6. Other types: 15% are a mix of different designs adapted to specific site conditions.



**Figure I.6:** Percentage of all types of dams in the world, excluding China (Al-Ansari et al, 2020)

- Embankment dams make up 77% of all dams worldwide:
- 64% are earth-fill dams.
- 13% are rock-fill dams.
- Concrete dams and other types make up the remaining 32%.
- Due to their construction materials and weaker foundations, embankment dams account for the majority of failures. (Al-Ansari et al, 2020)

The table I.5 below shows the number existing dams with failed dams and the failure ratio according to the dam type.

**Table I. 5:** Dam failures by type and failure ratio (Al-Ansari et al, 2020)

Dam Type	Existing Dams	Failed Dams	Failure Ratio (%)
VA – Arch	890	6	0.67%
CB – Buttress	340	8	2.35%
MV - Multi Arch	105	4	3.81%
PG – Gravity	5,571	46	0.83%
ER – Rockfill	2,378	33	1.39%
TE – Earth fill	21,977	209	0.95%
BM – Barrage	224	0	0.00%
XX - Unknown	715	5	0.70%

Dam Type	Number of Failed Dams
Arch	6
Buttress	8
Multi Arch	4
Gravity	46
Rockfill	33
Earthfill	209
Barrage	0
unknown	5

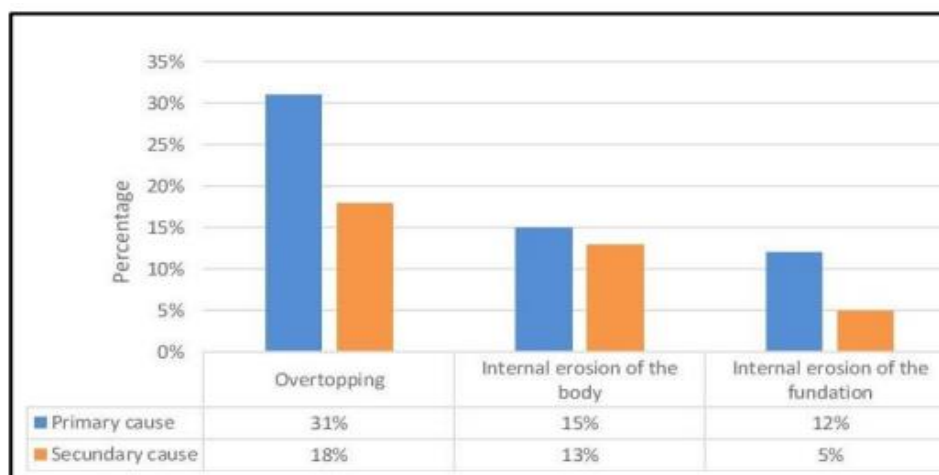
### I.6.3. Main causes of embankment dam failures

A 1998 study by Foster, Fell, and Spannagel analyzed large embankment dam failures using data from the ICOLD World Register, which includes 11,192 dams. Of the 136 recorded failures, 121 were due to hydraulic issues. Piping was identified as the leading cause, with half of these failures linked to conduits in the dam body or foundation. Nearly 50% of embankment piping failures occurred during first filling and 64% within the first five years, while 25% of foundation piping failures happened during first filling and 75% within the first five years.

The most common causes of dam failures are:

- Overtopping (35.9%) often due to inadequate spillways.
- Piping (internal erosion) (46.1%) occurs when water erodes soil inside the dam body or foundation.
- Structural failures for example: sliding, foundation failure less common, but still significant.
- Earthquakes/liquefaction (1.6%) rare, but highly destructive.
- About 50% of piping failures occur during the first filling of the reservoir, and 64% within the first five years of operation. (Al-Ansari et al, 2020)

Figure I.7 and the table I.6 illustrate and clarify the statistics above, the primary and secondary causes of embankment dam failures.



**Figure I.7:** Causes of failures in embankment dams (Al-Ansari et al, 2020)

**Table I. 6:** Summary of embankment failures (Al-Ansari et al, 2020)

Mode of failure	Number of cases		Percent failure (where known)	
	All failures	Failures in operation	All failures	Failures in operation
Overtopping	46	40	35.9	34.2
Spillway/ gate	16	15	12.5	12.8
Subtotal	62	55	48.4	47.0
Piping through embankment	39	38	30.5	32.5
Piping through foundation	19	18	14.8	15.4
Piping from embankment into foundation	2	2	1.6	1.7
Subtotal	59	57	46.1	48.7
Slides	7	5	5.5	4.3
Earthquakes/ Liquefaction	2	2	1.6	1.7
Unknown	8	7		
Total number of failures	136	124		

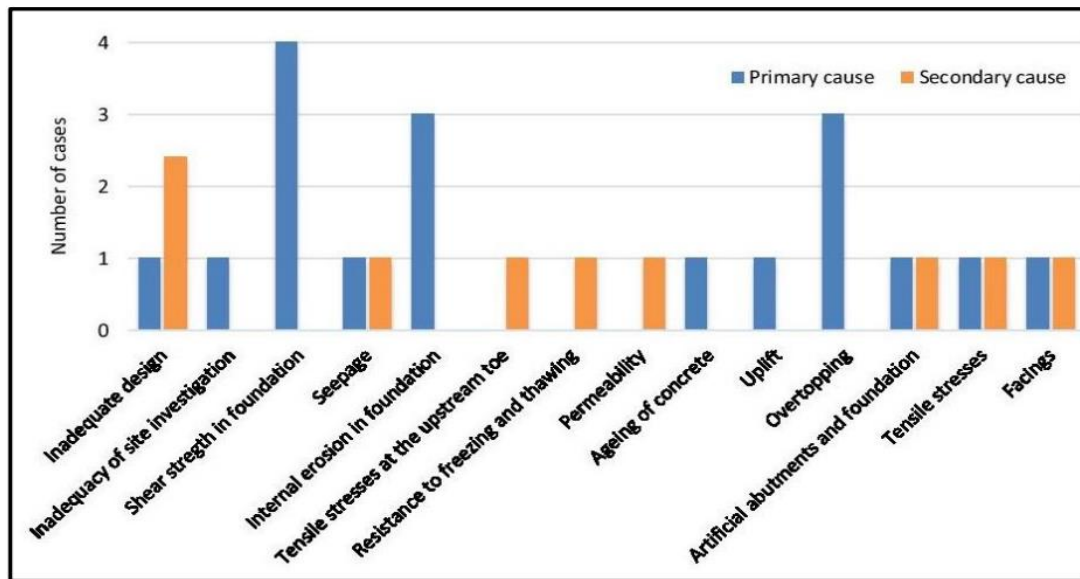
#### **I.6.4. Main causes of concrete dams' failure**

Failures in concrete dams are often related to:

- Poor design (structural weaknesses).
- Foundation issues (seepage, uplift pressure).
- Aging and permeability problems.
- Over 30% of concrete dam failures are due to overtopping or structural weaknesses.

## Chapter I: Dam failure statistics

Figure I.8 and table I.7 illustrate and clarify the statistics above, the primary and secondary causes of embankment dam failures. (Al-Ansari et al, 2020)



**Figure I.8:** Main causes of failure of concrete dams. (Al-Ansari et al, 2020)

**Table I. 7:** Main causes of failure of concrete dams (Al-Ansari et al, 2020)

	Details	Number of Cases	
		Primary Cause	Secondary Cause
Design	Inadequate design	1	14
Foundation	Inadequacy of site investigations	1	
	Shear strength of foundations	4	
	Seepage in foundations	1	1
	Internal erosion in foundations	3	
	Tensile stresses at the upstream toe		1
	Resistance to freezing and Thawing		1
Dam	Uplift	1	
	Permeability of concrete		1
	Aging of dam	1	
	Overtopping	3	
	Tensile stresses	1	1
	Facing	1	1

**I.6.5. Historical trends in large dam failures**

- According to a 1998 study analyzing 11,192 dams found that 136 large dams failed, with 121 attributed to hydraulic problems (mostly overtopping and piping).
- Internal erosion (piping) is responsible for nearly 50% of all embankment dam failures.
- Failures often occur in the early years of a dam’s life, highlighting the importance of proper design and first-filling precautions.

While these statistics underscore the risks associated with dam failures, it is essential to recognize that advancements in engineering and monitoring techniques can significantly mitigate these risks, enhancing overall dam safety. (Al-Ansari et al, 2020)

**I.7. Notable case studies**

Table I.8 shows different cases of dam failures around the world, illustrating the causes of the failure and number of victims.

**Table I. 8:** Cases of dam failures around the world

Date	Country	Dam Name	Cause of Failure	Number of Victims	Explanation of Failure
March 12, 1928 (Outland, 1977)	United States	St. Francis Dam	Geological instability and design flaws	~450	The dam collapsed due to inadequate foundation on unstable rock, releasing a massive flood.
December 2, 1959 (Londe, 1987)	France	Malpasset Dam	Geological fault and foundation failure	423	A tectonic shift caused the dam to rupture, leading to a catastrophic flood downstream.
August 11, 1979 (India, 1980)	India	Machchhu Dam II	Excessive rainfall and overtopping	~1,800–15,000	Heavy monsoon rains caused the dam to overtop and fail, flooding the surrounding area.
June 5, 1976 (Coleman, 2004)	United States	Teton Dam	Seepage and erosion of the dam core	11	Poor construction and inadequate sealing led to internal erosion and eventual collapse.

## Chapter I: Dam failure statistics

October 9, 1963 (Genevois, 2005)	Italy	Vajont Dam	Landslide into the reservoir	~2,000	A massive landslide caused a wave to overtop the dam, flooding the valley below.
November 9, 1977 (Associates-Wahler, 1978)	United States	Kelly Barnes Lake Dam	Poor maintenance and overtopping	39	Heavy rainfall caused the dam to overtop and fail, releasing a destructive flood.
September 10, 2023 (BBC-News, 2023)	Libya	Derna Dams (Abu Mansour & Al Bilad)	Extreme rainfall from Storm Daniel, poor maintenance, and structural weakness	Over 11,300 deaths, thousands missing	Heavy rainfall caused both dams to collapse, releasing floodwaters that destroyed large parts of Derna city. Years of neglect and lack of repairs contributed to the failure.

### I.8. Ways to reduce dam failures

#### 1.8.1. Use of trap bags

- Trap bags are used to reinforce dams and also to divert water from threatened areas. Trap Bags can be arranged to block and redirect water, saving communities costly repairs later.
- Infrastructure support: Trap Bag barriers can be placed in or around dams as a form of leak-resistant stabilization to prevent floods during heavy rainstorms, mitigating extensive damage, expensive repairs, and loss of employment.
- Dams & levees: Reliable dams are crucial in the event of natural disaster-induced flooding. Levees are water barriers that prevent floodwaters from infiltrating elevated surfaces, like roadways and agricultural plots. The leak-resistant structure of Trap Bags makes them the ideal solution for protecting people and property during a dam break.
- Diversion walls: During floods that occur after a dam breaks, displaced earth can smash into infrastructure, commercial properties, and homes, injuring people and leaving structural

damage in their wake. Trap Bags can be filled with concrete to build sturdy, protective walls that block and divert debris, keeping people and their property safer. (Trapbag, 2024)

### **I.8.2. Public outreach**

(FEMA, 2017) Public outreach should be taken to raise awareness about risk and to spread information as needed on improved planning, preparedness, mitigation, and recovery operations. Outreach actions can be performed by dam owners, emergency management personnel, dam safety officials, homeowner associations, and other stakeholders to increase dam risk awareness and facilitate coordination during emergency events.

Public outreach should be used for:

- a. Raise awareness of dam safety issues, facilitate cooperation, and provide a forum for the exchange of information.
- b. Provide information on the potential risks of living downstream of a dam and what actions have been taken to mitigate the risks.
- c. Help communities upstream and downstream of dams and communities that could be impacted by dam failure (e.g., loss of water for firefighting activities if they rely on a reservoir) to better understand their risk in order to be better prepared during an emergency.
- d. Dams should be technically approved at planning design and construction stages.
- e. Safety of the dam is ensured at the planning and construction stages through multilayered permits and approvals from the River Management Offices and third-party agencies The River Law stipulates that facilities located on the river should be safe in terms of water level, discharge, topography, geology, and expected loads such as dead weight and water pressure. (Dam Managemet , 2025)

### **I.9. Management and training**

Improving the professionalism and training of dam managers ensures better operational oversight and emergency can provide insights into its future response, allowing for better design and reinforcement strategies. (Charrak , 2023)

#### **I.9.1. Soil treatment techniques**

Improving the mechanical characteristics of the ground and modifying underground flows can significantly enhance the quality of dam foundations. Techniques include reducing permeability beneath hydraulic structures. (Charrak, 2022)

### I.9.2. Optimizing injection curtains

The design of injection curtains, including parameters like depth, position, number, inclination, and spacing, is crucial. Numerical modeling can help optimize these parameters to enhance the efficiency of the injection process. (Charrak, 2022)

### I.9.3. Control of seepage

Maintaining seepage characteristics below critical levels (flow rates, pore pressures, hydraulic gradients) is essential, as seepage is responsible for over 35% of earth dam accidents. (Charrak, 2022)

### I.10. Conclusion:

Dam failures, while relatively rare, pose significant risks to human life, infrastructure, and the environment. Through statistical analysis, this study has shown that failures are influenced by multiple factors, including structural weaknesses, foundation instability, extreme weather events, and human error. Despite improvements in engineering and safety regulations, failures continue to occur, particularly in aging dams and those exposed to inadequate maintenance.

The analysis of dam failures over time reveals a positive trend: while the number of dams worldwide has increased, the failure rate has steadily declined due to enhanced design standards, stricter safety measures, and improved risk management practices. However, the persistence of failures, particularly in embankment and concrete dams, underscores the need for continuous monitoring, predictive maintenance, and public awareness efforts.

To further reduce the likelihood of dam failures, future efforts should focus on adopting advanced monitoring technologies, improving soil treatment techniques, and enhancing risk perception among stakeholders. Strengthening regulations, investing in infrastructure resilience, and implementing proactive maintenance strategies will be essential to ensuring the long-term safety and reliability of dams worldwide.

By understanding historical failure patterns and addressing key risk factors, engineers and policymakers can develop more effective strategies to prevent future disasters, ultimately safeguarding communities and ecosystems that rely on these critical water structures.

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**Chapter II: Importance of the waterproofing system  
for the safety of dams**

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### II.1. Introduction

Dams play a very important role in water management, energy generation, and flood control. Water seepage is one of the challenges dam structures faces, which can lead to erosion, weakening of the foundation, and even catastrophic failure. Waterproofing systems are important in maintaining the safety, durability, and efficiency of dams by preventing water infiltration and controlling seepage. This chapter explores the importance of waterproofing, the various types and materials used, internal and external waterproofing techniques, foundation treatments, and recent advancements in waterproofing technologies. By understanding and implementing effective waterproofing measures, engineers can enhance dam resilience, minimize maintenance costs, and ensure long-term water resource sustainability.

### II.2. The role of waterproofing in dam safety

Waterproofing is necessary to ensure the safety and durability of dams since it minimizes seepage, enhances structural stability, and decreases maintenance expenses. Various materials and methods such as clay cores, geomembranes, and grouting are employed for effective waterproofing. Failures can, nevertheless, arise due to poor design, poor installation, aging of the materials, or damage due to differential settlement or earthquakes. A compromised waterproofing system leads to free seepage, high pore pressure, internal erosion, and structural deterioration, which, if undetected, will accumulate to total dam failure. (Cazzuffi et al, 2009)

- **Impervious Layers:** The use of impermeable materials like concrete and waterproof coiled layers significantly reduces permeability, improving resistance to frost and environmental stressors. (Xuanying, 2018)
- **Multilayer Structures:** Combining rigid and flexible waterproofing layers enhances overall performance against seepage and erosion, increasing dam longevity. (Shaofei, 2018)
- **Reinforcement and Buffering:** High-strength dams incorporate reinforcement layers and buffering materials to absorb water pressure, preventing moisture penetration and structural weakening. (Liu et al., 2023)
- **Structural Integrity:** Seepage control is essential to prevent erosion, material degradation, and potential dam failures, ensuring long-term stability. (Guosheng, 2019),

- Water Conservation: Effective waterproofing maximizes water retention in reservoirs, supporting irrigation, domestic water supply, and sustainable resource management. (Mioduszewski, 2012).

While waterproofing is essential for dam safety and efficiency, environmental impacts and long-term maintenance must also be considered to ensure sustainable water management.

### II.3. Bernoulli's equation and its application in dams

Waterproofing in dams and Bernoulli's equation are connected through fluid dynamics and seepage control. Bernoulli's principle helps in understanding how water moves through and around a dam, while waterproofing methods are designed to control this movement and prevent seepage-related damage.

$$P + \frac{1}{2}\rho v^2 + \rho gh = \text{constant}$$

where:

- $P$  = Pressure energy (Pa).
- $\rho$  = Water density ( $\text{kg/m}^3$ ).
- $v$  = Velocity of the water (m/s).
- $g$  = Gravitational acceleration ( $\approx 9.81 \text{ m/s}^2$ ).
- $h$  = Elevation head (m).

Application of Bernoulli in dams:

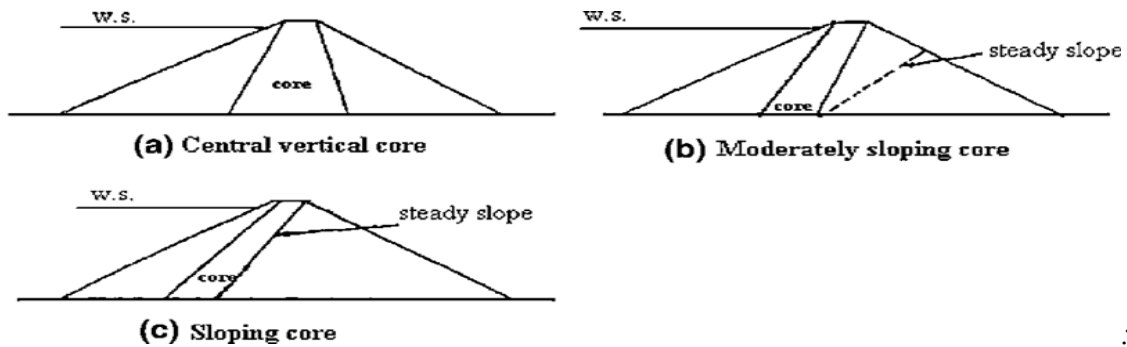
$$Z + \frac{p}{\rho g} = \text{constant}$$

## II.4. Internal waterproofing systems

Waterproofing systems in dams play a crucial role in controlling seepage, ensuring structural stability, and preventing failures. Internal waterproofing methods use low-permeability materials like clay, bitumen, and geosynthetics to form barriers inside the dam structure.

### II.4.1. Core-based waterproofing

Figure 1 Different types of central clay core.

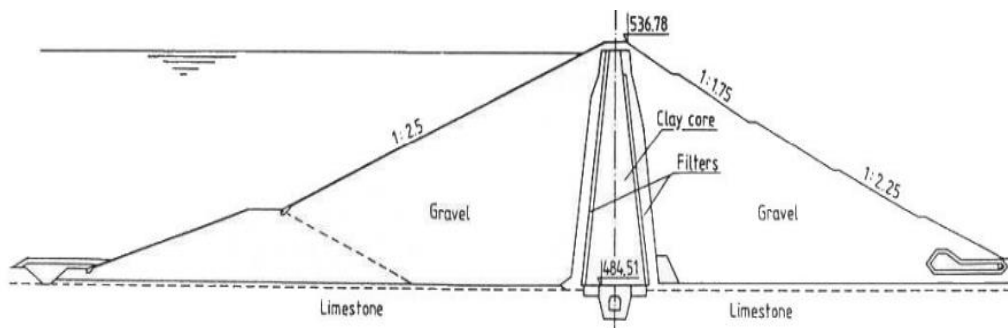


**Figure II.1:** Core shapes and their location in embankment dams' sections (Mirali, 2011)

Core-based waterproofing systems use low-permeability cores made of clay or asphalt to block water movement inside the dam.

#### 1. Central clay core

A central clay core is a vertical impermeable layer built within an embankment dam to prevent seepage. It is surrounded by rockfill or compacted soil to provide structural support. (USSD, 2011)



**Figure II.2:** Dam with a central clay core (Skutnik, 1997)

## Chapter II: Importance of the waterproofing system for the safety of dams

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The clay to be used has to have very low permeability that ranges between  $10^{-6}$  to  $10^{-8}$  m/s. The core can be relatively thin when the foundation consists of rock. This means that it is rigid, effectively prevents water seepage, and resists erosion well. These thin cores do not affect the stability of dikes, which is an advantage. (Amara and Dib, 2020)

a. Equation (permeability calculation): Permeability is the ability of a material to allow fluid to pass through it. In dam engineering, low permeability is essential to minimize water leakage, prevent piping and internal erosion.

b. Clay cores (darcy's law 1856)

$$Q = k \times A \times i$$

Where:

- $Q$  = Seepage flow rate
- $k$  = Permeability coefficient of the clay
- $A$  = Cross – sectional area of the dam core
- $i$  = hydraulic gradient it is equal to  $\frac{\Delta H}{L}$  ,

where:

$\Delta H$ = Difference hydraulic head.

$L$ = Seepage path length.

From this equation the permeability is derived which is equal to  $k = \frac{Q}{A i}$ .

Low permeability in central clay core is controlled by:

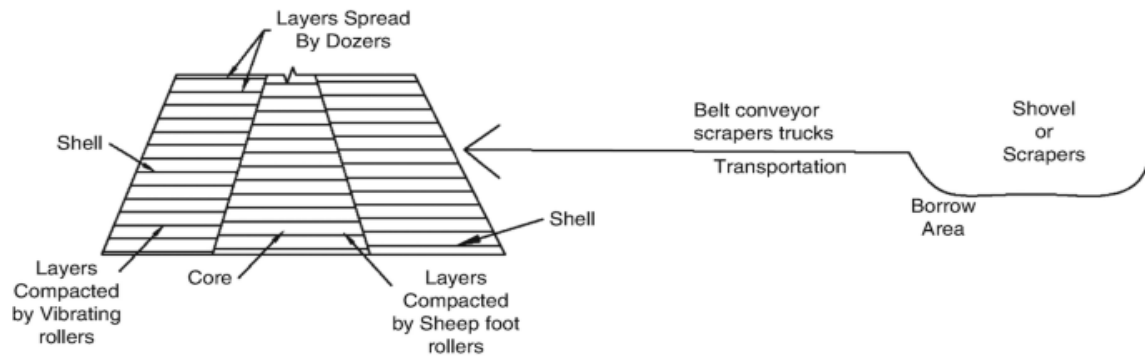
Using fine-grained clay with high plasticity.

Proper compaction to reduce voids.

Moisture control to avoid cracks and shrinkage. (Cambridge Press, 2009)

c. Compaction

Compaction is the process of increasing soil density by reducing air voids, which improves strength and reduces permeability. The figure below shows different compacted layers.



**Figure II.3:** Compaction process of embankment dam with the central clay core (Asthana et al, 2022)

- Compaction Density Equation (Standard Proctor Test):

$$\gamma_d = \frac{\gamma_m}{1 + \omega}$$

Where:

- $\gamma_d$  = Dry unit weight (compacted density).
- $\gamma_m$  = Moist unit weight.
- $w$  = Moisture content.

(ASTM, Standard Proctor Test)

Clay cores must be compacted to  $\geq 95\%$  Standard Proctor density and each layer of clay is placed in 15-30 cm thickness before compaction. (USSD, 2011) the compaction is very important for the global stability of the dam because it prevents cracking due to shrinkage, increases shear strength, ensures uniform permeability and avoiding concentrated seepage paths. (Narita, 2000)

#### d. Seepage control measures

Seepage control is achieved using granular filter layers (sand or gravel) around the clay core to prevent piping and erosion. -Coarse gravel (drainage layer) allows water to escape safely. -Fine sand filter prevents clay particles from eroding. (Cazzuffi et al, 2009)

#### e. Filter criteria (Terzaghi's soil retention equation):

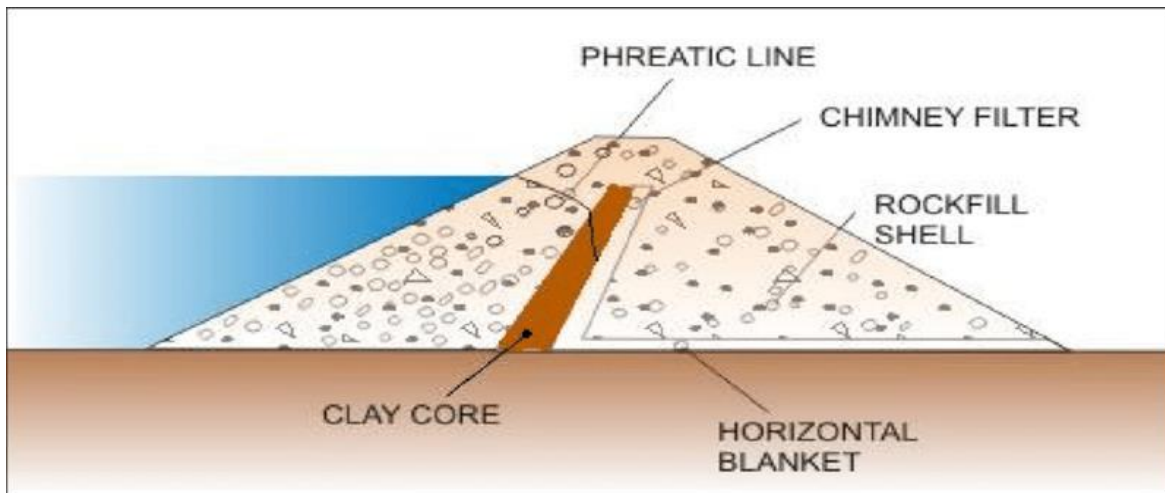
$$D_{15} \leq 4 \times d_{85}$$

- $d_{85}$  = Particle size of the core material at 85% finer.
- $D_{15}$  = Particle size of the filter at 15% finer. (Terzaghi, 1943)

- Granular filters are placed adjacent to the clay core to prevent fine particles from washing away. (USSD, 2011) filters are very important because they prevent internal erosion by stopping fine particles from moving this relieves excess water pressure and protecting dams against failure.

### 2. Inclined Clay Core

An inclined clay core is a waterproofing barrier positioned closer to the upstream face rather than at the center. It is designed to improve stability and efficiency. Figure II.4 below illustrates a dam with inclined clay core.



**Figure II.4:** Inclined clay core. (Bentaher, 2012)

The granulometry of core materials should be continuous, ranging from clay ( $<0.002$  mm) to sand ( $<2$  mm). A well-graded and uniform granulometry enhances self-sealing but simultaneously increases the risk of liquefaction. To optimize performance, selecting materials with a high plasticity index is recommended. Since the core functions as a barrier against water seepage, it must be composed of impermeable materials with a permeability coefficient of  $10^{-6}$  m/s or lower. Clayey silts, characterized by low to medium plasticity and a liquid limit below 50%, should contain at least 5% clay to ensure minimal permeability. Additionally, morainic materials are advantageous when they include more than 15% silt and over 2% clay, contributing to improved impermeability. (Pougatsch et al, 2011)

### a. Set up of an inclined core

The thickness of an inclined core positioned in the upstream of the dam should be 1/6 the height of the structure never less than 2m. Towards the top, the core must be mounted above the highest water and practically, taking into account capillary rise, up to the crest of the dam. The layers should lay at 15-30 cm, compacted to achieve  $\geq 95\%$  Standard Proctor Density using rollers and moisture content should be monitored to avoid shrinkages which lead to cracks.

Inclined clay core is important to reduce differential settlement, improving dam stability also it shortens the seepage path, making water resistance more efficient. And reduces stress on the core during earthquakes. (Salmasi et al, 2020)

### b. Drainage & filtration

- Install downstream drainage layers to relieve water pressure.
- Place sand filters to prevent erosion and material displacement. (Narita, 2000)

### c. Equation for seepage through inclined cores: (Sazzad et al, 2015)

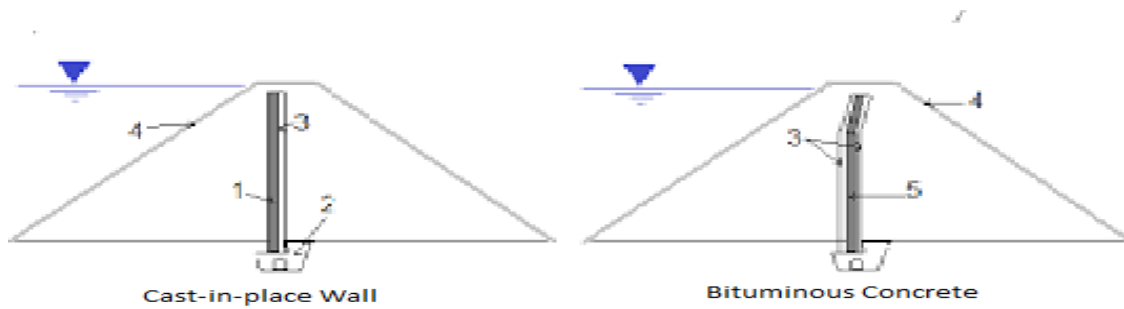
$$L_{\text{eff}} = \frac{L}{\cos(\theta)}$$

Where:

- $L_{\text{eff}}$  = Effective seepage path length.
- $L$  = Core thickness.
- $\theta$  = Inclination angle.

## II.4.2. Internal waterproofing membranes

Internal waterproofing membranes act as artificial seepage barriers made from bituminous materials or diaphragm walls.



**Figure II.5:** Embankment dams with central membranes (Amara and Dib, 2020)

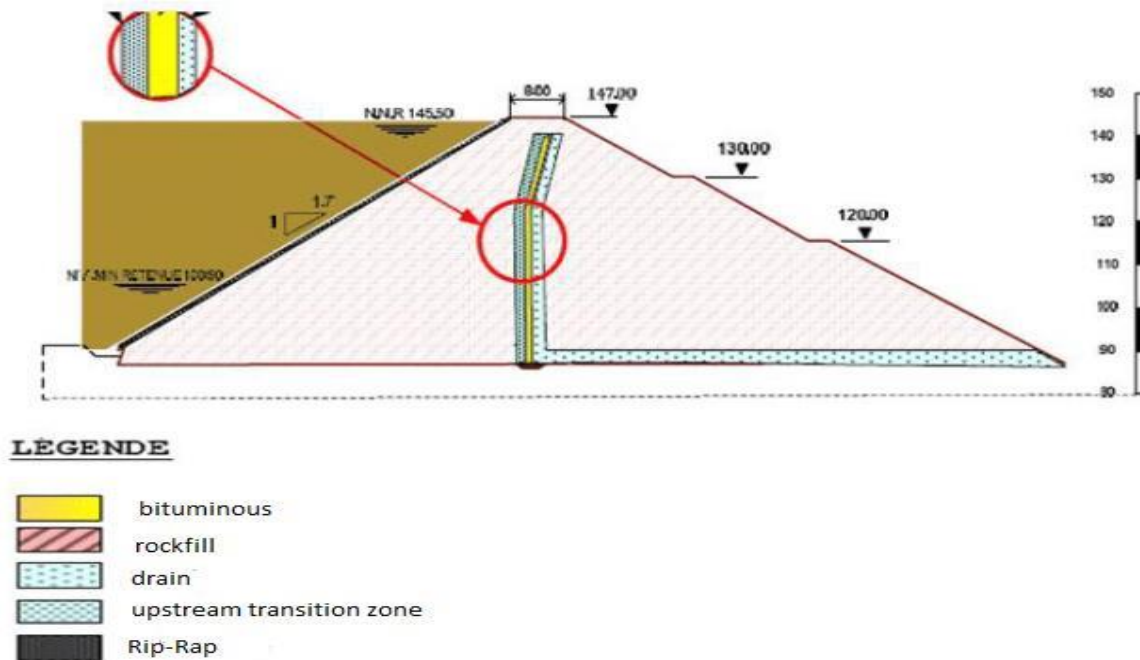
1): Membrane (Bentonite + Cement) 2): Injection Gallery 3): Transition Zones 4): Surface Protection 5): Bituminous Membrane

The central membrane solution is an interesting alternative when suitable clay materials for constructing a watertight core are not available near the construction site. The main implementation methods for this internal membrane are:

- A bituminous core ( $e_{\min} = 50 \text{ cm}$ ;  $H/e \leq 120$ ).
- A dry diaphragm wall ( $e_{\min} = 80 \text{ cm}$ ).
- Sheet piles, particularly for cofferdams and lateral dikes along a watercourse.

(Pougatsh et al, 2011)

### 1. Composition of bituminous core



**Figure II.6:** Dam with bituminous waterproofing system (Bendjema and Benmbarek, 2015)

The bituminous concrete mix used for the core consists of bitumen, filler, sand, and gravel, following a continuous granulometry based on the Fuller-Thompson formula:  $D (\%) = (d/d_{\max})^{1/2}$ . The maximum grain diameter ( $D_{\max}$ ) is typically 16 or 22 mm but should not exceed 40 mm or 1/5 of the layer thickness to facilitate placement and minimize segregation.

A bitumen content of around 6% by weight is sufficient to fill voids, with slight adjustments (+0.2 to 0.5%) to improve workability and flexibility. The optimal dosage is determined through void content tests and triaxial tests to assess mix behavior.

The filler plays a crucial role in filling voids, enhancing binder viscosity, and reducing segregation risks. For optimal performance, a consistent-quality filler should be used. (Pougatsh et al, 2011)

### 2. Construction & implementation techniques

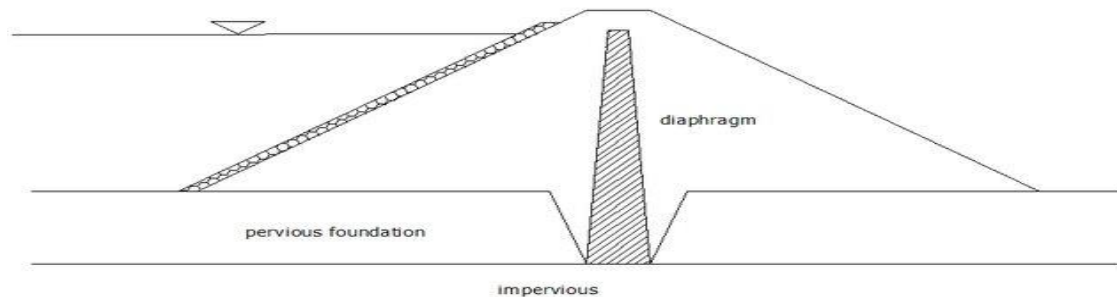
The construction of an embankment dam with a bituminous core requires specialized companies with proper equipment and high-quality control standards. The bituminous core and transition

zones are placed in 20 cm layers using a paver, with bitumen compacted at 160–180°C to prevent seepage into filters.

Different construction methods exist, including the stone and bitumen method, successfully applied in Norwegian dams. This technique uses crushed stones leveled in thin horizontal layers (0.2–0.3 m) before hot bitumen is pumped in to fully saturate the voids. To avoid air or water entrapment, filling starts from one end and advances gradually. (Pougatsh et al, 2011)

### II.4.3. Diaphragm walls as a waterproofing barrier

The diaphragm wall is an effective solution for addressing sealing issues in embankment structures, ensuring complete impermeability. In areas with soft soil, it can be extended deeper to reach a more compact zone. However, this method is only suitable for low-height dams due to the rigidity of diaphragm walls, which can cause problems in case of settlement or earthquakes.



**Figure II.7:** A cross section of a dam with a diaphragm as a waterproofing (Sirwan, 2013)

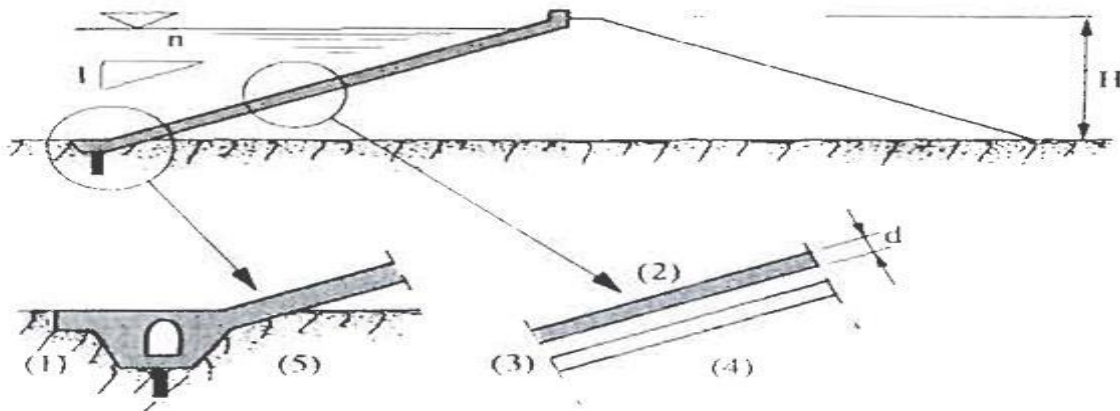
The general principle consists of installing a central diaphragm wall from the crest once the embankment is completed. This wall extends through the entire embankment and the soft part of the foundation. The trench, which is 0.80 to 1 meter wide, is filled with a self-hardening slurry (bentonite, cement, water). This technique requires that the surrounding material is not too permeable to prevent excessive slurry losses, which could lead to the risk of wall collapse. (Amara and Dib, 2020)

### II.5. Upstream facing

Upstream facing is used to prevent infiltration, leakage and damage. Innovation has played its role to enhance the waterproofing systems in dams hence ensuring their durability and reliability. In the case of an insufficient quantity of materials for constructing a clay core, the solution of a watertight element in the form of an upstream face lining on the surface can be considered. For medium- to large-height dams ( $H > 50$  m), the materials used today for the face are mainly:

- A reinforced concrete slab poured in successive sections over the entire upstream surface.
- One or more layers of bituminous concrete.

For low-height dams, flexible synthetic membranes are used, typically thick PVC sheets supplied in rolls and welded together. For low-height dams, flexible synthetic membranes (geomembranes) are also used, typically thick PVC sheets supplied in rolls and welded together. The sheets are laid on a transition layer of fine material to prevent tearing of the membrane, which would otherwise rest directly on the rockfill, and are protected by slabs or paving stones. (Pougatsh et al, 2011)



**Figure II.8:** Upstream face (Pougatsh et al, 2011)

- 1). Plinth 2). Upstream mask of thickness  $d$  -3). Support and transition zones 4). Support body-5). Rock foundation

### II.5.1. Concrete face waterproofing

On rock filled dams a reinforced concrete slab is constructed on the upstream face of the dam the concrete slab serves as sealing element on the upstream side of the dam. There are fibers that are used to enhance concrete faced rockfill dams such as polypropylene, MEXO200 and steel. (Payam, 2019)

For concrete masks: The slope of upstream face should be between 1.35 to 1.40 is used for unaltered rock foundations.

The thickness of the upstream face be equal to 35 to 45 cm.

The reinforcement is between 0.3% to 0.4%. (Pougatsh et al, 2011)

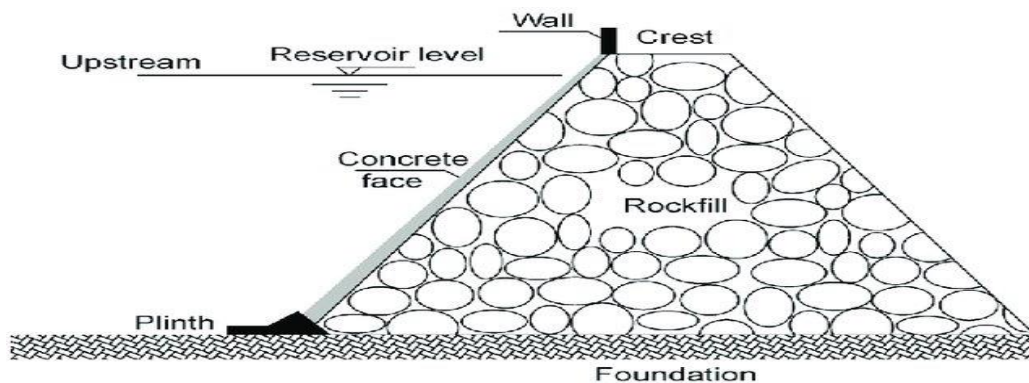


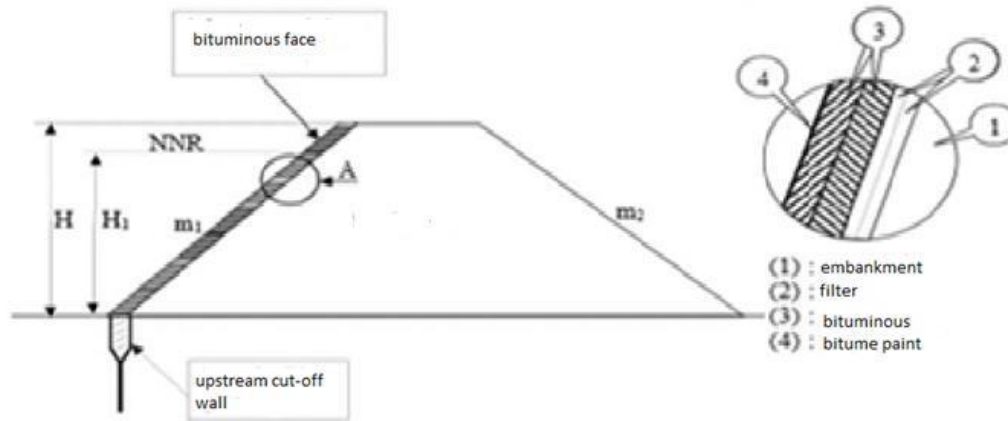
Figure II.9: Rockfill dam with a concrete face (Do Rocio Marconcin, 2018)

### II.5.2. Bituminous facing

Bituminous concrete facing is a cost-effective water barrier for embankment dams, offering advantages over traditional earth core and reinforced concrete facings. It allows for a pore pressure-free embankment, reducing seepage and rapid drawdown effects while enabling easy inspection and maintenance after reservoir drawdown. Its flexibility accommodates embankment deformation, and it performs well under seismic conditions. Suitable for both coarse-grained and compressible embankments, it can be placed on steep slopes using modern construction techniques. (ICOLD, 1999)

For bitumen masks the maximum slope of bituminous face should be 1.70 to 1.75 is chosen for construction feasibility. The thickness of the face is defined as  $H/300$  when  $H > 30$  m.  $H$  is the

height of the dam. The maximum height should be equal to 75 m suggests that this method is suitable for dams up to this height. (Pougatsh et al, 2011)

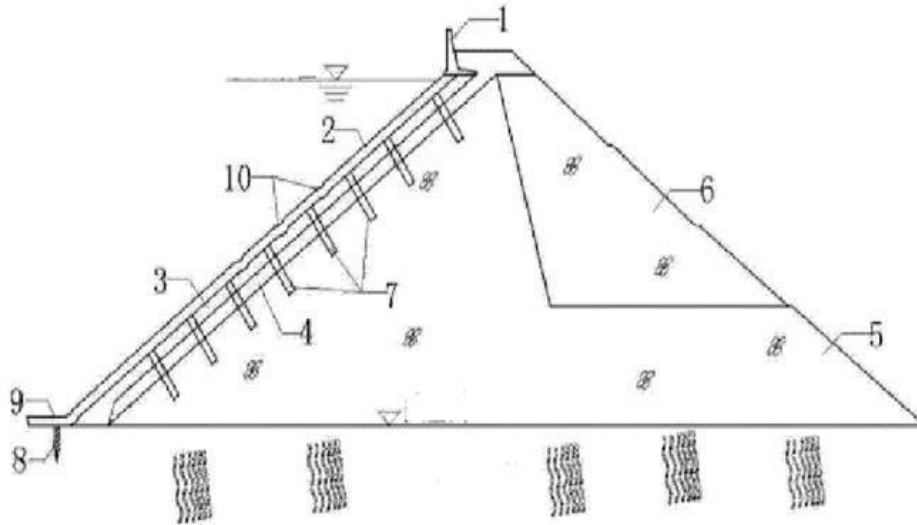


**Figure II.10:** Upstream bituminous face (Amara and Dib, 2020)

### II.5.3. Steel upstream face

Steel membrane system panel is designed for rockfill dams, providing both waterproofing and structural reinforcement. The steel membrane panel is welded into a single unit using polyolith steel plates, which are prefabricated with grooves for deformation induction located either in the middle or at the edges to manage structural stresses. Structurally, the system includes a reinforced concrete wave wall and a reinforced concrete toe board, ensuring additional stability. One end of the steel membrane panel extends into the wave wall at the dam crest and is welded to internal reinforcement bars, while the other end stretches into the toe board at the bottom of the dam, also welded to reinforcement bars. The sides of the membrane panel are further anchored into both dam shoulders for improved structural integrity. To prevent corrosion, the panel surface above the dead water level is coated with epoxy anticorrosive paint, while the submerged sections are equipped with anodic protection. The steel plate thickness ranges from 6 mm to 20 mm, and each deformation induction groove has a width and depth of 10 cm, with three horizontal and vertical grooves in the middle and one groove along the periphery for additional flexibility. To enhance stability, 30 mm diameter anti-skid bars are welded between the steel plates, each with a length of 10 m. The dam itself has a height of 100 m, a crest width of 10 m, and a wave wall height of 1.5

m, with an upstream slope of 1:1.4 and a downstream slope of 1:1.3. This design ensures effective seepage control, structural flexibility, and long-term durability against environmental and mechanical stresses. (Lian et al, 2013)



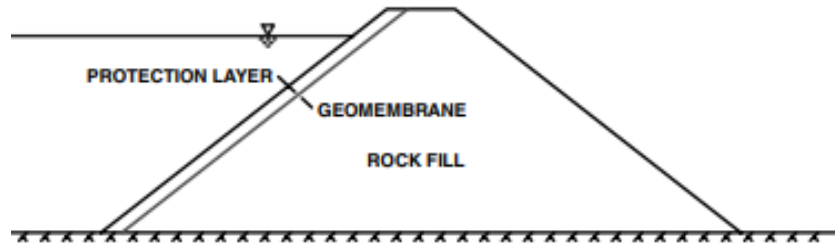
**Figure II.11:** Steel upstream face (Lian et al, 2013)

1. Crest Structure: The topmost part of the dam.
2. Steel Upstream Face: A steel membrane panel placed on the upstream side.
3. Stiffeners: Reinforcement elements for structural stability.
4. Anchoring System: Provides stability to the steel face.
5. Downstream Slope: The sloped face on the downstream side.
6. Rockfill Body: The main mass of the dam made of rockfill.
7. Toe Board: Lower structural support at the base of the upstream face.
8. Foundation Connection: Connects the structure to the base.
9. Sealing/Waterproofing Layer: Ensures watertight integrity.
10. Additional Reinforcement Bars: Used to strengthen the structure.

### II.5.4. Polyvinyl chloride (PVC) upstream face

Geomembranes have been used in earth fill dams since 1959 for water tightness due to their low permeability. The most common types are PVC (Polyvinyl Chloride) and HDPE (High-Density Polyethylene), which are stronger and have a higher friction angle than alternatives like CSPE and

EPDM. A high friction angle between the geomembrane and surrounding soil is crucial for stability, especially on slopes. These properties make geomembranes an effective solution for enhancing dam performance and preventing seepage. (Erlingsson, 2009)



**Figure II.12:** Geomembrane (PVC) upstream face (Erlingsson, 2009)

Friction between a geomembrane and its surrounding soil is highly dependent on the surface characteristics of the geomembrane. It is also dependent on various properties of the soil. Therefore, it is necessary to have good understanding of the interaction between the soil and the membrane. A friction coefficient between the two layers can be defined as:

$$E = \frac{\tan(\delta)}{\tan(\phi)}$$

Where  $\delta$  is the friction angle between a geomembrane and its surrounding soil and  $\phi$  is the friction angle of the soil. (Erlingsson, 2009)



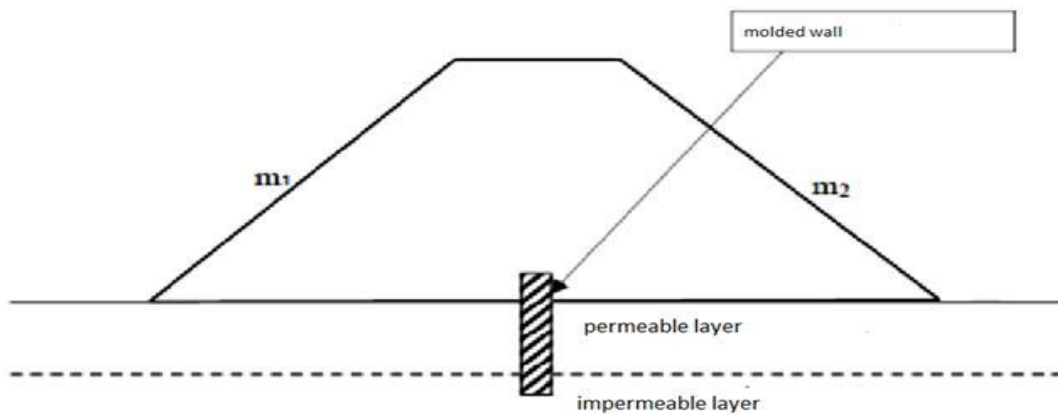
**Figure II.13:** Installation of membrane (Amara and Dib, 2020)

### II.6. Foundation waterproofing system

Foundation is lower part of the dam which transmits the weight to the ground and also to the valley floor and abutments. Various types of waterproofing system are used to improve strength reduce seepage, prevent piping, improve rock mass resistance and minimize differential settlement in order to provide stability of the dam. (Renolit, 2025)

#### II.6.1. Molded walls

Molded walls are vertical barriers built from the foundation surface through excavation without shoring. The excavations are then filled with self-hardening bentonite-cement grout or plastic concrete, creating a waterproof structure. This technique is suitable for soft soils and rock foundations, where advanced methods like hydro fraise technology can be used. (Amara and Dib, 2020)



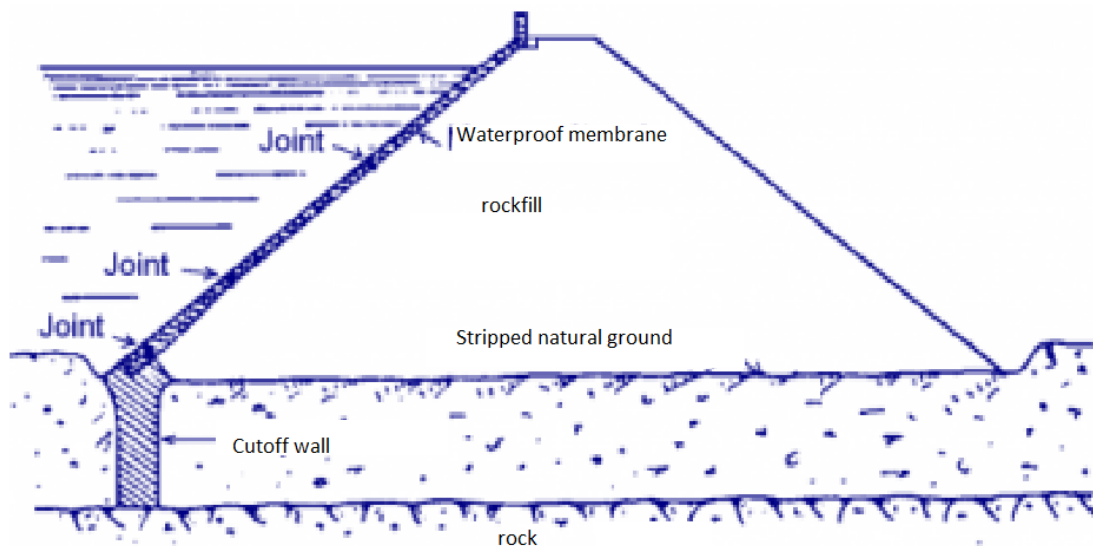
**Figure II.14:** Molded wall foundation waterproofing (Ouandjeli, 2018)

1. Molded walls use concrete panels (5–6 m long, 0.5–0.6 m wide) and are built using mechanical grabs or hydro fraise, ensuring deep foundation waterproofing.
2. Plastic concrete walls are made with bentonite, cement, aggregates, and water, offering flexibility and waterproofing. Their high deformability and low cement ratio (0.15–0.25) improve stability.
3. Grout walls use self-hardening slurry, which remains fluid before gradually solidifying, creating a waterproof and flexible barrier. Mineral additives enhance durability and impermeability. (Amara and Dib, 2020)

### II.6.2. Cut off wall

Impermeable trenches ensure sealing by cutting through permeable layers and anchoring into an impermeable substrate, mainly when the impermeable layer is thin. It is divided into three types: (Amara and Dib, 2020)

- Deep Trench with Compact Clay: A 0.8 m wide trench, excavated mechanically in 5–10 m sections, is backfilled with compacted clay, ideal for deep sealing (5–8 m).
- Bulldozer Pre-Trench with Manual Deepening: A 0.2 m clay layer, compacted manually, allows additional deepening (up to 1.5 m) if unexpected permeable layers appear. Cost-effective but stability remains a challenge.
- Narrow Deep Trench with Bentonite-Cement Grout: A 0.6–0.8 m trench, excavated in 5–10 m panels, is immediately filled with grout, preventing drying and cracking using polyane sheets. (Amara and Dib, 2020)



**Figure II.15:** Cut off wall (Ouandjeli, 2018)

### II.6.3. Injection curtains

Injections are an effective method to limit seepage and uplift pressure. This process involves injecting self-hardening grout into permeable or semi-permeable materials through drilled holes. It is suitable for both soft soil foundations and fractured rock masses. The materials used include bentonite-cement grouts, special grouts, resin, and silicate gel.

#### 1. Types of injection grouts

##### i. Cement suspension grouts

- Stabilized with bentonite to reduce sedimentation and improve penetration.
- Stable grouts: Dense, high mechanical resistance.
- Unstable grouts: Cement-water mix that settles quickly; 1-2% bentonite added for stabilization. (Amara and Dib, 2020)

Grout composition follows these equations (Amara and Dib, 2020)

- Water-cement ratio:  $E = \frac{\text{Cement}}{\text{water}}$
- Sand/cement ratio:  $C = \frac{\text{Sand or Inert filter}}{\text{Cement}}$
- Clay/cement ratio:  $c = \frac{\text{Clay}}{\text{cement}}$

##### ii. Liquid grouts (silicate-based) (Amara and Dib, 2020)

- Colloidal solutions that form gels upon reaction with acids.
- Reagent concentration:  $\alpha = \frac{\text{weight of reagent}}{\text{volume of silicate}}$
- Dilution ratio:  $\beta = \frac{\text{volume of water}}{\text{volume of silicate}}$

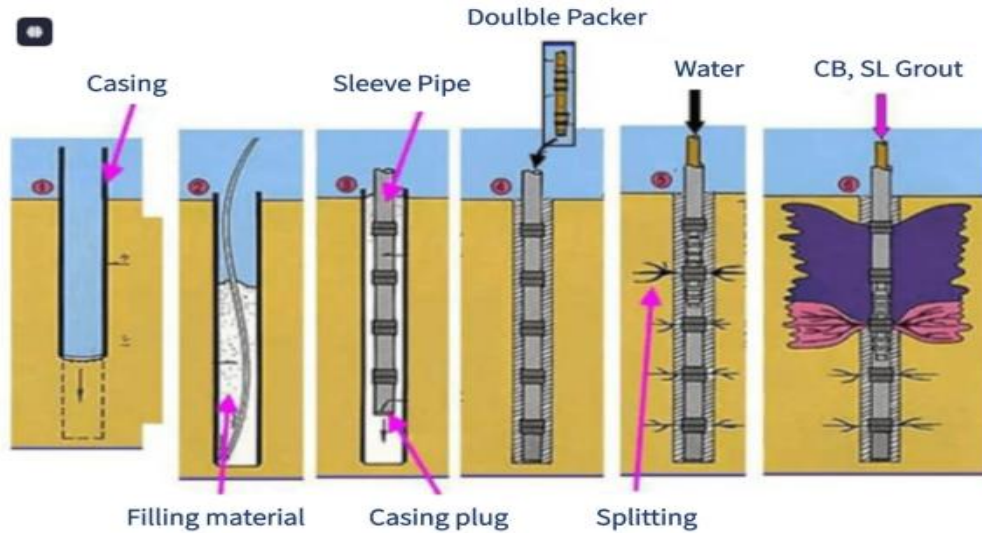


Figure II.16: Grout curtain construction process (jines Construction Co, 2020)

### iii. Resins

High viscosity, polymerizing liquids, effective but costly and require careful handling.

Suitable for very fine cracks but not widely used due to advancements in silicate gel technology. (Amara and Dib, 2020)

### 2. Reasons for implementing injection curtain

- Fractured rocks: which is used to seal fissures in rock foundations.
- Injection in alluvial soils: multiple of the lines are required for effectiveness in embankment dams and one line for concrete dams. They are parallel to the dam's axis for efficiency.
- Cavity filling injection: used for karst cavities with bentonite cement grouts.

The injection pressure should be controlled according on foundation type and grout properties, excessive pressure can cause fissure or uplifts. (Amara and Dib, 2020)

### 3. Depth of the sealing curtain

Depends on geology and dam height, typically between 35% to 100% of the dam height, with a minimum of 50m. The depth of the injection curtain is calculated using:

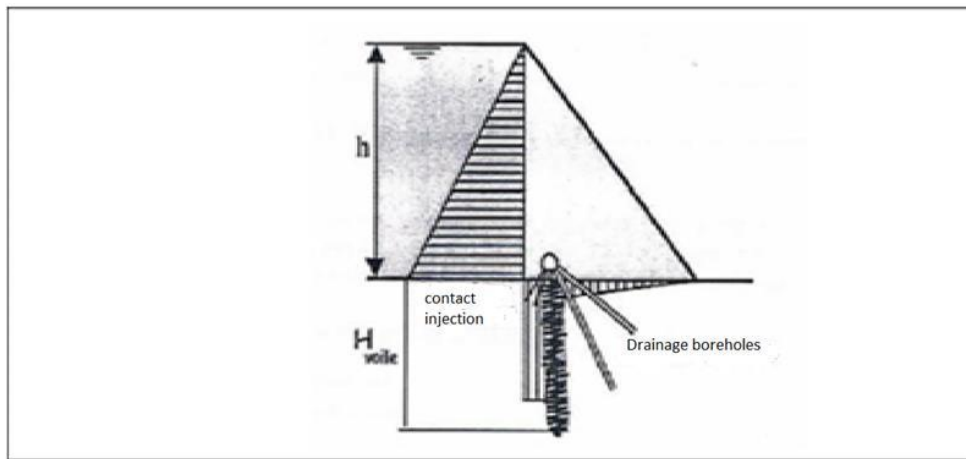
$$H_{voile} = \frac{1}{3}H + c$$

where:

- $H$  = Height of the dam.
- $C$  = Coefficient (varies between 8m and 25m).

The injection can be vertical or inclined, depending on foundation characteristics.

A polar diagram is used to optimize orientation to intersect the maximum number of fissures. (Amara and Dib, 2020)



**Figure II.17:** Depth of injection (Amara and Dib, 2020)

### II.7. Conclusion

Waterproofing is a very important aspect of dam safety, protecting structures from seepage-induced failures and extending their lifespan. The effectiveness of waterproofing systems depends on the appropriate selection of materials, techniques, and maintenance strategies. Advances in nanotechnology, real-time seepage monitoring, and innovative waterproofing materials continue to improve the reliability and efficiency of these systems. As climate change and increasing water demands put additional pressure on dam infrastructure, the development and implementation of advanced waterproofing solutions will be important in ensuring sustainable and secure water management.

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## **Chapter III: Importance of drainage system for dam safety**

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### III.1. Introduction

The drainage system has developed into a standard component for all types of dams. It has proven to offer an efficient, economic and versatile tool for a wide range of purposes as there is mainly safe handling of seepage water inside embankments dams, controlling of seepage gradients in foundations and managing the hazards of internal erosion and piping. It also helps stabilize the downstream slopes of dams and prevents waterlogging.

### III.2. Hydraulic parameters affected by the drainage system

Internal erosion results from the detachment and transport of material under the effect of water flow, in the dam body or foundation. When the transport is concentrated bedload in a conduit, it is called a piping. When the transport is diffuse throughout the solid matrix and only involves suspended fines, it is called suffusion. These two fundamental concepts define the hydraulic gradient and the critical seepage velocity. They occur at all stages of grain removal or transport. A drainage system has a direct impact on hydraulic parameters according to Darcy's Law. Proper drainage reduces seepage forces, controls interstitial pressure, and provides stability for the soil structure. (Amara and Dib, 2020)

#### III.2.1. Flow velocity:

The flow velocity of water in a soil mass depends on the geometry of the soil pores open to water circulation and also on the differences in hydraulic head between points in the mass. The relationship between flow velocity and hydraulic head in a one-dimensional flow was determined experimentally in 1856 by Darcy, who studied the flow rate of water in a tube filled with sand. Darcy measured both the pressure drop between the two ends of the pipe and the corresponding filtration rate when steady-state flow was reached. A device similar to that used by Darcy. Darcy's law is written as:

$$v = k \frac{\Delta h}{\Delta l} = ki$$

Where:

v: Flow velocity (filtration rate).

i: Hydraulic gradient.

k: Coefficient of proportionality, called the permeability coefficient (m/s) characterizes the soil's ability to be crossed by a fluid. (Bencherrat and Mostefa kara, 2018)

Permeability varies depending on the nature of the soil as showing in table III.1.

**Table III. 1:** Order of magnitude of soil permeability (Horsin , 2016)

Permeability	Order of Magnitude of the Permeability Coefficient k (m/s)	Soil Type
Very High	$10^{-1}$ to $10^{-2}$	Medium to coarse gravels
Fairly High	$10^{-3}$ to $10^{-5}$	Small gravels, sands
Low	$10^{-5}$ to $10^{-7}$	Very fine sands
Very Low	$10^{-7}$ to $10^{-9}$	Silt
Practically Impermeable	$10^{-9}$ to $10^{-12}$	Compact clay

### III.2.2. Flow rate

This relationship, known as Darcy's law, can be expressed as:

$$Q = k.i.s$$

Where:

Q: Flow rate through the sample.

s: Cross-section of the soil sample.

Darcy's law was generalized by Schlichter to the case of three-dimensional flow in a homogeneous and isotropic soil, in the form:

$$\vec{v} = k.\vec{i} = -k.\text{grad } h$$

Where:

$\vec{v}$ : Flow velocity vector, v (x, y, z, t).

$\vec{i}$ : Hydraulic gradient vector, i (x, y, z, t).

k: Soil permeability coefficient (k constant in homogeneous media).

h: Hydraulic head h (x, y, z, t).

In an isotropic soil, the flow velocity is therefore parallel to the hydraulic gradient, which is itself normal to the equipotential surfaces of the flow. Consequently, the flow velocity is normal to the equipotential surfaces. (Bencherrat and Mostefa kara, 2018)

### III.2.3. Hydraulic gradient

The hydraulic gradient is a function of the spatial coordinates of the point M considered. The hydraulic gradient, in its general formulation, is the vector defined as:

$$\vec{i} = -\overrightarrow{\text{grad}} h$$

The hydraulic gradient between two points (A and B) is:

$$i = -\frac{\Delta h}{\Delta l} = \frac{A - B}{l}$$

With  $l$  is the distance between these two points. (Bencherrat and Mostefa kara, 2018)

### III.2.4. Factor of safety (Fos)

To prevent internal erosion of a dam, the observed gradient ( $i$ ) under the dam must remain below the critical gradient ( $i_c$ ) by applying a safety factor such that  $i \ll i_c$ . In practice, it is recommended to apply a safety factor (Fs) of at least 3. (Seepage pressure, 2024)

$$\text{Fos} = \frac{i_c}{i} \geq 3$$

### III.2.5. Lane's coefficient (C)

As the length  $l$  increases in the equation  $i=H/l$ , the hydraulic gradient  $i$  decreases, this increasing safety with respect to the critical gradient, the length  $L$  of the pathways is the essential parameter. Lane established an equation that is used for the calculation of dams. (Amara and Dib, 2020)

$$L_v + \frac{L_h}{3} \geq C \times H$$

$L_v$  : vertical seepage length.

$L_h$  : horizontal seepage length.

$H$ : hydraulic head difference.

$C$ : safety coefficient (Lane's coefficient).

$i = \frac{H}{l}$  where  $l$  is the total seepage path so after Lane's coefficient:

$$\frac{H}{L_v + \frac{L_h}{3}} \leq \frac{1}{C} \rightarrow i_{\max} = \frac{1}{C}$$

Lane's coefficient depending on soil type

Table below III.2 shows Lane's coefficient depending on soil type.

**Table III. 2:** Lane's coefficient in different types of soil (Amara and Dib, 2020)

Soil Type	C
Fine sands and silts	8.5
Fine sands	7
Medium sands	6
Coarse sands	5
Small gravel	4
Coarse gravel	3
Mixture of gravel and large pebbles	2.5
Plastic clay	3
Stiff clay	2
Hard clay	1.8

### III.2.6. Hydraulic critical gradient ( $i_c$ )

The phenomenon of boiling figure III.1 occurs when the water flow is upward and the pressure of the flow, combined with the buoyant force (Archimedes' thrust), cancels out the weight of the soil particles. This is generally only possible if the soil is fine and powdery. By opposing the weight of the grains, this component can reach values that allow the grains to float. (Amara and Dib, 2020)

This phenomenon occurs when the hydraulic gradient  $i$  is upward, causing the grains to be carried away by the water. The critical hydraulic gradient  $i_c$  is defined as the value for which the resultant of forces is zero, meaning the soil grains are on the verge of being carried away.

$$i_c = \frac{\gamma'}{\gamma_w}$$

For earth dams, the risk of uplift exists if significant seepage occurs through the foundation soil.

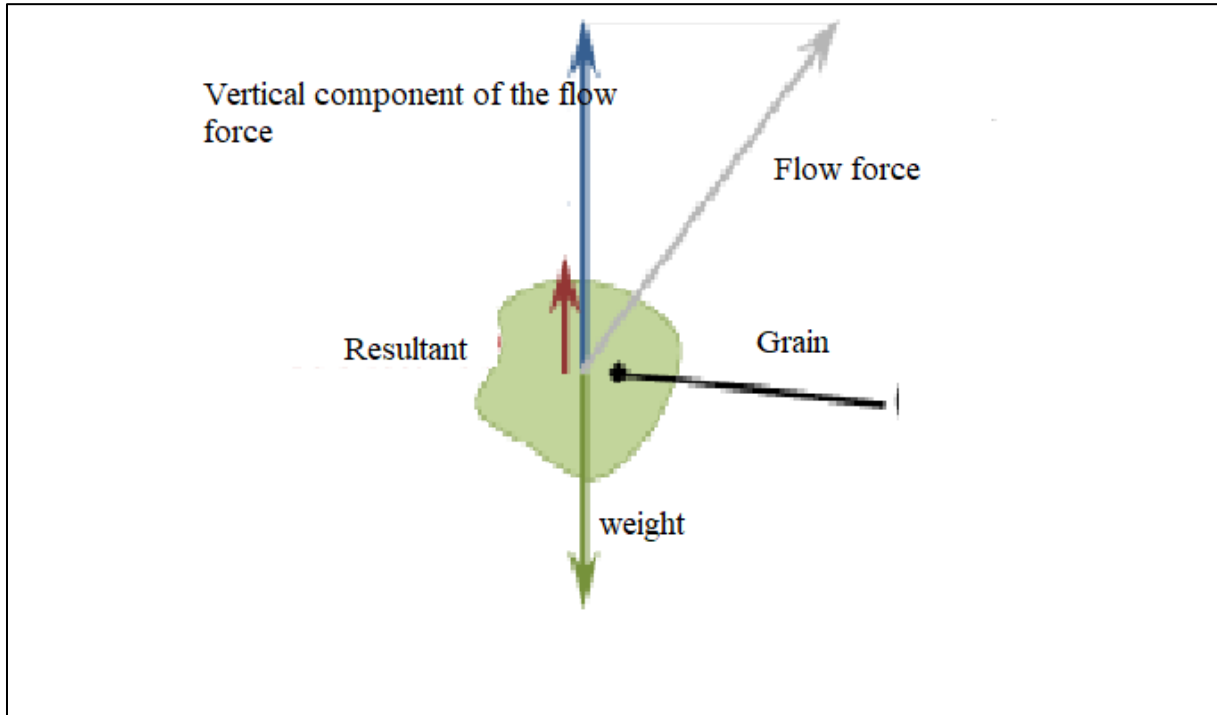


Figure III. 1: Forces involved in uplift (Horsin , 2016)

### III.2.7. Water pressure

$$U_w = \gamma_w * h$$

$U_w$  = water pressure.

$\gamma_w$  = unit weight of water.

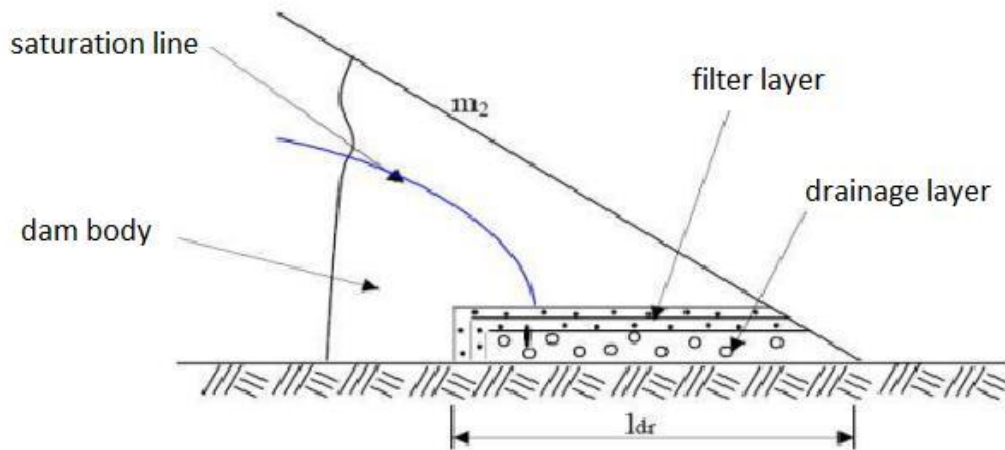
$h$  = water height.

### III.3. Types of drainage systems in dams and their dimension

#### III.3.1. Horizontal drains

Perforated pipes or gravel-filled trenches within the dam to reduce pore water pressure and improve stability. However horizontal drains should be evaluated with caution if the aim is to

lower water tables. The use of horizontal drains significantly reduces pore water pressure in the foundation below the downstream portion of the dam. Very effective when piping occurs in homogeneous permeable soil foundation. (Bencherrat and Mostefa kara, 2018)



**Figure III. 2:**Horizontal drain (Bencherrat and Mostefa kara, 2018)

#### -Dimensioning

The thickness of the horizontal drain is chosen to be able to evacuate the infiltration flow through the bed and its foundation without overflowing with a minimum of 50 cm and often more. The drain extends over a length of  $\frac{1}{4}$  to  $\frac{1}{3}$  of the dam area. (Bencherrat and Mostefa kara, 2018)

#### III.3.2. Vertical drain (chimney drains)

To prevent the risk of anisotropy, a vertical drain is installed from the bottom of the homogeneous embankment up to 0.20 to 0.30 meters above the normal water level to prevent any risk of bypassing. Installed near the downstream face, it increases the waterproofing effect of the upstream embankment. The drain is constructed by re-excavation of the embankment in every 5 to 6 compacted layers using a shovel and then the coarse sand is put carefully to filter properly. Material is selected carefully to create filtering conditions so that water is allowed to flow but not the soil particles. The percolating water picked up by this filter drain is either released out through a drainage pipe system or through a horizontal drain, particularly if foundation drainage is required as well. (Bencherrat and Mostefa kara, 2018)

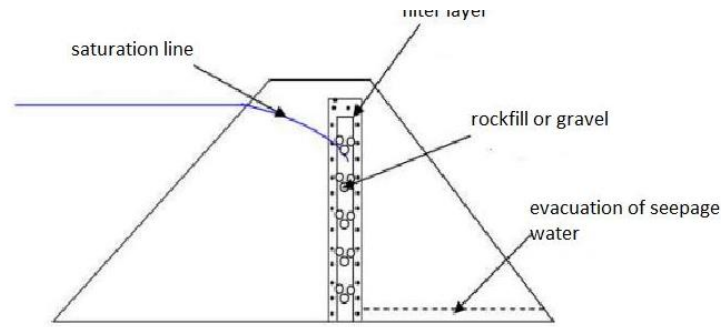


Figure III. 3: Vertical drainage system (Bencherrat and Mostefa kara, 2018)

The percolating water picked up by this filter drain is either released out through a drainage pipe system or through a horizontal drain, particularly if foundation drainage is required as well. (Bencherrat and Mostefa kara, 2018)

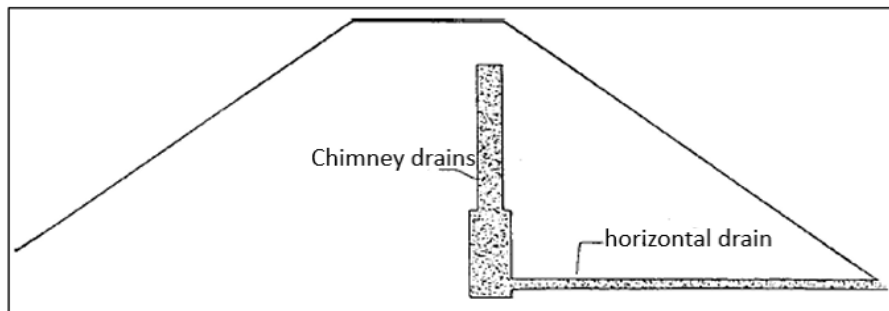


Figure III. 4: Drainage device for a homogenous clay (Bencherrat and Mostefa kara, 2018)

**- Dimensioning of a vertical drain**

**1. Drain thickness**

The minimum thickness of the drain is 50cm, as the embankment rises, based on the  $H^2\sqrt{V}$  H is the hydraulic height and V is the speed of water flowing through the dam material. The table number shows the recommended minimum thickness in sand.

Table III. 3: Recommended minimum thickness in sand (Bencherrat and Mostefa kara, 2018)

$H^2\sqrt{V}$	< 30	30 to 100	100 to 300	300 to 700	700 to 1500
Thickness (m)	0,50	0,80	1,00	1,20	1,50

## 2. Height of the chimney drain

The chimney drain has a variable height. The option of lowering the water table using a drain installed up to the highest water level is the generally preferred solution. The choice of this measure depends on economic considerations. (Bencherrat and Mostefa kara, 2018)

### III.3.3. Prism drain

It is designed when there is water downstream of the dam with a variation in level, but its construction requires a significant volume of rockfill, making its choice dependent on the availability of borrow areas near the dam site where rockfill is available in sufficient quantity and of acceptable quality. (Bencherrat and Mostefa kara, 2018)

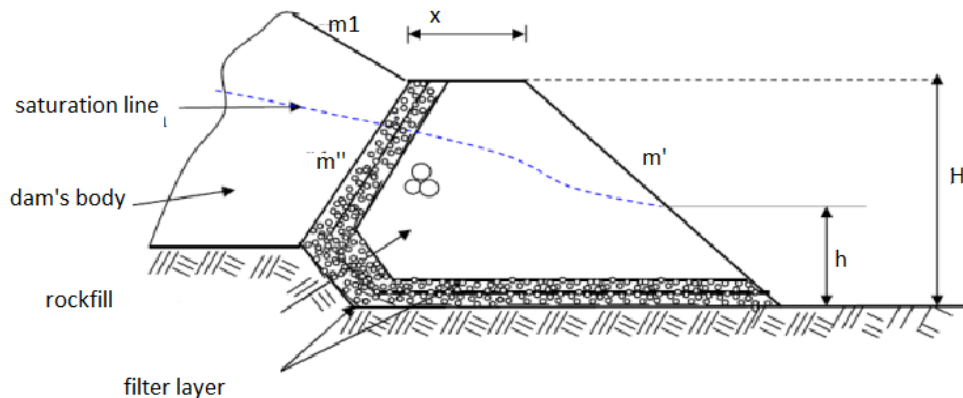


Figure III. 5 Prism dam (Bencherrat and Mostefa kara, 2018)

$x$ : Width of the berm.

$H$ : Height of prism drain.

$m'$  and  $m''$ : Downstream and upstream sides of the prism of drainage.

$m_1$ : Slope of the downstream face of the dam.

$h$ : Water level downstream of the dam.

#### - Dimensioning

Width of the berm(x) is generally determined based on the equipment used for its construction is  $\geq 3\text{m}$ .

For the small dams the width is smaller for economic reasons  $x=0.5$  to  $2\text{m}$ .

Height of prism drain(H) is fixed if the water level in the downstream side is known with precision.

$$H=h+(0.5\text{ to }1\text{m}).$$

When there is low probability of water in the downstream the height is fixe following the expression:

$$H= (0.15 \text{ to } 0.18) H'$$

H 'being the total height of the dam.

The downstream slope depends on the characteristics of the rock fill and therefore its stability to sliding and wave effects. It is generally determined as follows:

$$m'=(1 \text{ to } 1.5\text{m}) m_1$$

The upstream slope:

It is closely linked to the saturation line and therefore to the stability of the embankment, but it also plays a very important role in quantifying the infiltration rate. It is usually determined as follows:

$$M'' = (1.25 \text{ to } 2\text{m}) *m_1.$$

$m_1$  is the downstream slope of the dam.

(Bencherrat and Mostefa kara, 2018)

### III.3.4. Toe drains

The toe drain generally consists of a perforated collector pipe placed in a trench, the trench is then backfilled with filter material surrounding the toe pipe. (Charrak, 2022)

Located at the downstream toe of the dam to collect seepage and direct it safely away. Also collects the rain water falling on the surface of the dam. The minimum depth of the toe drain should be 0.60 m, with gradual increase depending upon the site conditions and the gradient provided to the bed of the toe drain. However, the maximum depth of toe drain should not exceed 1.20 m for ease of construction. (Mahmoud and Zhen,, 2023)

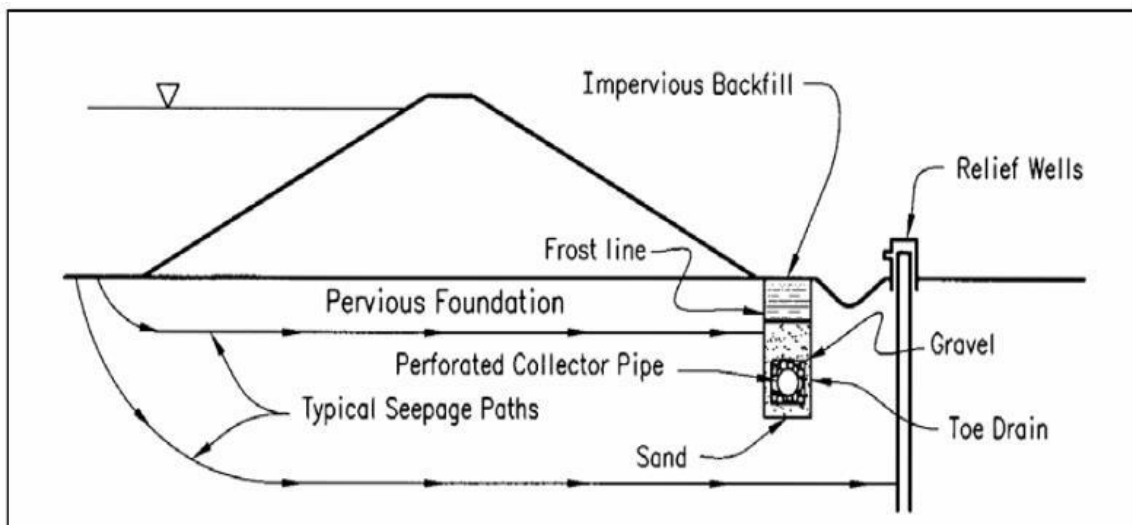


Figure III. 6: Toe drain (Charrak, 2022)

### III.3.5. Surface drainage

This type of drainage is used in the construction of small reservoirs. It easily repairable when damaged and it does not require a lot of riprap materials.

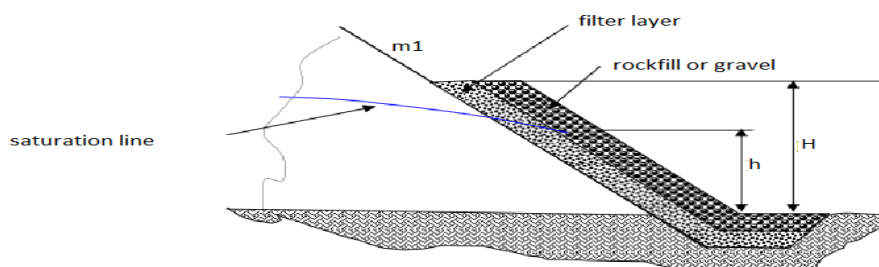


Figure III. 7: Subsurface drainage (Messaid, 2009)

$m_1$ : Slope of the downstream embankment of the dam.

$h$ : Water height downstream of the dam.

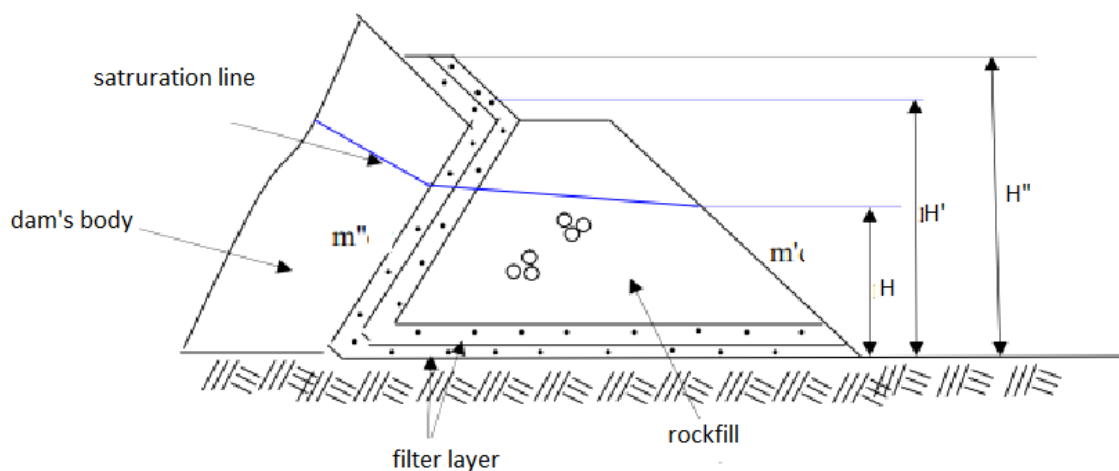
$H$ : Height of the surface drain.

- Surface drainage is dimensioning as follows:

The height ( $H$ ) of the surface drainage is often determined based on the downstream water depth. This height is chosen in the same way as for the drainage prism, even when there is no water downstream. The thickness of the surface drainage is designed to evacuate the infiltration flow without overflow and must be checked to ensure it is not altered by wave action. (Messaid, 2009)

#### III.3.6. Drainage prism with surface drainage

This is a variant that combines the two previous variants. It is used in cases where the hydrological study highlights the possibility of an exceptional rise in the downstream water level, which risks exceeding the crest of the drainage prism. The prism portion is sized in the same way as for the prism alone. The same applies to the surface drainage portion, but taking into account the maximum height of the downstream level. (Messaid, 2009)



**Figure III. 8:** Combination of surface drainage with prismatic drainage. (Messaid, 2009)

$H''$  = exceptional down Stream water height

### III.3.7. Prismatic drain with horizontal drain

The more often and for reasons of safety of the structure, the two are combined, variants of the drainage prism and the horizontal drain. Thus, the drainage prism is extended to the interior of the massif by an internal horizontal drain. they are two variants depending on whether the foundations are permeable or not. (Messaid, 2009)

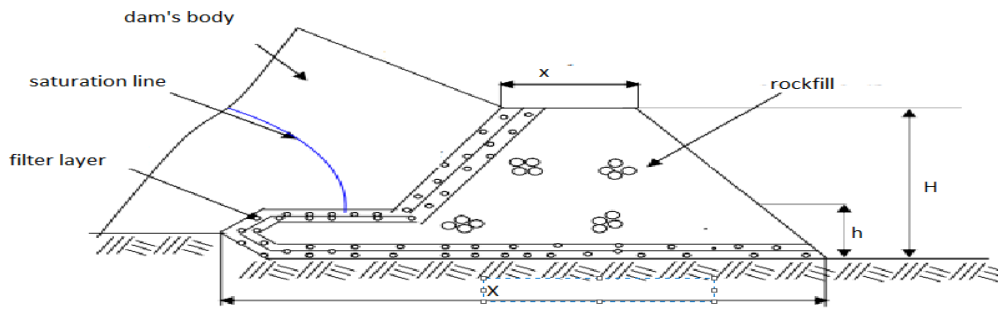


Figure III. 9: Prismatic drain with horizontal drain with impermeable foundation, (Messaid, 2009)

The sizing of such drainage is done in the same way as for the prism and horizontal drain separately.

### III.3.8. Belt drainage

It is a variant of the horizontal drain but the drainage strip is not continuous on the downstream part. This is replaced by discontinuous strips. This type of drainage is provided when the amount of riprap and gravel is not sufficient and that the foundation is impermeable. The drainage strip can be replaced by drains pipes. (Messaid, 2009)

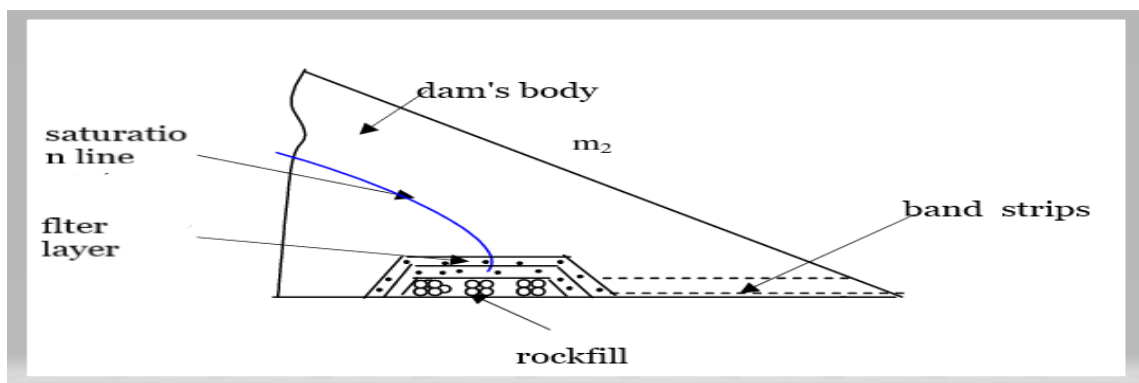


Figure III. 10: The figure above shows the belt drain, (Messaid, 2009)

### III.4. Role of drains

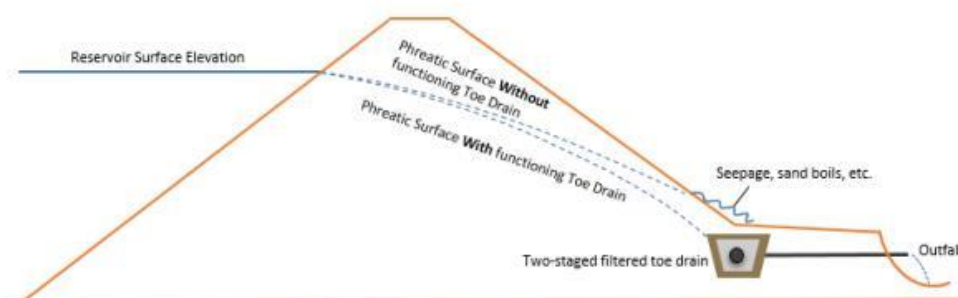
Drains in earthen dams have a multitude of very important functions:

- Intercept seepage water and discharge it downstream of the dam.
- Lower the saturation line and avoid resurgences on the downstream slope.
- Lower the saturation line, to keep much of the backfill unsaturated in order to preserve the geotechnical characteristics of the material used.
- The presence of the drain in an earthen dam serves to minimize the leakage rate on the work.
- It also serves to decompress the foundation and therefore minimize pressure Interstitial.
- The presence of the drain makes it possible to activate the consolidation of the backfill.

(Messaid, 2009)

### III.5. Drainage system design considerations

Drains are sentinels for water, controlling flow and ensuring safety. But secreted beneath their massive bulk, water is continually attempting to seek passage. A toe drain is a quiet but potent protector, collecting and releasing seepage water safely before it can undermine the stability of the dam. Let alone or inadequately designed, it can lead to internal erosion, slope failure, and even dam collapse. (Freeman et al, 2018)



**Figure III. 11:**General profile of phreatic surface in a dam with and without a functioning toe drain (Freeman et al, 2018)

#### III.5.1. The purpose of a toe drain

A toe drain is positioned at the downstream toe of an embankment dam to:

1. Control seepage before it accumulates and increases water pressure inside the dam.
2. Reduce uplift pressure that could destabilize the dam's foundation.
3. Prevent internal piping and erosion, the quiet assassin that can lead to disastrous failure.
4. Allow monitoring, an early warning system for excessive seepage.

A well-designed toe drain can prevent disasters by addressing issues early. (Freeman et al, 2018)

### III.5.2. Important design factors

The drain needs to be well-designed to be available, efficacious, and long-lasting. The following are the basic design considerations.

#### 1. Pipe size & placement (Freeman et al, 2018)

- a. Minimum pipe diameter: 10 inches (25 cm) permits, easier maintenance and camera inspection. Smaller diameters are more susceptible to clogging.
- b. Maximum spacing between monitoring wells: 500 feet (150 meters) Allows for the ease of monitoring and cleaning access.
- c. Pipe grade: self-cleaning velocity (3–5 ft/s or 0.9–1.5 m/s) Does not allow sediment to accumulate within the pipes.

#### 2. Drainage flow & capacity

Perforation size: must be equal to that of the neighboring filter material to prevent soil particles from entering and blocking the system.

Outlet elevation: outfall must be at a level above the highest flood levels to prevent backflow of water into the system.

#### 3. Filter & drainage material (Freeman et al, 2018)

Two-stage filters (sand + gravel) are recommended They provide more drainage and less clogging compared to single-stage filters.

Gravel permeability should be 10–100 times the permeability of surrounding soil to provide free water flow.

### 4. Outfall protection

Flap gates and screens should be installed at the outfall to exclude rodents and debris blockages. This table summarize what we take in consideration in designing a drain system.

**Table III. 4:** Summary of the consideration should take in drainage design

Parameter	Value	Purpose
Minimum Pipe Diameter	10 inches (25 cm)	Allows for easier access and maintenance
Maximum Pipe Length Between Wells	500 feet (150 meters)	Ensures accessibility for monitoring and cleaning
Recommended Flow Velocity	3–5 ft/s (0.9–1.5 m/s)	Prevents sediment accumulation
Filter System Type	Two-stage (sand + gravel)	Improves drainage and prevents clogging
Pipe Material Recommendation	HDPE, reinforced concrete	Resists corrosion and deformation
Outfall Placement	Above flood levels	Prevents water from backflowing into the drain
Cleaning Method	High-pressure jetting (3,000–5,000 psi)	Removes sediment and mineral buildup
CCTV Inspection Frequency	Every 5 years	Detects blockages and structural damage

### III.6. Common problems and how to prevent them

Even the best-designed toe drains can have problems develop over time. Regular maintenance captures and fixes problems before they are serious. (Freeman et al, 2018)

#### III.6.1. Blockages & clogging (Freeman et al, 2018)

Sedimentation from soil erosion may reduce water velocity and build up pore pressure.

Plant roots in the surrounding area can grow through pipes and restrict flow.

Perforations clog slowly due to biofouling (bacterial growth) and mineral deposits.

-Solution: Periodic CCTV inspections and high-pressure jetting to clear debris and deposits.

### III.6.2. Pipe degradation (Freeman et al, 2018)

Clay or metal pipes corrode or crack with age.

Plastic pipes (HDPE, PVC) are corrosion-resistant but can deform under heavy cover when underground.

Solution: Use reinforced HDPE or concrete pipes that are flexible but strong.

### III.6.3. Poor drainage design

Steep slopes lead to erosion of filter material, and flat pipes result in ponding.

Perforations that are too small admit fines, clogging the system.

Solution: Use proper filter design, slope conditions, and flow calculations to provide uninterrupted water flow.

## III.7. Inspection & maintenance

A toe drain is only as good as the maintenance it receives. Without continual observation, even the best systems will fail. (Freeman et al, 2018)

### III.7.1. Inspection frequency & methods

CCTV camera inspections should be carried out at least every 5 years. Yearly visual checks of outfalls should be made, especially after heavy rain events. (Freeman et al, 2018)

### III.7.2. Cleaning & rehabilitation

High-pressure jetting (3,000–5,000 psi) helps to remove accumulated sediment and mineral deposits. Manual flushing and sediment removal are required in the event of severe blockages.

Replacement of filters may be necessary in the event of significant evidence of clogging or internal erosion. (Freeman et al, 2018)

### III.7.3. Monitoring of warning signs

Abnormal seepage flow increases can indicate filter failure or internal erosion.

Cloudy or muddy drain water may indicate piping, a serious threat to dam stability.

Reduction in the flow of water could mean that the system has been clogged and needs cleaning.

If all these signs appear, immediate response is required. (Freeman et al, 2018)

### III.8. Conclusion

Drains can be said to be essential components for the proper operation of earth dams, but their effectiveness is closely linked to their design and location. Some types of drains have dimensions dictated by local conditions specific to each structure, such as the thickness of the impermeable zone beneath the dam, the height of the downstream level, or the drain's role. In this work, two types of drains (the internal blanket drain and the drainage prism) were given special attention, as the other types are easily deduced from them.

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**Chapter IV: Analysis of hydraulic behavior in a dam  
using GeoStudio: the effect of waterproofing on  
seepage and stability, case of Boughrara dam.**

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### **IV.1. Introduction**

The stability and hydraulic behavior of a dam are influenced by various factors. This study investigates the effects of different dam core base lengths (ranging from 20m to 60m), different grout curtain lengths (ranging from 20 to 60) and different grout curtain positions (ranging from the upstream area to the downstream) on different hydraulic parameters. By comparing these different configurations, this study aims to determine the most favorable case for hydraulic stability and efficiency.

### **IV.2. Context of the thesis**

The core and grout curtain are fundamental components in earth dams, ensuring water tightness and structural stability. The core, typically composed of low-permeability materials such as clay, serves as the primary seepage control barrier, while grout curtains act as a secondary measure to reduce water infiltration through the foundation. The effectiveness of these elements depends on their design parameters, particularly their length and position, which influence seepage patterns, internal pressures, and overall dam stability.

In the case of Boughrara dam, understanding the hydraulic behavior of these waterproofing structures is crucial for ensuring long-term safety and efficiency. By modifying the length of the core base and grout curtains, engineers can optimize seepage control while minimizing risks such as internal erosion and piping failure. However, determining the optimal configuration requires an advanced numerical modeling approach capable of simulating water flow and pressure distribution under different scenarios.

For this purpose, GeoStudio, a widely used geotechnical modeling software, offers the ability to simulate seepage dynamics within the dam body and foundation. The results of this study will provide a comparative analysis of different design configurations, allowing engineers to make informed decisions regarding core base and grout curtain length for optimal hydraulic performance. This research contributes to the broader field of dam engineering, offering insights that can be applied to similar hydraulic structures in varying geotechnical conditions.

### **IV.3. Research objectives**

Considering the case of Boughrara dam, this thesis aims to analyze the conceptual and hydraulic aspects of the structure by evaluating the impact of the core base length and the grout curtain length on its seepage behavior. This study is motivated by two fundamental factors: the need to optimize seepage control and stability and the importance of adapting design parameters to the dam's geological and geotechnical conditions.

Based on these considerations and using numerical modeling with GeoStudio, the research is guided by a parametric analysis focused on the following design variations:

- Variation in the length of the core base and its effect on seepage and pressure distribution.
- Variation in the grout curtain length to assess its efficiency in reducing water infiltration.
- Variation in the grout curtain position and its effect on seepage and reducing water infiltration.
- Comparative analysis of all parameters to determine the most effective configuration for improving dam stability.

The hydraulic behavior of the dam will be analyzed by observing hydraulic parameters, seepage flow network and the saturation line under different configurations. Through this study, the research aims to propose an optimal design approach for enhancing the hydraulic and structural efficiency of the Boughrara dam, ensuring long-term stability and performance.

### **IV.4. Presentation of the dam under study**

#### **IV.4.1. Typical profile of the dam**

Boughrara dam is located in the western part of the Wilaya of Tlemcen, near the commune of Hammam, downstream of the confluence of the Mouillah and Tafna rivers. It is approximately 10 km from the chief town of the Daira of Maghnia as shown in figure IV.1.

The detailed preliminary project was developed in 1988 by the Russian company Selkhozpromexport. The execution studies were entrusted to the engineering firm Tractebel, which also supervised the construction work in collaboration with EDF.

## Chapter IV: Analysis of hydraulic behavior in a dam using GeoStudio: the effect of waterproofing on seepage and stability, case of Boughrara dam.

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The construction of the dam was assigned by the National Agency for Dams and Transfers (ANBT) to the Italian company CONDOTTE. The Lambert coordinates of the dam are  $X = 102.92$  and  $Y = 185.20$ . (Smail, 2014)

The dam is built within a highly fractured Jurassic massif. The presence of fractures in the sandstone influenced the design of the sealing curtain to ensure water retention.

Miocene marls lie unconformably over the Jurassic deposits.

These marls form a 60 m thick cover on the right bank and the upper part of the left bank.

The marls are clayey, compact, and range in color from gray to greenish. (Smail, 2014)

The figure IV.1 shows the position of Boughrara dam in the wilaya of Tlemcen-Algeria from google map.



**Figure IV. 1:** Map situation of Boughrara dam (Smail, 2014)

### IV.4.2. Dam infrastructure

Boughrara dam includes several key structures (Smail, 2014)

- A zoned embankment dyke.
- A main spillway (lateral weir) on the right bank.
- A secondary spillway (fuse plug spillway with concrete slabs) on the right bank.
- Injection and drainage galleries under the dam and the main spillway.
- A water intake tower.

- A diversion gallery, later repurposed for bottom outlet drainage and technical access.

#### **IV.4.3. Key technical specifications**

- Total capacity: 175.446 hm<sup>3</sup>.
- Usable capacity: 156.285 hm<sup>3</sup>.
- Type: Compacted alluvial embankment with a clay core.
- Crest elevation: 311.5 NGA.
- Height above valley floor: 61 m.
- Crest length: 1,100 m.
- Crest width: 8.5 m.
- Upstream slope: 2.5:1.
- Downstream slope: 2.25:1.
- Foundation material: Sandstone and marl.
- Upstream berm elevation: 280 NGA.
- Downstream berm elevation: 266 NGA.
- Main spillway: 169 m weir at 305 NGA, with a capacity of 3,000 m<sup>3</sup>/s.
- Fuse plug spillway: 250 m weir at 309.5 NGA, with a capacity of 2,880 m<sup>3</sup>/s.
- Construction period: 1994 – 1998.
- Reservoir filling date: November 11, 1998. (Smail, 2014)

#### **IV.5. Characteristics of the dam**

##### **IV.5.1. The main characteristics of the dyke are as follows**

- Type: Zoned embankment.
- Crest level: 311.5 NGA.
- Height above the valley floor: 61 m.
- Crest length: 1,100 m.
- Crest width: 8.5 m.
- Upstream slope: 2.5:1.
- Downstream slope: 2.25:1.
- Upstream berm: Level 280 NGA.
- Downstream berm: Level 266 NGA.
- RN (Normal Retention Level): 305 NGA.

## Chapter IV: Analysis of hydraulic behavior in a dam using GeoStudio: the effect of waterproofing on seepage and stability, case of Boughrara dam.

- PHE (Probable Highest Elevation): 309.95 NGA.

### IV.5.2. The embankment of the dyke is composed of the following materials

- T1: A central waterproof core made of clay. The core is leveled at elevation 310.6m, where its width is 6 m. Below this level, the upstream and downstream slopes are 10H:3V.
- T2: Upstream and downstream reinforcements made of pebble-gravel.

### IV.5.3. The cofferdam

The cofferdam, located upstream of the dyke, is constructed across the riverbed and is integrated into the main body of the dam. (Smail, 2014)

Foundation level: Approximately 249 NGA-Crest level: 280 NGA, with a width of 8 the figure IV.2 shows a typical cross-section of Boughrara dam.

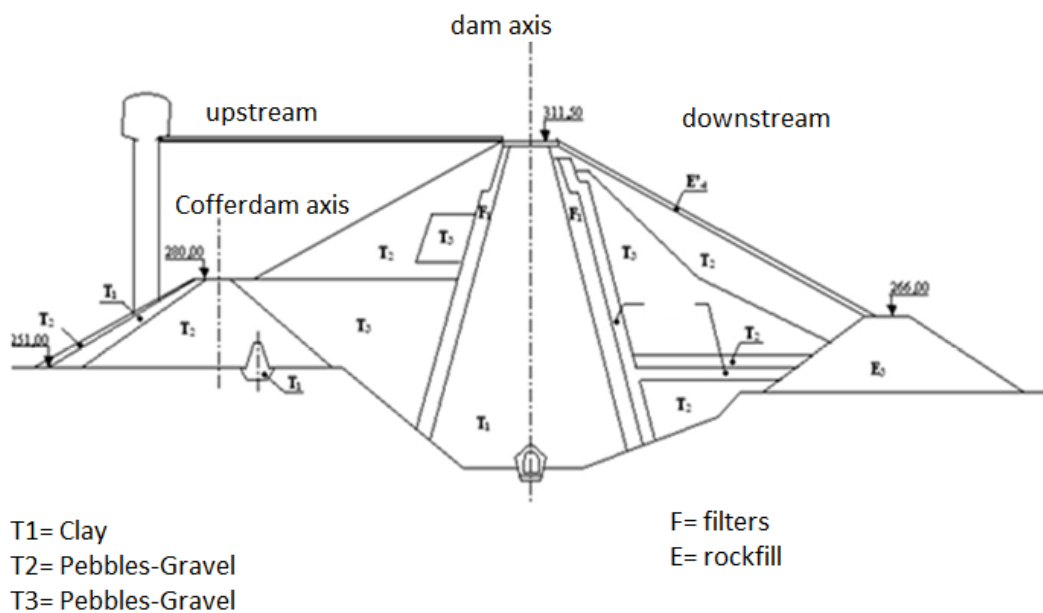


Figure IV. 2: Typical cross-section of the dam (Smail, 2014)

### IV.6. Characteristics of the dam's grout curtain and drainage

The injection and drainage gallery are a 920-meter-long sub-dyke tunnel located at the base of the dam's central core, extending beneath the main spillway. It is embedded halfway into the

foundation, with access points on both the right and left banks. To enhance stability, consolidation injections were carried out from the core foundation to a depth of 8 meters, arranged in a 4 m x 4 m grid. Additionally, a vertical grout curtain was constructed along the gallery, varying in height from 30 to 100 meters, depending on the section. Grouting and sealing injections were applied at the upstream and downstream base at 2-meter intervals. However, seepage risks were identified on both banks. On the left bank, water infiltration occurs through permeable lacustrine deposits with a permeability of  $\sim 10^{-4}$  m/s, posing a risk of ground saturation that could affect Hammam Boughrara. On the right bank, sandstone layers beneath the fuse plug spillway create preferred seepage paths, with the added risk of retrogressive erosion in downstream gullies. To prevent water bypass and erosion-related instability, sealing curtains were implemented on both banks, ensuring the dam's long-term integrity and safety. (Smail, 2014)

#### **IV.7. Presentation of the calculation code used for modeling**

GeoStudio is a modeling software designed for geotechnical and geological studies. The software offers rigorous analytical capabilities, sophisticated product integration, and broad applications for various geotechnical and geological problems.

It allows users to:

- Combine multiple analyses within a single integrated project.
- Draw geometry directly or import CAD files.
- Solve multiple analyses simultaneously.
- Interpret results with visualization tools and graphs.

GeoStudio is supported by a set of sub-programs, including:

- **SLOPE/W**: Calculates the safety factor of a natural or artificial slope using classical analysis methods.
- **SEEP/W**: Designed for water infiltration calculations using the finite element method.
- **SIGMA/W**: Analyzes deformation and stress problems using the finite element method.
- **QUAKE/W**: Examines soil behavior under seismic effects using the finite element method.
- **TEMP/W**: Analyzes geothermal issues in soil using the finite element method.

#### **IV.8. Consistency of the modeling**

The comparative parametric analysis focuses on the hydraulic behavior of the core and grout curtain of the Boughrara dam. The first objective is to analyze the influence of the core base length and grout curtain extension on seepage control. To achieve this, the study includes a series of numerical simulations with different core base lengths and grout curtain depths and position using GeoStudio.

The first set of simulations examines the impact of core base length variation, with five different configurations:

- Case 1: base core length equal to 20m.
- Case 2: base core length equal to 30m.
- Case 3: base core length equal to 43m.
- Case 4: base core length equal to 50m.
- Case 5: base core length equal to 60m.

The objective of this phase is to determine the optimal core base length that ensures minimal seepage and pore pressure buildup while maintaining structural integrity.

In the second set of simulations, the focus shifts to the effect of grout curtain extension by varying its depth within the foundation. The cases considered are:

- Case 1: Grout curtain depth equal to  $1/3$  of the dam height.
- Case 2: Grout curtain depth equal to  $2/3$  of the dam height.
- Case 3: Grout curtain depth equal to the full height of the dam.

In the third set of simulations, the effect of grout curtain on different position within the foundation. The cases considered are:

- Case 1: Grout curtain in the upstream side.
- Case 2: grout curtain in the core (start, middle and end).
- Case 3: Grout curtain in the downstream side.

By analyzing the hydraulic gradients, pore water pressures, and seepage rates under these different scenarios, the study aims to identify the most efficient design parameters for

optimizing dam impermeability and stability. These results will provide valuable insights for dam design improvements, ensuring optimal hydraulic performance and long-term structural reliability of the Boughrara dam.

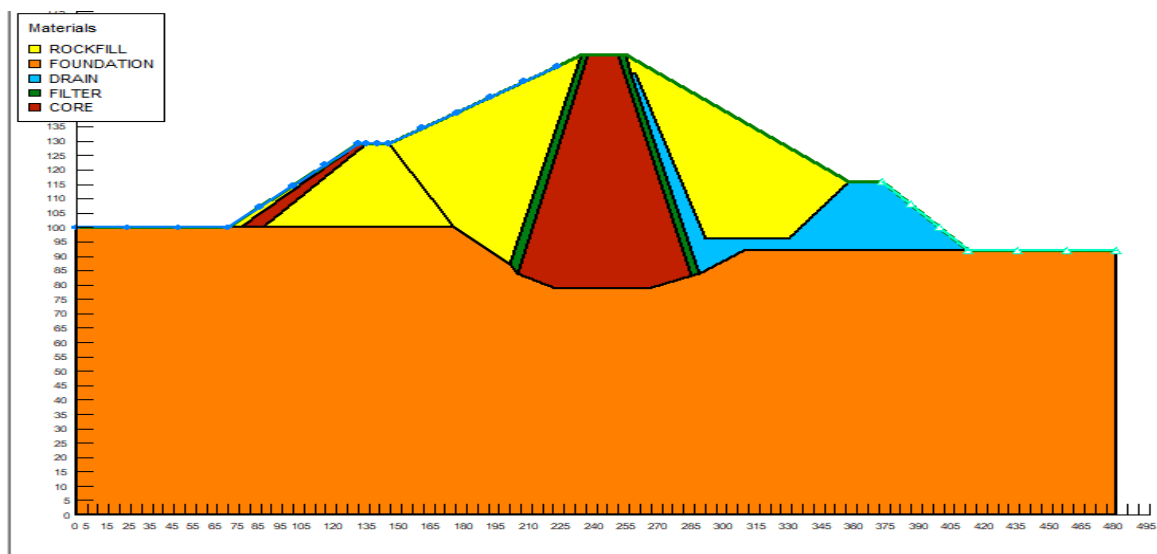
#### **IV.9. simulation of the dam**

##### **IV.9.1. Discretization of the dam**

The geometric profile of the Boughrara dam, including its foundations, has been discretized in X, Y coordinates to accurately represent the different materials composing the dam structure. The materials considered in the numerical model are:

- Dam shell and foundation: Composed of clay, providing structural integrity and stability.
- Filters surrounding the core: Made of sand, serving as a protective barrier to prevent fine particle migration.
- Transition drain: Constructed with gravel, ensuring proper drainage and reducing pore pressure accumulation.
- Downstream filter-drain system: Sand and gravel, designed to effectively control seepage and enhance dam safety.

Figure IV.3 shows the simulation model with the different materials we are using in our study in the Boughrara dam.



**Figure IV. 3:** Discretization model of the dam.

## Chapter IV: Analysis of hydraulic behavior in a dam using GeoStudio: the effect of waterproofing on seepage and stability, case of Boughrara dam.

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This discretization approach allows for a realistic numerical simulation of the dam's hydraulic and mechanical behavior, ensuring accurate evaluation of seepage dynamics, stress variations, and structural deformations under different core base and grout curtain configurations.

### IV.9.2. Material characteristics

This section describes the properties of the materials used in the dam's construction, including their mechanical, hydraulic, and physical attributes.

Table IV.1 provides the various properties of the materials used in the modeling, specifically for each material that makes up the typical profile of the dam.

**Table IV. 1:** Properties of materials used for modeling

<b>Dam Elements</b>	<b>Conductivity (Ks) (m/s)</b>
Rockfill	$10^{-5}$
Foundations	$10^{-5}$
Core	$10^{-8}$
Filter	$10^{-4}$
Drain	$10^{-3}$
Grout curtain	$10^{-12}$

### IV.9.3. Modeling results

This section presents the results obtained from the modeling, including analysis of the dam's behavior under different conditions. It provides insights into key parameters such as seepage, stability, stress distribution, and overall performance of the structure based on the simulations.

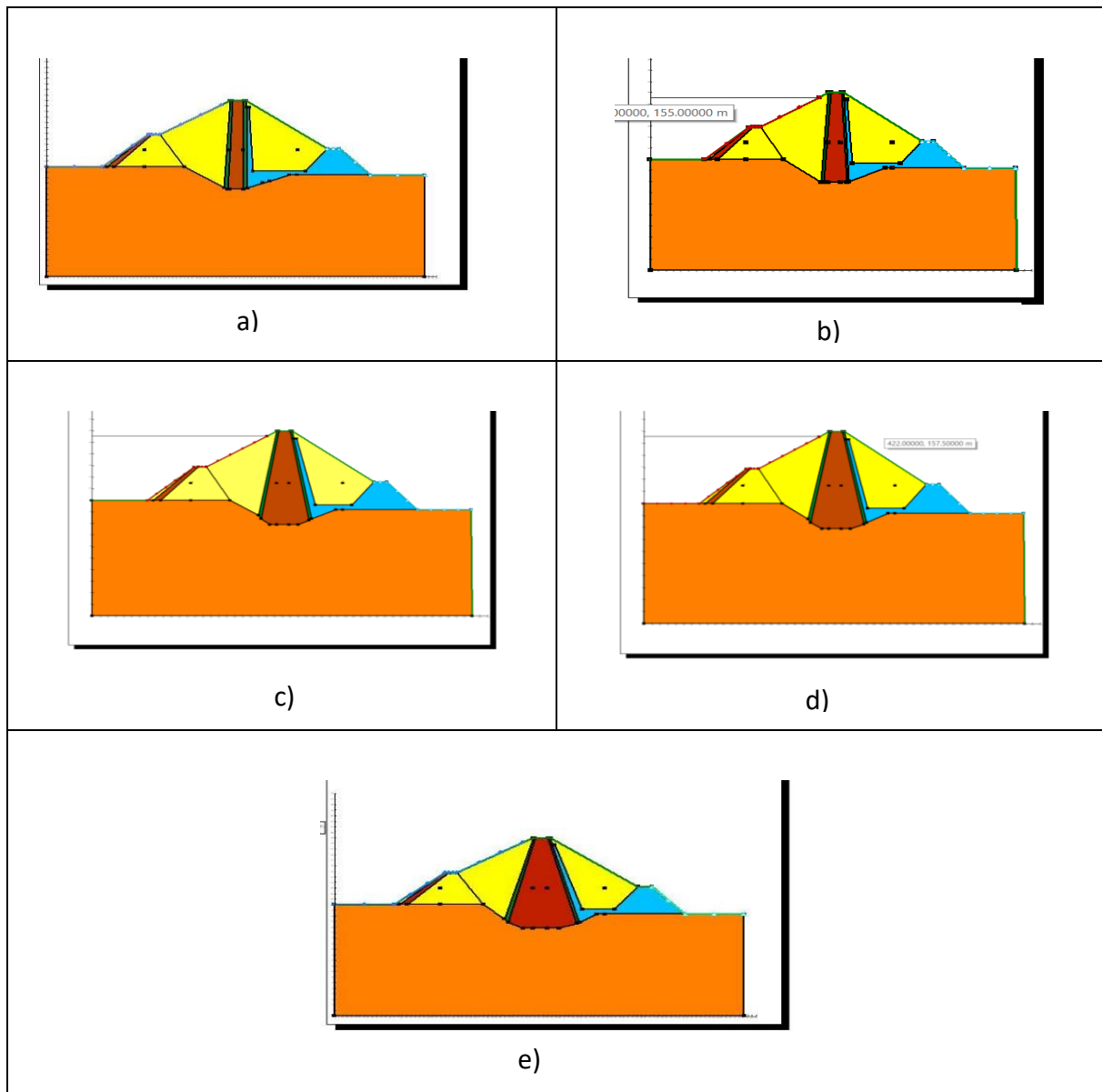
#### 1. The case of variable core length base

In this study, we will analyze the impact of varying the base length of the core on three hydraulic parameters: total hydraulic head, hydraulic gradient, and flow rate. To achieve this, we will examine five different base lengths, comparing their effects with the actual base length of 43 meters. The analysis will be conducted at various points, including the upstream area, the core,

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and the downstream region, to comprehensively assess how changes in base length influence these hydraulic variables. By identifying potential variations in stability and performance, this study aims to determine whether an optimal base length exists that enhances structural integrity and efficiency in water-retaining structures.

Figure IV.4 shows the different core base lengths (20,30,43,50 and 60 meter) that we are studying with GeoStudio.



**Figure IV. 4:** Different base lengths experimented in GeoStudio

a) L=20m, b) L= 30m, c) L=43m, d) L=50m, e) L=60m

a. Effects of the variation of the base on the saturation line

Figure IV.5 shows the behavior of the saturation line in different core base lengths (ranging from 20 to 60 m).

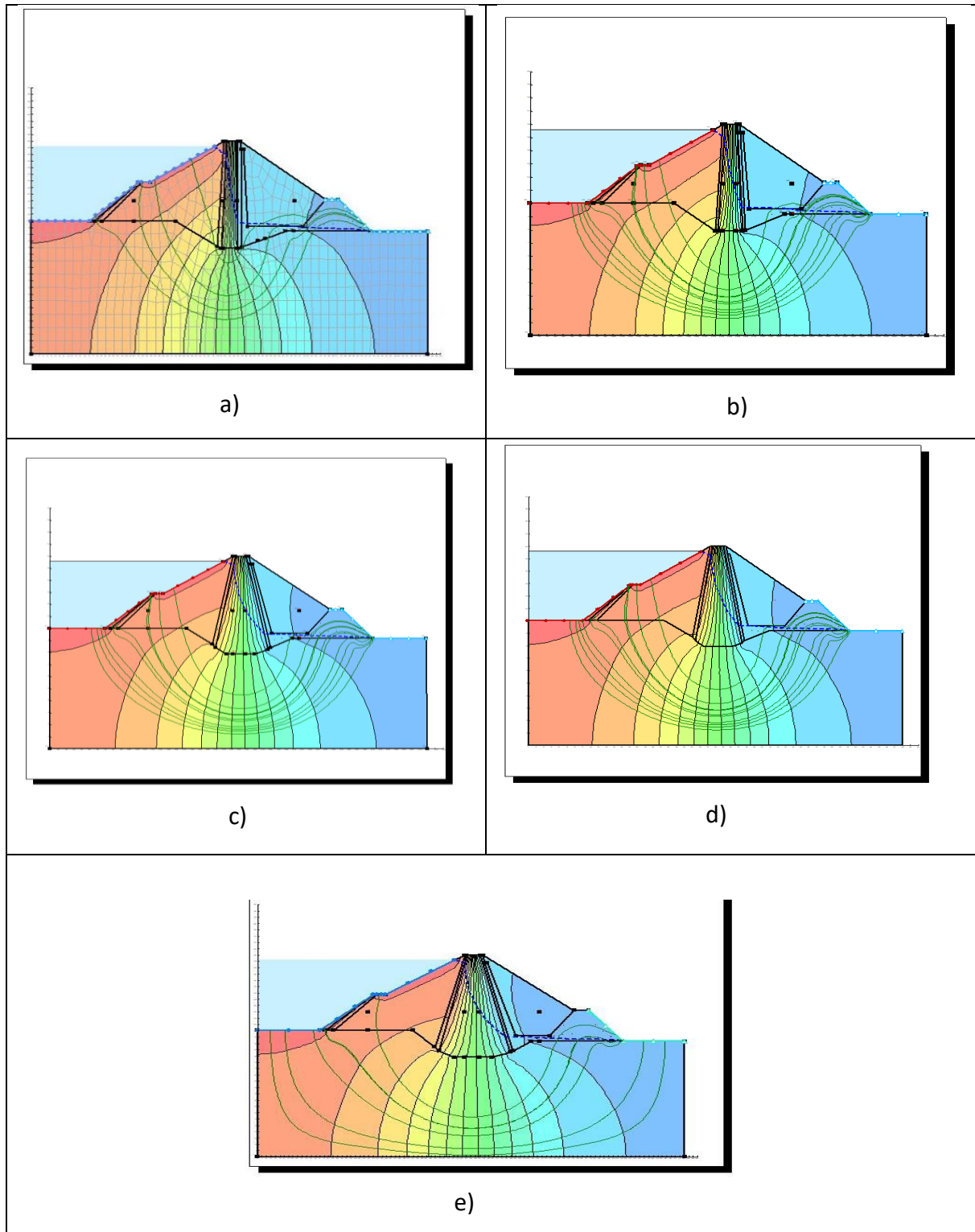


Figure IV. 5: Different position of the saturation line according to the core base length.

a) L=20m, b) L= 30m, c) L=43m, d) L=50m, e) L=60

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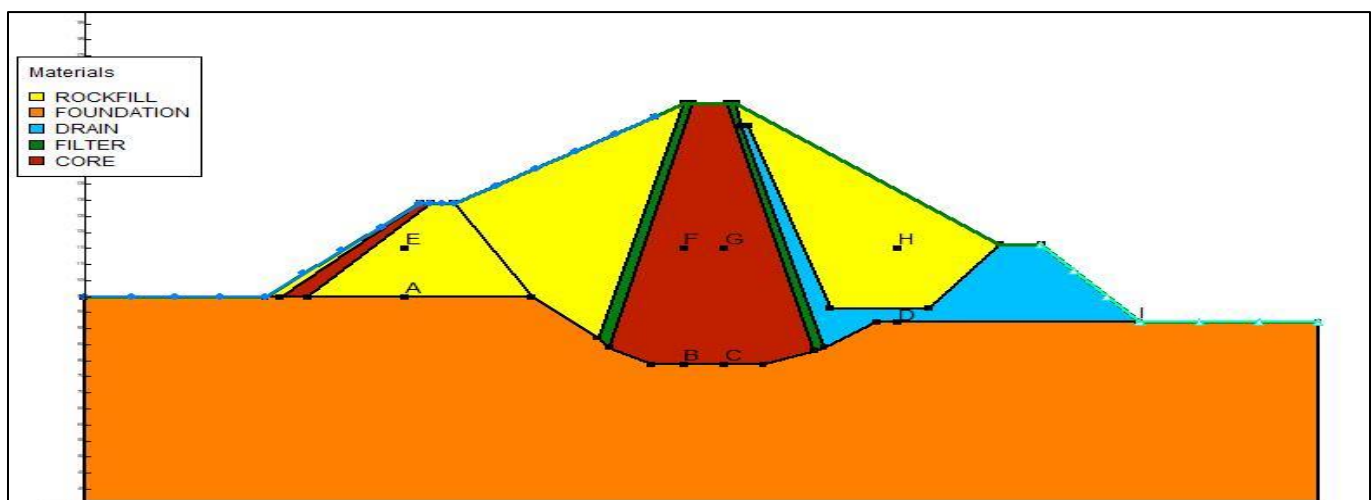
The length of the core base plays a critical role in shaping the saturation line, which defines the boundary between the saturated and unsaturated zones within the dam. This line directly influences seepage behavior, hydraulic pressure distribution, and overall structural stability.

The core base length affects the line of saturation meaning in the shorter base lengths (20 and 30m) the line of saturation passes above the drainage system this implicates that water reaches areas that should remain dry. This can reduce the efficiency of the drainage system and increases failure risks.

The longer the core base length (43m,50m and 60m) the saturation line passes in the drainage system ensuring proper drainage functionality and global stability.

### b. The hydraulic parameters analysis

In this part, we are going to examine different hydraulic parameters in various locations of points in the area that appear to be affected by the core base length. The locations of the points are illustrated in the following figure IV.6.



**Figure IV. 6:** Different comparative study points

Table IV.2 below shows the position of the specific points studied in the dam.

**Table IV. 2:** the positions of the points studied in the dam

Area	Upstream	Core	Downstream
Points	A-E	B-C-F-G	D-H-I

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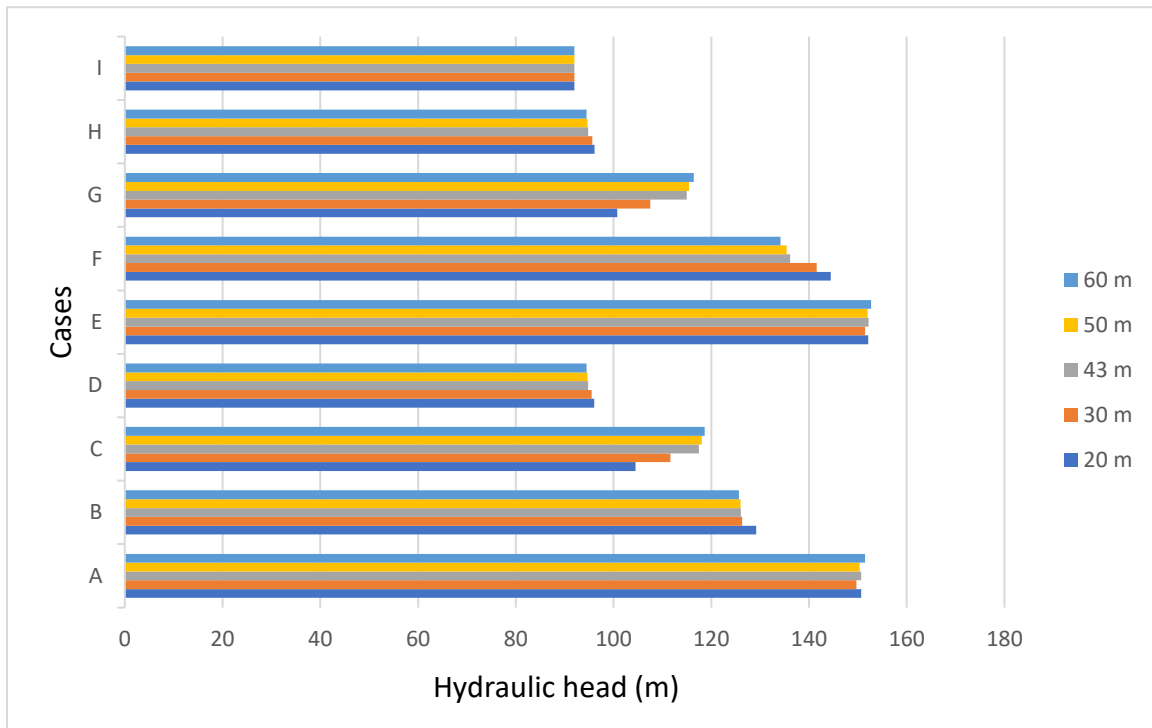
**i. Hydraulic head**

Table IV.3 shows the variation of the hydraulic head (m) at the level of the reference points in the indicated zones as a function of different core base length.

**Table IV. 3:** Variation of the total hydraulic head in different positions

Cases	A	B	C	D	E	F	G	H	I
20 m	150.68	129.19	104.51	96.06	152.16	144.47	100.78	96.15	92
30 m	149.72	126.33	111.62	95.56	151.48	141.61	107.52	95.64	92
43 m	150.68	126.09	117.49	94.80	152.19	136.12	114.97	94.82	92
50 m	150.39	125.99	118.04	94.67	151.97	135.40	115.47	94.66	92
60 m	151.47	125.66	118.66	94.49	152.74	134.16	116.40	94.47	92

Figure IV.7 shows the comparison between the values of the hydraulic head in the specific selected points with the different core base length.



**Figure IV. 7:** Variation of the hydraulic head (m) in different core base length

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### Interpretation

- We remark that the upstream points (A, E) have maximum hydraulic head at all times (~150–152 m). Middle points (B, C, F, G) show comparatively moderate values of head which increase with an increase in the base length.
- Downstream points (D, H, I) show minimum and constant hydraulic head, especially having the same value at 92 m at all times.
- The hydraulic head is always greater in the upstream because that is where the water is retained and the pressure of water is highest before it is, transmitted through or below the dam
- Expanding core base length slightly adds overall hydraulic head in core locations (C, F, G), locations like C and G experience notable rises (e.g., C:104.5 to 118.7 m as base increases from 20 m to 60 m), these points have the higher values because the core base length increases as the longer core slows down the flow of water, causing more water to accumulate in the core, this means higher pressure and hydraulic head at these points.
- Hydraulic head at downstream points change little, indicating the expanded core doesn't significantly affect pressure dissipation.

### ii. Pressure load

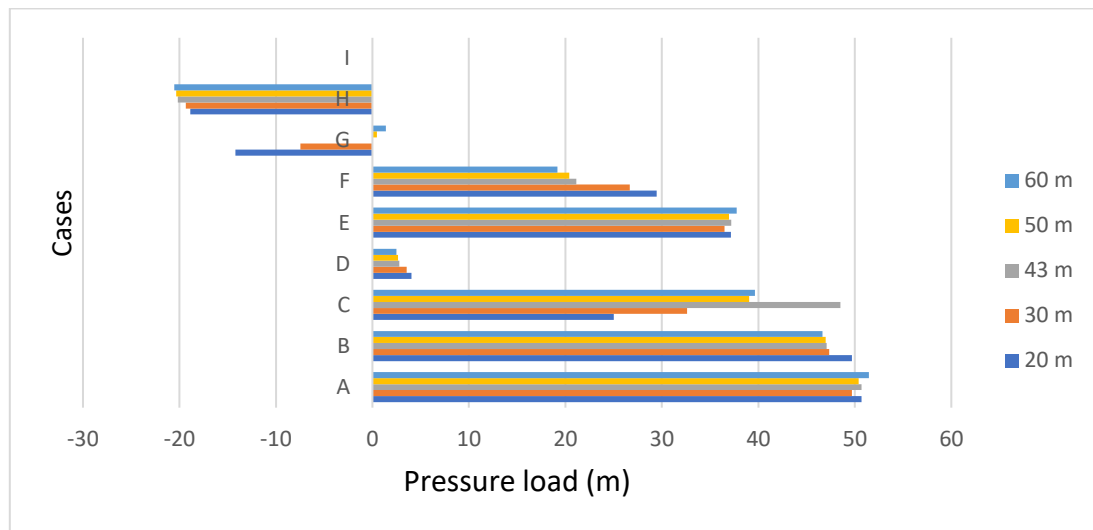
Table IV.4 shows the variation of the pressure load (Kpa) at the level of the reference points in the indicated zones as a function of different core base lengths.

**Table IV. 4:** Variation of the pressure load in different positions

Cases	A	B	C	D	E	F	G	H	I
20 m	50.68	49.69	25.01	4.06	37.16	29.45	-14.21	-18.87	0
30 m	49.72	47.33	32.62	3.56	36.48	26.69	-7.47	-19.35	0
43 m	50.68	47.09	48.49	2.8	37.18	21.12	-0.027	-20.17	0
50 m	50.39	46.99	39.05	2.67	36.970	20.40	0.47	-20.33	0
60 m	51.47	46.66	39.66	2.49	37.74	19.16	1.40	-20.52	0

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Figure IV.8 shows the comparison between the values of the pressure load in the specific selected points with the different core base length.



**Figure IV. 8:** Variation of the pressure load (m) in different core base length

### Interpretation

- Upstream points (A, B) have the highest pressure.
- Shorter base lengths (20m, 30m) record highly variable pressures, especially at G.
- The 43m base length stabilizes pressure distribution, keeping values in balance across the core.
- Pressure load is more evenly distributed at 50m and 60m but only minimally at over 50m
- Point I show zero pressure in all cases, likely showing a reference or atmospheric condition.
- Core point (G) moves from negative to slightly positive or near-zero with increasing base length (i.e., pressure recovery).
- Water is trying to pull through at those points, not push and that's why pressure is negative. It usually happens when:
  - The flow velocity is high downstream and the water level is quite lower at this point. longer core bases help to mitigate this issue as shown in the graph.
  - At the point G, pressure varies from -14.2 m at 20 m to +1.4 m at 60 a big reduction, which implies that base extension reduces uplift pressure risks.

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- Point C has the greatest pressure rise: from 25 m to nearly 50 m when the base length at the center is longer, the flow paths are longer, longer core base is equal to farther distance water has to travel through low-permeability material (core), this lead the water not escaping so readily, hence more hydraulic head is built up at these positions before it is able to dissipate. So, C and G are in transition zones, become increasingly active as core geometry changes.

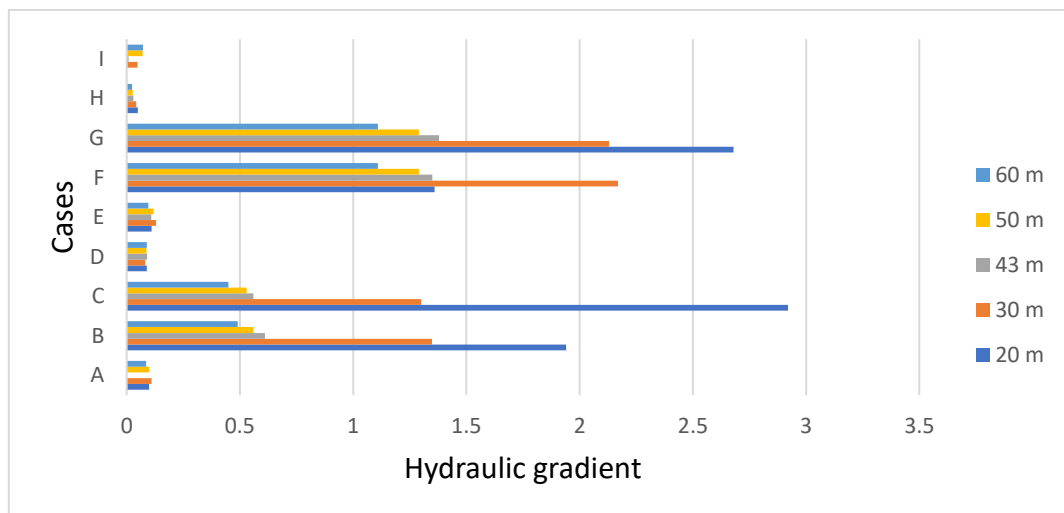
**iii. Hydraulic gradient**

Table IV.5 shows the variation of the hydraulic gradient at the level of the reference points in the indicated zones as a function of different core base length.

**Table IV. 5:** Variation of the hydraulic gradient in different positions

Cases	A	B	C	D	E	F	G	H	I
20 m	0.099	1.94	2.92	0.089	0.11	1.36	2.68	0.05	0,099
30 m	0.11	1.348	1.30	0.082	0.13	2.17	2.13	0.042	0.048
43 m	0.001	0.61	0.56	0.09	0.109	1.35	1.38	0.03	0.008
50 m	0.10	0.56	0.53	0.088	0.119	1.29	1.29	0.027	0.07
60 m	0.086	0.49	0.45	0.089	0.096	1.11	1.11	0.024	0.072

Figure IV.9 shows the comparison between the values of the hydraulic gradient in the specific selected points with the different core base length.



**Figure IV. 9:** Variation of the hydraulic gradient in different core base length

### **Interpretation**

- Higher hydraulic gradient lead to higher seepage risk.
- In our case the highest gradient at core points (B, C, F, G), especially for shorter base lengths, downstream (A, E) and upstream points (D, H, I) consistently have low gradients.
- The lengths of 43m and 50m significantly reduces the gradient in high-gradient zones like B and C. E.g., Point C: from 2.92 → 0.45, quite a reduction, reducing the gradient, meaning lower seepage and better stability, 60m achieves the lowest gradient, but again, the difference is minor compared to 50m.
- Suggests that a longer core flattens hydraulic paths, reducing seepage risk and internal erosion or piping potential.

#### **iv. Flow rate**

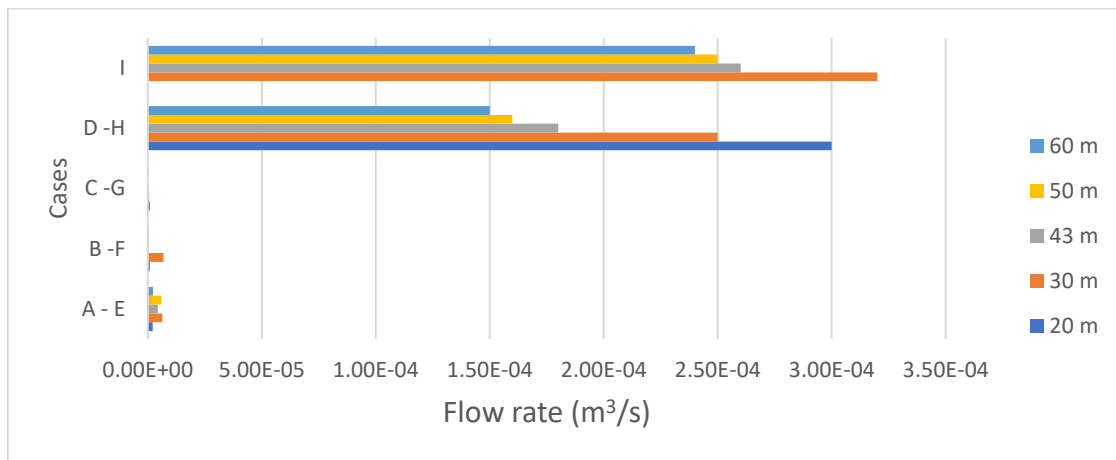
Table IV.6 shows the variation of the flow rate ( $\text{m}^3/\text{s}$ ) at the level of the reference points in the indicated zones as a function of different core base length.

**Table IV. 6:** Variation of the flow rate in different positions

Cases	A - E	B -F	C -G	D -H	I
20 m	2.14E-6	9.33E-7	8.07E-7	0.0003	0
30 m	6.28E-6	6.84E-6	5.89E-7	0.00025	0.00032
43 m	4.33E-6	3.96E-7	3.79E-7	0.00018	0.00026
50 m	5.93E-6	3.96E-7	3.59E-7	0.00016	0.00025
60 m	2.25 <sup>E</sup> -6	3.099E-7	3.18E-7	0.00015	0.00024

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Figure IV.10 shows the comparison between the values of the flow rate in the specific selected points with the different core base length.



**Figure IV. 10:** Variation of the flow rate (m<sup>3</sup>/s) in different core base length

**Interpretation**

The downstream zones experience the highest flow rate (D-H) and I, which strongly suggests the presence of seepage through the dam’s body or foundation. This phenomenon occurs when water from the upstream side finds pathways through the dam structure, embankment, or foundation, ultimately emerging on the downstream side. If left unchecked, excessive seepage can lead to internal erosion, piping failure, and structural instability.

This serves to reduce seepage, especially in core and downstream regions, by longer cores.

**v. Final Comparison**

The following table IV.7 provides a comparative overview of the impact of different core base length on hydraulic head, pressure load, hydraulic gradient, and flow rate to establish the most appropriate configuration.

**Table IV. 7:** Final comparison between the cases studied

Base Length (m)	Seepage Risk	Hydraulic head Stability	Pressure Control	Gradient (Lower = Better)	Flow Rate (Lower = Better)
20m	High (worst)	Unstable	High variation	Very High	Highest

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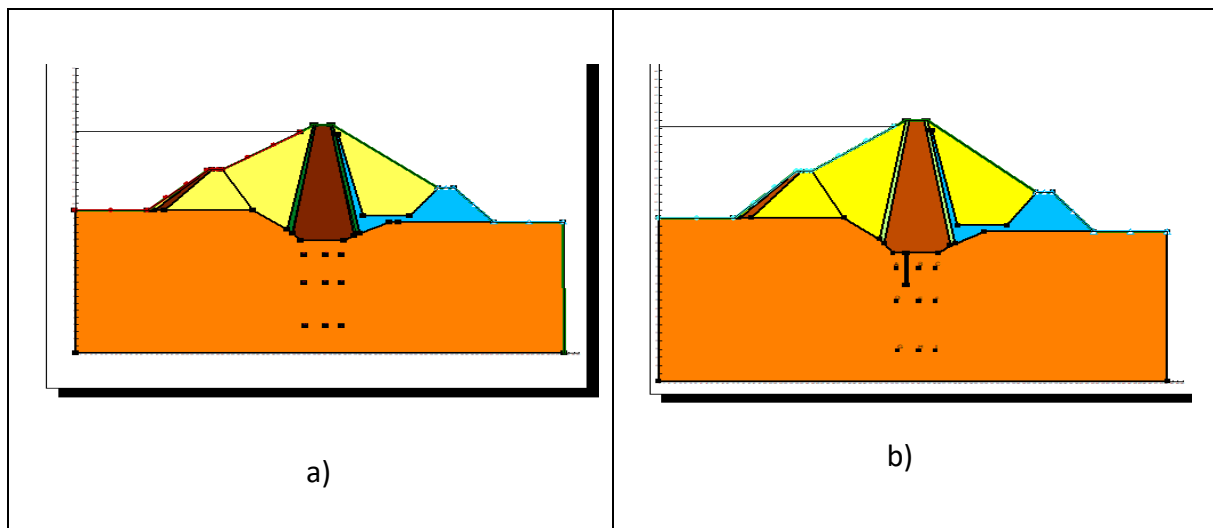
30m	High	Unstable	Moderate variation	High	High
43m	Balanced	Stable	Good	Low	Low
50m	Best balance	Stable	Best	Very Low	Very Low
60m	Best, but overkill	Best	Best	Lowest	Lowest

The optimal base length is 43m or 50m as it provides the best trade-off between seepage control, stability, and efficiency.

**2. Analysis of the influence of injection curtain depth**

This study aims to analyze the impact of injection curtains on three critical parameters influencing dam stability: hydraulic head, hydraulic gradient, and flow rate. Specifically, we will investigate how varying the depth of injection curtains affects these parameters and assess their role in enhancing the overall stability of dams.

Figure IV.11 shows the different cases of the grout curtain depth (without curtain, 20, 40 and 60 meter) that we are studying with GeoStudio.



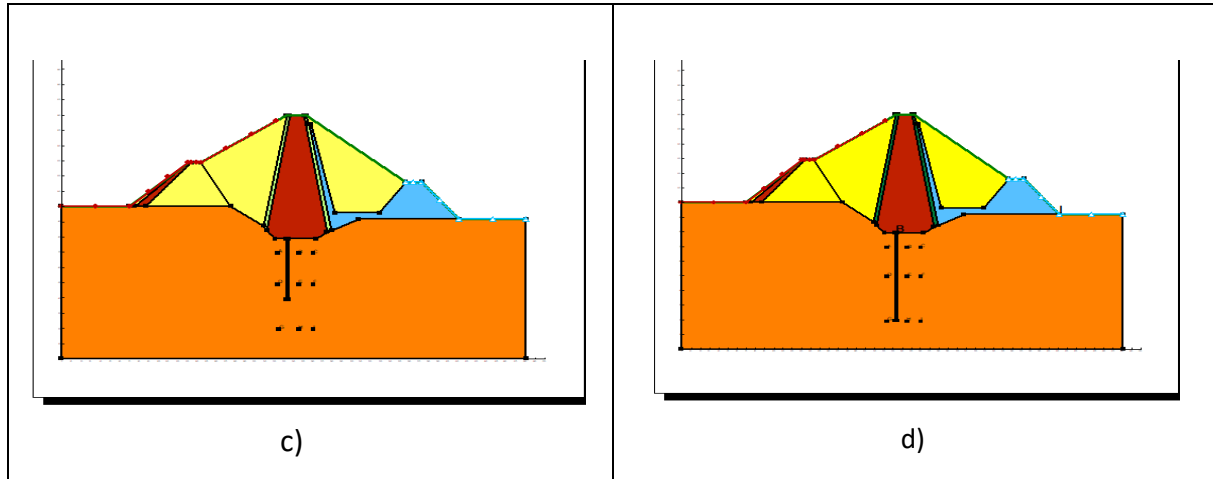
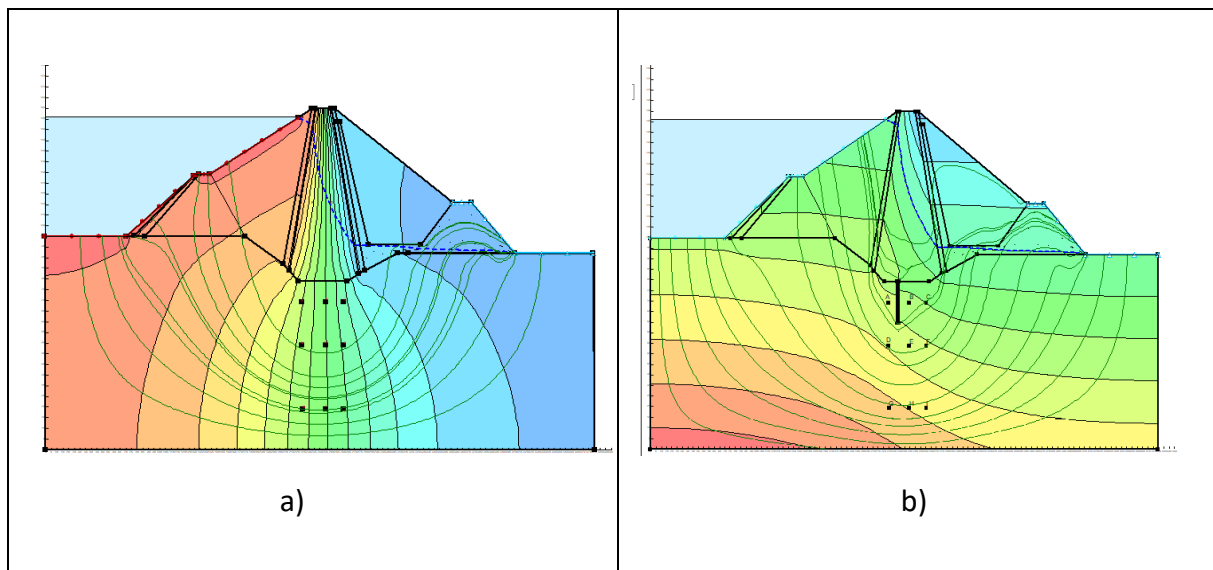


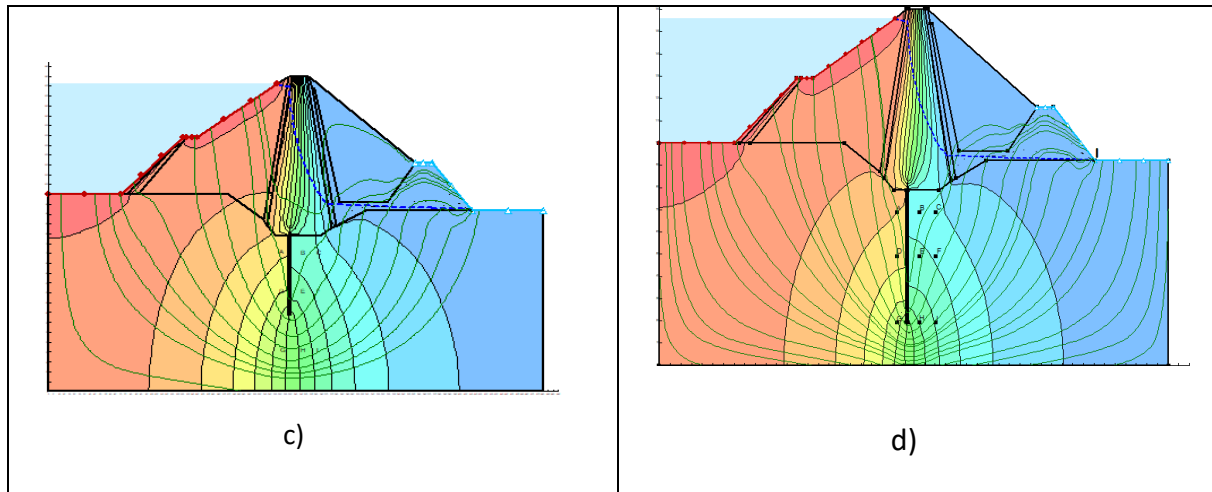
Figure IV. 11: Different depth for the grout curtain experimented in GeoStudio

a) L=0m, b) L=20m, c) L=40m, d) L=60m

**a. Effects of the depth of the grout curtain on seepage flow networks**

Figure IV.12 shows the behavior of the seepage flow network in different grout curtain depth (ranging from 0 to 60 m).





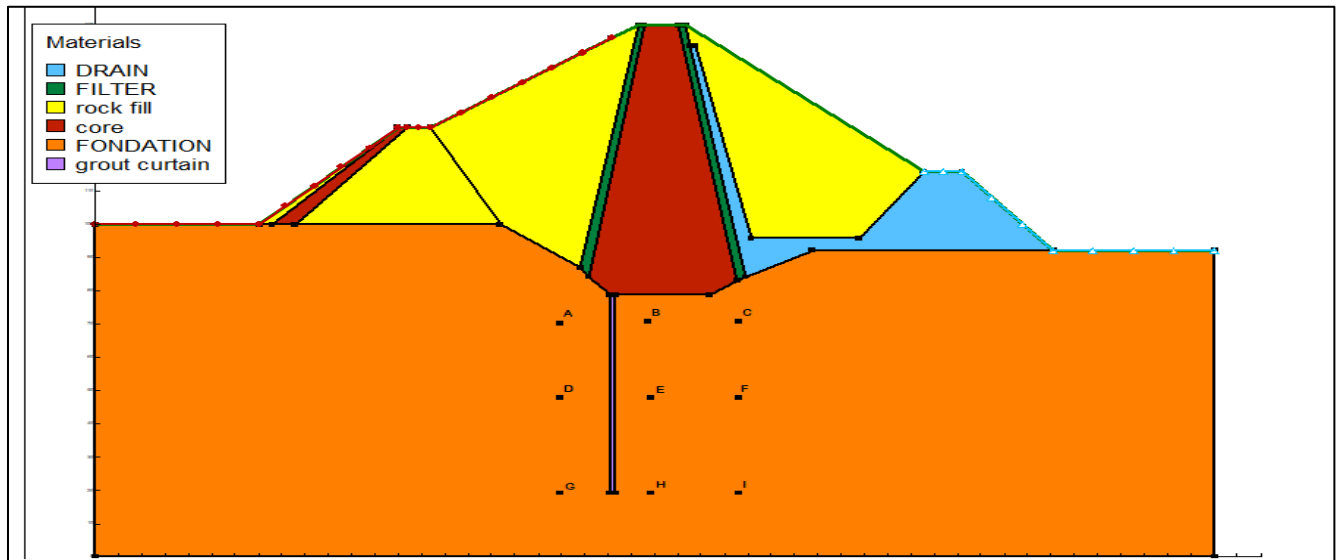
**Figure IV. 12:** Variation of the flow network according to the depth of the grout curtains.

The analysis of the flow network under different conditions reveals important variations in water movement depending on the presence and depth of the injection curtain. In the baseline case, without any injection curtain, the flow lines are continuous, indicating seepage with high hydraulic gradients near the base, leading to uncontrolled water movement. Introducing a grout curtain at different levels (20 m, 40 m, and 60 m) progressively improves seepage control. Grout curtain depth of 20 m, there is a slight reduction in water infiltration, though leakage remains evident. Increasing the injection to 40 m results in a more noticeable decline in seepage, as the hydraulic gradient is altered and the barrier becomes more effective in redirecting flow. The most effective scenario is with an injection of 60 m, where the flow paths are significantly restricted, demonstrating optimal control over water movement and reducing pressure on downstream areas. This comparison highlights that higher injection levels lead to better seepage mitigation, with Injection 60 m providing the most efficient solution for controlling water infiltration.

### **b. Hydraulic parameters analysis**

In this part, we are going to examine different hydraulic parameters in various locations of points in the area that appear to be affected by the grout curtain depth.

Figure IV.13 illustrates the specific points where the parameters will be measured and analyzed



**Figure IV. 13:** Different specific studied points

All the points to be studied are located under the core area to observe the effect of the grout curtain depth on the hydraulic parameters.

In this study we compare among the real case of the dam without the grout curtain and the same dam with grout curtain of depth 20,40 and 60m.

**i. Total hydraulic head**

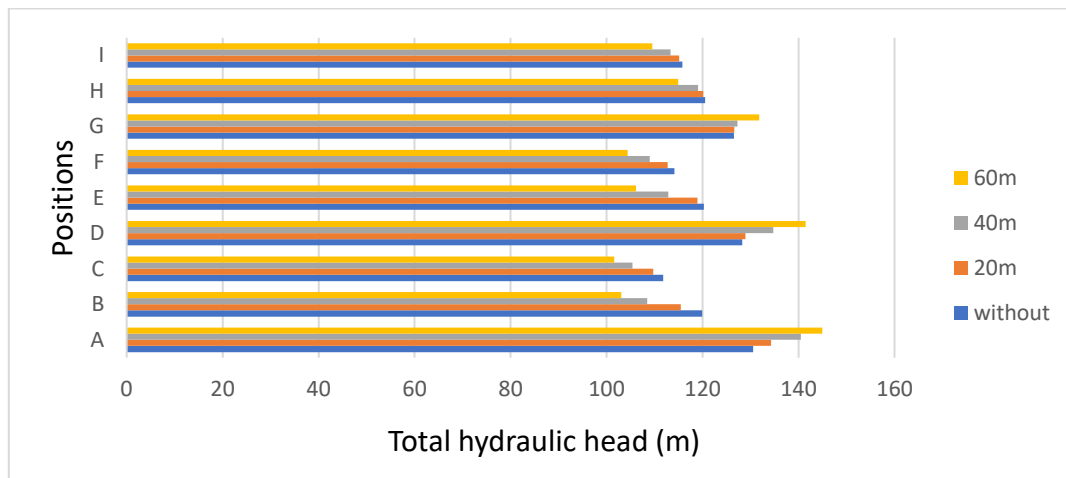
Table IV.8 shows the variation of the hydraulic head (m) at the level of the reference points in the indicated zones as a function of different grout curtain depth.

**Table IV. 8:** Variation of the total hydraulic head in different positions

Cases	A	B	C	D	E	F	G	H	I
0m	151.27	126.13	117.81	94.79	152.60	136.16	114.86	94.81	92
20m	134.25	115.47	109.72	128.93	118.95	112.75	126.59	120.12	115.15
40m	140.47	108.47	105.41	134.72	112.87	108.97	127.26	119.06	113.32
60m	144.97	103.05	101.60	141.51	106.15	104.39	131.83	114.95	109.51

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Figure IV.14 shows the comparison between the values of the total hydraulic head in the specific selected points with the different grout curtain length.



**Figure IV. 14:** Variation of the total hydraulic head (m) in different grout curtain depths

### Interpretation

- The hydraulic head decreases significantly with the introduction of grout curtain (especially from "without" to 20m)., it increases again slightly with deeper curtains (40m → 60m). in the case of no curtain, water pressure is more freely distributed, hence higher hydraulic heads.
- Deeper than 20m, grout curtains can backup water upstream, slightly increasing the load again by back-pressure
- Points like A, E, G (further upstream) tend to have higher load values due to higher upstream pressure, downstream points (D, H, I) are comparatively lower loads but increase when grout curtain depths cause pressure redistribution.

So longer curtain is equal to more seepage control, but also increases upstream pressure, hence a non-linear hydraulic head trend.

Without grout curtain, the total hydraulic head is high.

### ii. Hydraulic gradient

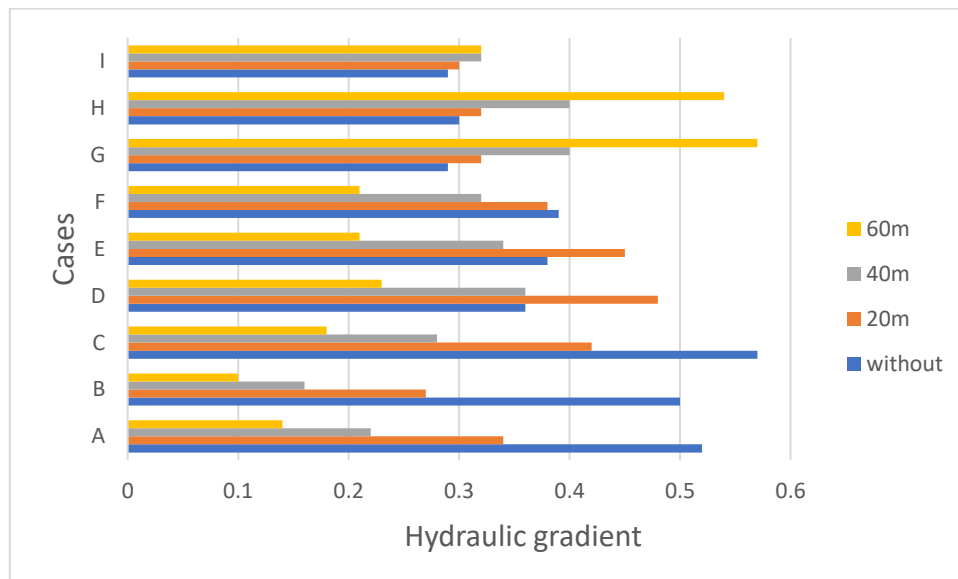
Table IV.9 shows the variation of the hydraulic gradient at the level of the reference points in the indicated zones as a function of different grout curtain length.

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**Table IV. 9:** Variation of the hydraulic gradient in different positions

Cases	A	B	C	D	E	F	G	H	I
without	0.52	0.50	0.57	0.36	0.38	0.39	0.29	0.30	0.29
20m	0.34	0.27	0.42	0.48	0.45	0.38	0.32	0.32	0.3
40m	0.22	0.16	0.28	0.36	0.34	0.32	0.40	0.40	0.32
60m	0.14	0.10	0.18	0.23	0.21	0.21	0.57	0.54	0.32

Figure IV.15 shows the comparison between the values of the hydraulic gradient in the specific selected points with the different grout curtain length.



**Figure IV. 15:** Variation of the hydraulic gradient in different grout curtain depths

**Interpretation**

- Before the placement of the grout curtain, points ABC has the highest gradient after the placement of the grout curtain observation are made that at the depth of 60m injection curtain points G and I experience the highest gradient.
- Even decline with increasing curtain depth for all points up to 40m.
- At 60m, irregular rise is shown by some points (e.g., G and H).
- Hydraulic gradient reduces as grout curtain resists seepage paths, leading to less energy loss in the flow domain.

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- At 60m, in some regions, increased gradient may occur due to flow redirection or concentration, especially in regions like G and H.
- Upstream points (A–C) show abrupt gradient drop-offs with longer curtains the flow impact cut off early.
- Mid-dam points (D–F) show transitions, less uniform behavior.
- Downstream points (G–I) show greater gradient at 60m, showing downstream concentration of flow paths.

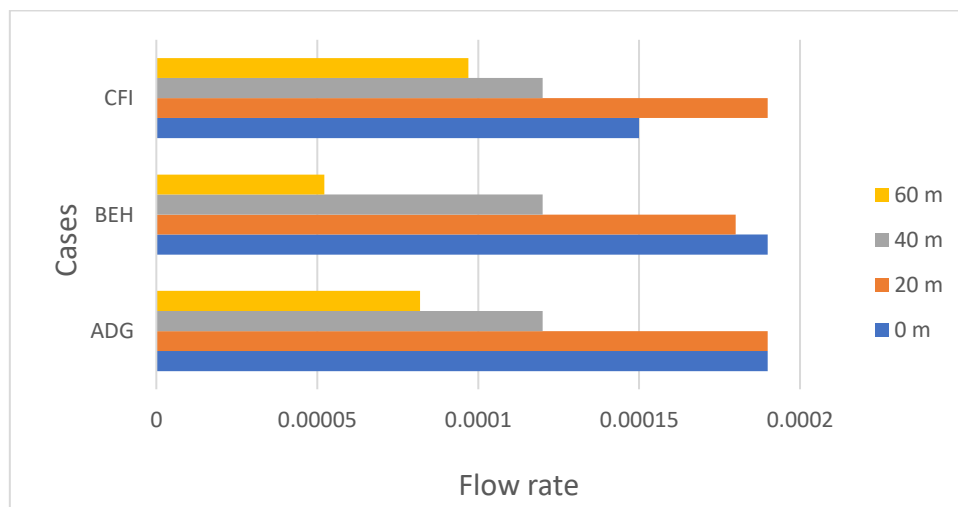
**iii. Flow rate**

Table IV.10 shows the variation of the flow rate ( $m^3/s$ ) at the level of the reference points in the indicated zones as a function of different grout curtain depth.

**Table IV. 10:** Variation of the flow rate in different positions

Cases	ADG	BEH	CFI
0m	0.00019	0.00019	0.00015
20m	0.00019	0.00018	0.00019
40m	0.00012	0.00012	0.00012
60m	$8.19^{E-5}$	$5.22^{E-5}$	$9.70^{E-5}$

Figure IV.16 shows the comparison between the values of the flow rate in the specific selected points with the different grout curtain depth.



**Figure IV. 16:** Variation of the flow rate ( $m^3/s$ ) in different grout curtain depths

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**Interpretation**

- The flow rate decreases slightly with 20 m, significantly with 40 m and 60 m. The grout curtain stops subsurface seepage, thus lowering flow rates directly.
- Maximum reduction occurs at 40 m and 60 m, which indicates the seepage zone is below deep and has a longer barrier length required to trap the main flow paths.
- The groups of points: ADG (left wing), BEH (centerline), CFI (right wing) are taken into account. All share same trend, but:

BEH (centerline) shows minimum value at 60m (5.22E-5), which means that center grout curtain depth contributes importantly to sealing efficiency, ADG and CFI are marginally higher, likely due to side leakage paths not fully overlapped by vertical curtain.

- Clearly inverse relationship: increased depth = lower flow rate due to increased interception of seepage paths.

**iv. Final comparison**

The following table IV.11 provides a comparative overview of the impact of different grout curtain depth on hydraulic head, hydraulic gradient, and flow rate to establish the most appropriate configuration.

**Table IV. 11:** Final comparison between the studied cases

Parameters	Effect of Curtain Length	Effect of Point Position (A–I)	Cause of Increase	Cause of Decrease
Hydraulic head (m)	Decreases from 0m → 20m; Slight increase from 40m → 60m	Higher at upstream points (A, E); Lower at downstream (D, H, I)	Increased upstream pressure due to deeper curtain; flow accumulation	Reduced seepage and pressure due to curtain acting as a barrier
Hydraulic Gradient	Decreases significantly with curtain depth to 40m; Some increases at 60m	Sharp drop at upstream (A–C); Rise again at downstream (G, H) at 60m	Flow concentration at downstream zones due to longer curtain; redirection effects	Flow obstruction reduces gradient and seepage energy across the profile

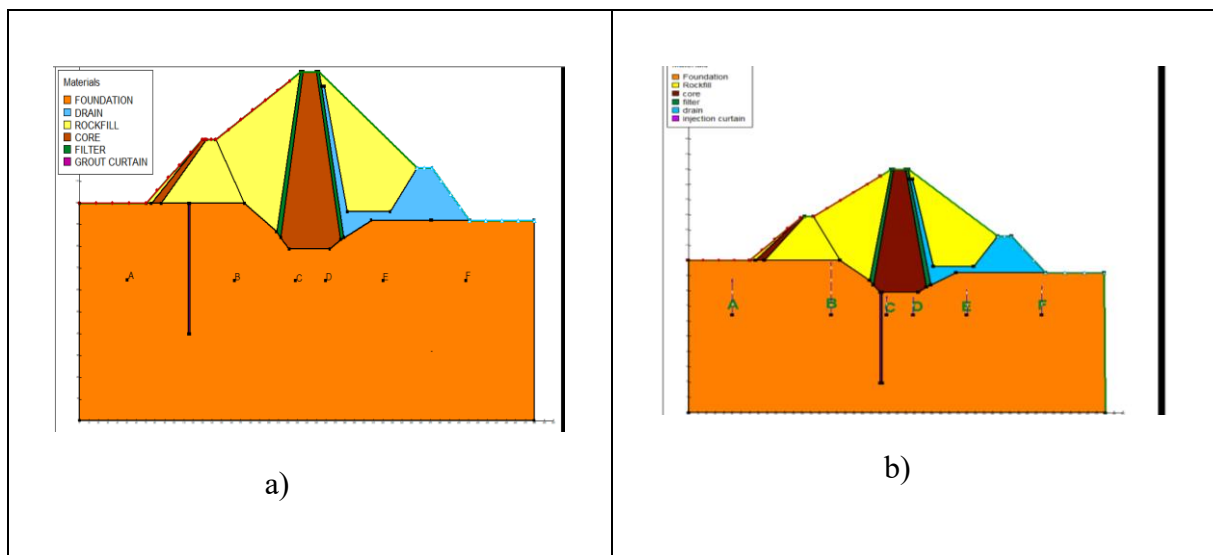
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Flow Rate (m <sup>3</sup> /s)	Minimal change at 20m; Sharp reduction at 40m and 60m	BEH (centerline) sees biggest reduction; Side zones (ADG, CFI) slightly higher	Side leakage or incomplete sealing in side areas; deeper curtain increases flow path	Effective interception of flow paths by deeper grout curtain
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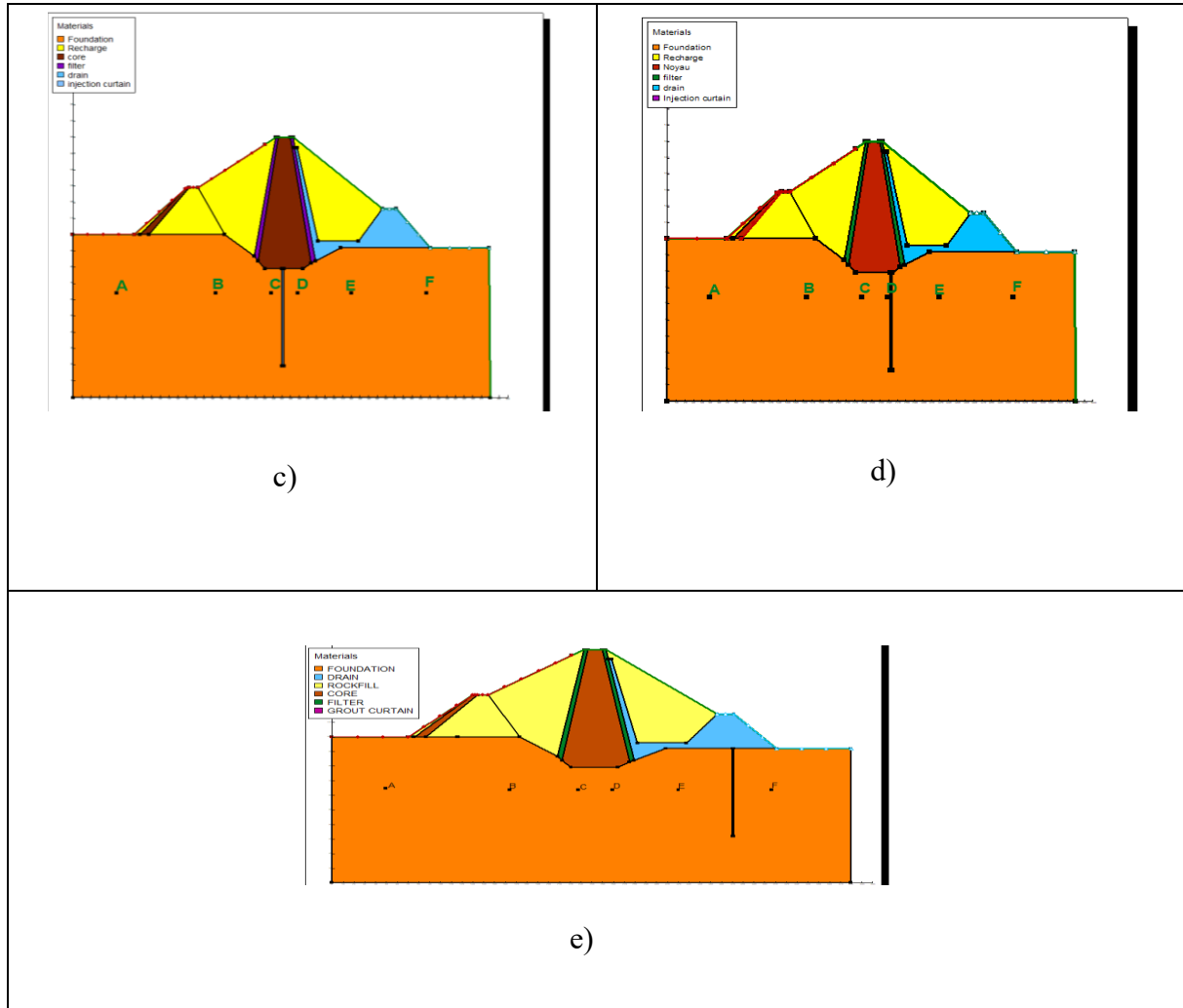
**3. Analysis of the influence of the grout curtain position**

In this study, analysis of the impact of changing the position of the grout curtain on the hydraulic parameters: hydraulic head, pore water pressure, hydraulic gradient, and flow rate. To achieve this, we will examine five different positions, comparing their effects. The analysis will be conducted at various points, including the upstream area, the core, and the downstream region, to comprehensively assess how changes in position influence these hydraulic variables. By identifying potential variations in stability and performance, this study aims to determine whether an optimal position exist that enhances structural integrity and efficiency in water-retaining structures.

Figure IV.17 shows the different cases of the grout curtain positions (upstream, core and downstream) that we are studying with GeoStudio.



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**Figure IV. 17:** Different positions for the grout curtain experimented in GeoStudio

- a) Upstream, b) Core start, c) Core middle, d) Core ending, e) Downstream

a. Effects of different position of the grout curtain on seepage flow networks

Figure IV.18 shows the behavior of the seepage flow network in different grout curtain positions (upstream, core and downstream).

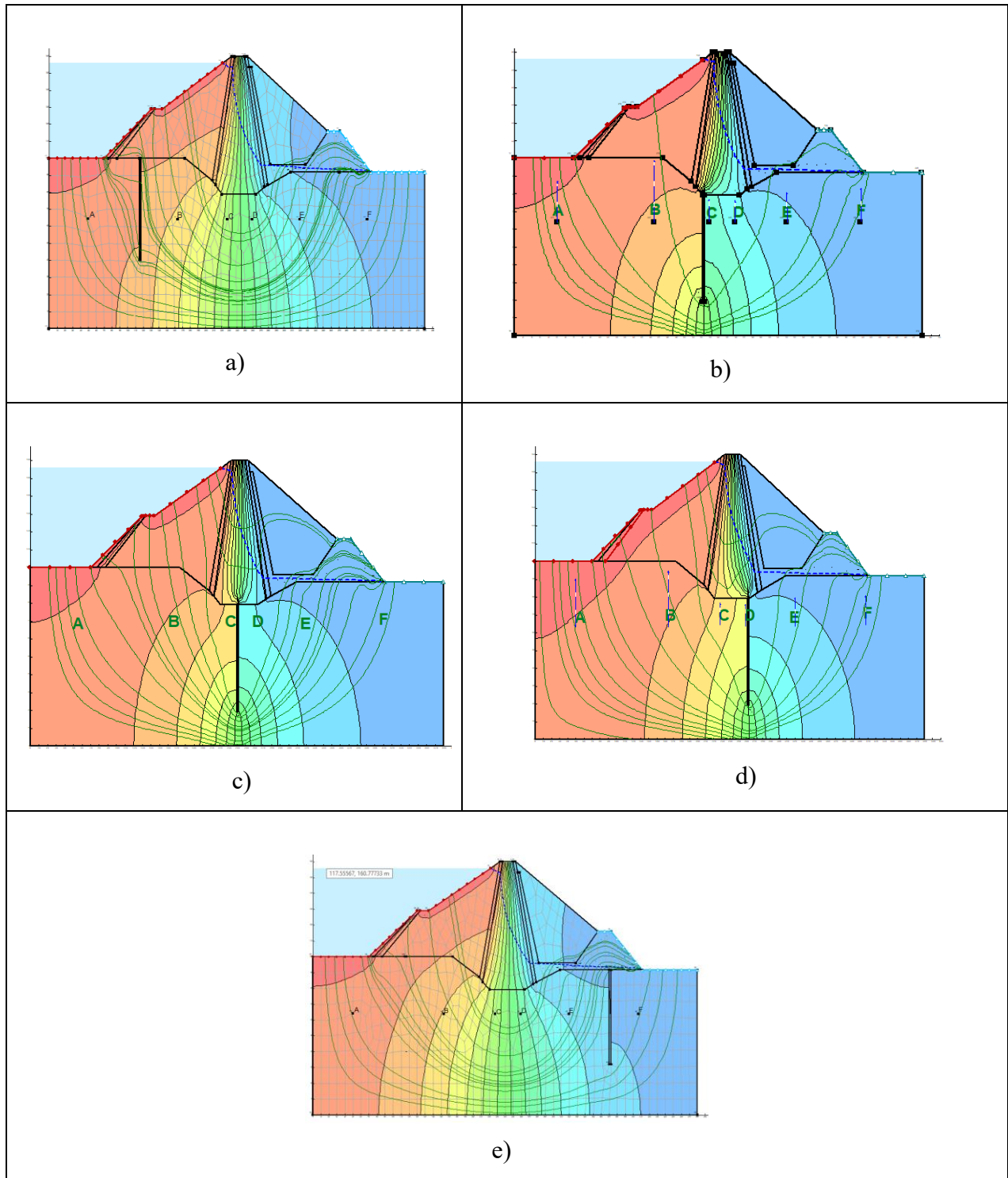


Figure IV. 18: Variation of the flow network according to different positions of the grout curtains.

a) Upstream, b) Core start, c) Core middle, d) Core ending, e) Downstream

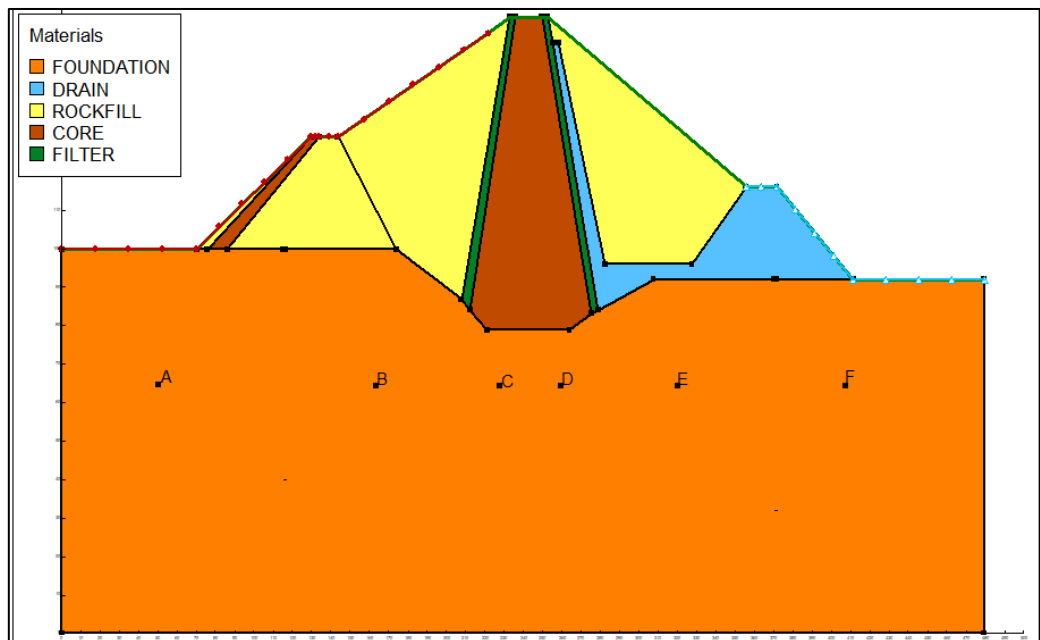
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The flow network patterns show that the installation of the grout curtain in the core especially toward its tip more effectively disrupts seepage paths with the creation of flow lines of equal concentration. Positioning upstream or downstream, however, leads to more random flow patterns, higher gradients, and potential bypassing of the barrier, with a loss of overall efficiency

### b. Hydraulic parameters analysis

In this study the impact of changing the position of the drain is observed on the hydraulic parameters.

Figure IV.19 below illustrates the specific studied points.



**Figure IV. 19:** Positions of the analysis points

All the points to be studied are located under the foundation area to observe the effect of the grout curtain position on the hydraulic parameters.

Table IV.12 below shows the position of the specific points studied in the dam.

**Table IV. 12:** Positions of the points studied in the dam

Area	Upstream	Core	Downstream
Points	A-B	C-D	E-F

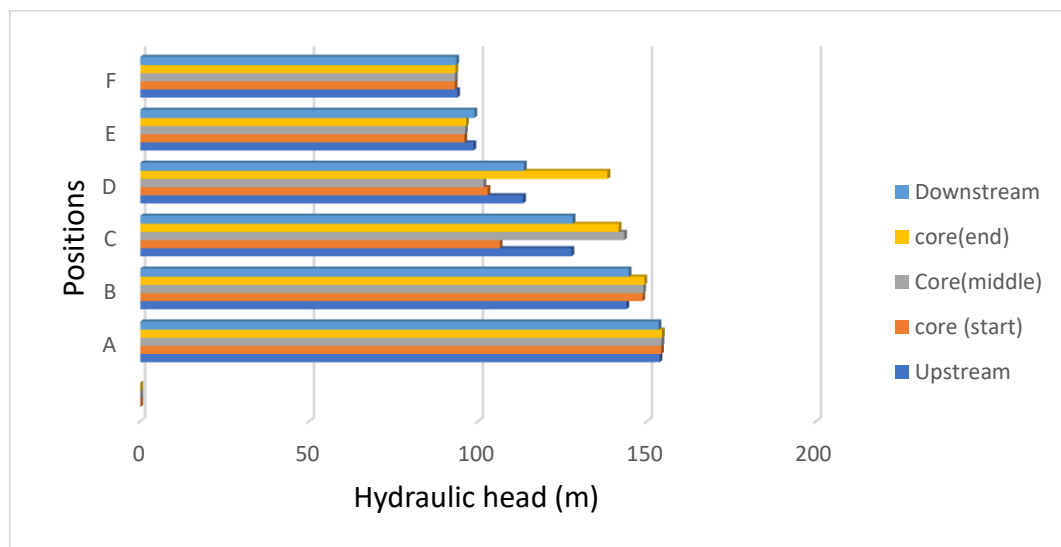
**i. Hydraulic head**

Table IV.13 shows the variation of the total hydraulic (m) load at the level of the reference points in the indicated zones as a function of different grout curtain position.

**Table IV. 13:** Variation of the total hydraulic head in different positions

Cases		A	B	C	D	E	F
Upstream		153.71	143.92	127.66	113.33	98.63	93.84
Core	Start	154.16	148.64	106.44	102.84	95.97	93.11
	Middle	154.30	148.89	143.24	101.682	96.17	93.18
	End	154.41	149.21	141.60	138.32	96.47	93.32
Downstream		153.41	144.59	127.99	113.60	98.94	93.56

Figure IV.20 shows the comparison between the values of the hydraulic head in the specific selected points with the different grout curtain position.



**Figure IV. 20 :** Variation of the total hydraulic head (m) influenced by grout curtain position

**Interpretation**

- Maximum values are always seen upstream (points A, B).
- Values decrease slowly towards downstream (points E, F).
- The core-end grout curtain experiences larger hydraulic heads in the core (C, D) compared to others.
- The core-start location causes a sharp decrease in the load in the core zone (especially at point C).

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- High loads in the upstream are expected because the pressure of water is naturally higher there. When the curtain is placed at the end of the core, it has higher water pressure in the core zone, as seepage is further restricted downstream. Conversely, early start permits water to escape more readily through the core, thus lower pressure in midpoints.
- As a conclusion the hydraulic head is higher as the curtain is driven deeper into the core, especially towards the end.

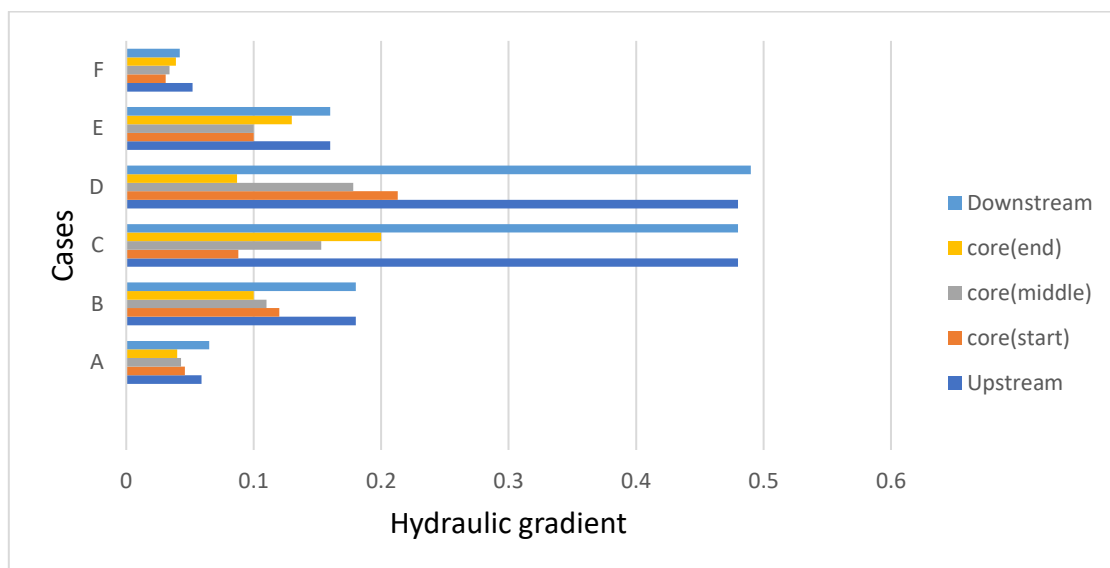
**ii. Hydraulic gradient**

Table IV.14 shows the variation of the hydraulic gradient at the level of the reference points in the indicated zones as a function of different grout curtain position.

**Table IV. 14:** Variation of the hydraulic gradient for different positions of grout curtain

Cases		A	B	C	D	E	F
Upstream		0.059	0.18	0.48	0.48	0.16	0.052
Core	Start	0.046	0.12	0.088	0.213	0.10	0.031
	Middle	0.043	0.11	0.153	0.178	0.10	0.034
	End	0.040	0.10	0.20	0.087	0.13	0.039
Downstream		0.065	0.18	0.48	0.49	0.16	0.042

Figure IV.21 shows the comparison between the values of the hydraulic gradient in the specific selected points with the different grout curtain positions.



**Figure IV. 21:** Variation of the hydraulic gradient influenced by grout curtain position

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**Interpretation**

- Downstream and upstream curtains experience high gradients (especially at points C and D).
- Core-start curtain experiences significant decrease in central points' gradients.
- Core-end curtain offers moderate gradients overall
- High gradients show steeper water flow paths with increased chances of seepage and erosion.
- Core-start curtain reduces these gradients by reducing seepage early, dispersing flow energy.
- End-core curtain delays the flow path by offsetting the gradient but still allowing some seepage to attain mid-core zones.
- As conclusion the hydraulic gradient decreases when grout curtain is placed at the beginning or halfway in the core, limiting water flow. No curtain or downstream allows high gradients unfit for dam stability.

**iii. Flow rate**

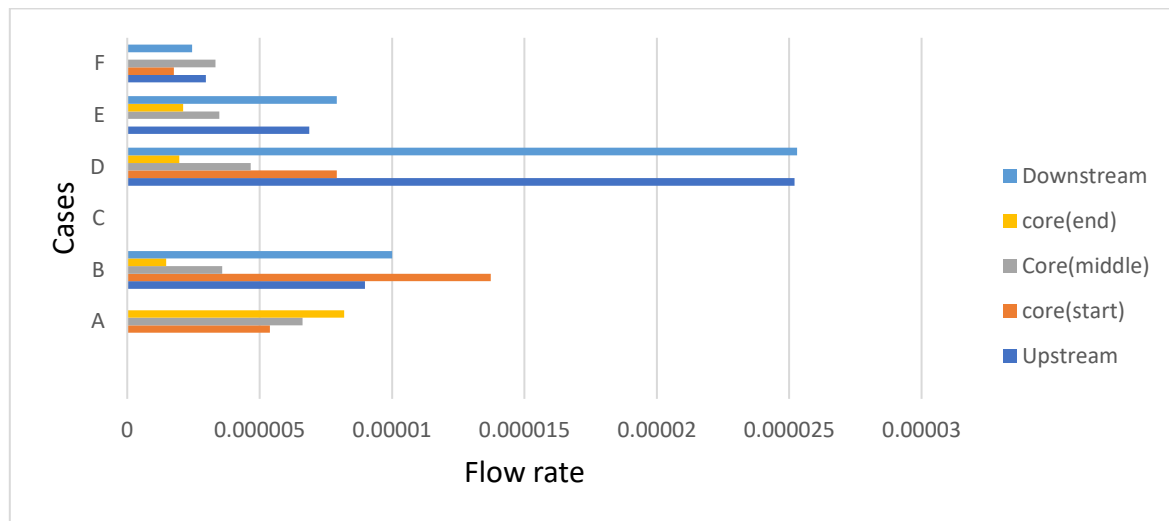
Table IV.15 shows the variation of the flow rate ( $m^3/s$ ) at the level of the reference points in the indicated zones as a function of different core base positions.

**Table IV. 15:** Variation of the flow rate in different positions

Cases		A	B	C	D	E	F
Upstream		0	8.98E-6	0	2.52E-5	6.88E-6	2.97E-6
Core	Start	5.384E-6	1.373E-5	0	7.918E-6	0	1.763E-6
	Middle	6.621E-6	3.583E-6	0	4.658E-6	3.474E-6	3.335E-6
	End	8.191E-6	1.47E-6	0	1.971E-6	2.108E-6	0
Downstream		0	1E-5	0	2.53E-5	7.91E-6	2.45E-6

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Figure IV.22 shows the comparison between the values of the flow rate in the specific selected points with the different grout curtain positions.



**Figure IV. 22:** Variation of the flow rate ( $\text{m}^3/\text{s}$ ) influenced by grout curtain position

### Interpretation

- Upstream and downstream curtain positions have higher flow rates, especially at point D.
- Core-start curtain effectively reduces flow at multiple points.
- Core-end curtain also reduces flow but not as effectively in mid-core.
- Flow rate is directly proportional to the path of least resistance placing the curtain earlier in the seepage path impedes more flow.
- When the curtain is at core start, it truncates seepage early and has the effect of minimal water reaching downstream areas.
- End-core curtain blocks flow near the exit, but much water already flows through by that time representing less than minimum but not minimal flow.
- As a conclusion the most efficient in minimizing seepage flow is the core-start curtain. Flow rate is greater when the curtain is too far down stream with additional path for water to exit.

### iv) Final comparison

The following table IV.16 provides a comparative overview of the impact of different grout curtain placements on hydraulic head, hydraulic gradient, and flow rate to establish the most appropriate configuration.

**Chapter IV: Analysis of hydraulic behavior in a dam using GeoStudio: the effect of waterproofing on seepage and stability, case of Boughrara dam.**

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**Table IV. 16:** Final comparison between the studied cases

Parameter	Increase/Decrease	Caused by	Best Curtain Position
Hydraulic head	↑ With upstream curtain ↓ with core curtain	More resistance to flow, pressure buildup	Core-end or core-middle
Hydraulic Gradient	↑ With upstream curtain ↓ with core curtain	Flow energy intercepted early	Core-start or core-middle
Flow Rate	↑ With early curtain ↓ with core curtain	Seepage blocked sooner	Core-start

An early curtain in the center (core start or middle) produces optimum seepage control and gradient decrease. If the goal is to prevent back pressure (e.g., to maintain upstream head), a mid-total curtain would be preferable.

**IV.10. Conclusion**

The current chapter presented a rigorous examination of hydraulic behavior for Boughrara dam considering the implications of the variation of core base length, grout curtain depth, and grout curtain location on a number of parameters such as hydraulic head, gradient, and seepage flow. These outcomes presented a refinement in pressure distribution with a reduction in seepage by the increase in core base length with satisfactory performance displayed between 43 to 50 meters. Extensions of the core base of 40–60 meters significantly enhance seepage control, while a curtain position at the start or middle of the core is most effective in reducing flow rate and hydraulic gradient. Overall, the ideal arrangement for delivering dam stability and waterproofing effectiveness is the synergy between an efficiently extended core base and an appropriately placed and sufficiently deep grout curtain.

The most favorable overall arrangement is achieved with a 50 m core base length; a 60 m deep grout curtain placed at the start of the core.

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## **Chapter V: Analysis of drainage systems influence on dam's behavior**

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### V.1. Introduction

Drainage systems are important in dams. A good drainage system means an efficient working dam. In this chapter the impact of drainage system is observed in the dam. The length and the position of the drainage system are changed using Geo studio simulation which has been introduced previously in chapter IV.

### V.2. Consistency of the modelling

This analysis focuses on the effect of drains the case of the Boughrara dam. The main objective is to analyse the effect of drains on the dam's foundation and generally the whole dam stability. To achieve this, the study includes numerical simulations with different drain length and changing the position of the drain using Geo studio.

The first and the second sets of simulations examine the impact of changing the length of the drain. The first case being the effect of changing the length drain only, then a grout curtain is added.

- Case 1: drain length equal to 20m
- Case 2: drain length equal to 40m
- Case 3: drain length equal to 60m.

In the third and the fourth set of simulations, the focus shifts to changing the positioning of the drain within the foundation. The cases considered are:

- Case 1: changing the position of the drain
- Case 2: drain is placed on the upstream and the downstream of the grout curtain.

By analyzing the hydraulic gradients, pore water pressures, and seepage rates under these different scenarios, the study aims to identify the most efficient design parameters for optimizing dam impermeability and stability. The main objective is to examine the effect of altering the length and position of the drainage system inside a dam structure on the key hydraulic parameters.

V.2.1. Analysis of the drain depth influence

This study aims to analyze the impact of the drain system on a number critical parameters influencing dam stability. Specifically, we will investigate how varying the depth of the drain affects these parameters and assess their role in enhancing the overall stability of the dam.

Figure V.1 shows the different cases of the drain depths (20, 40 and 60 meters) that are studied with GeoStudio.

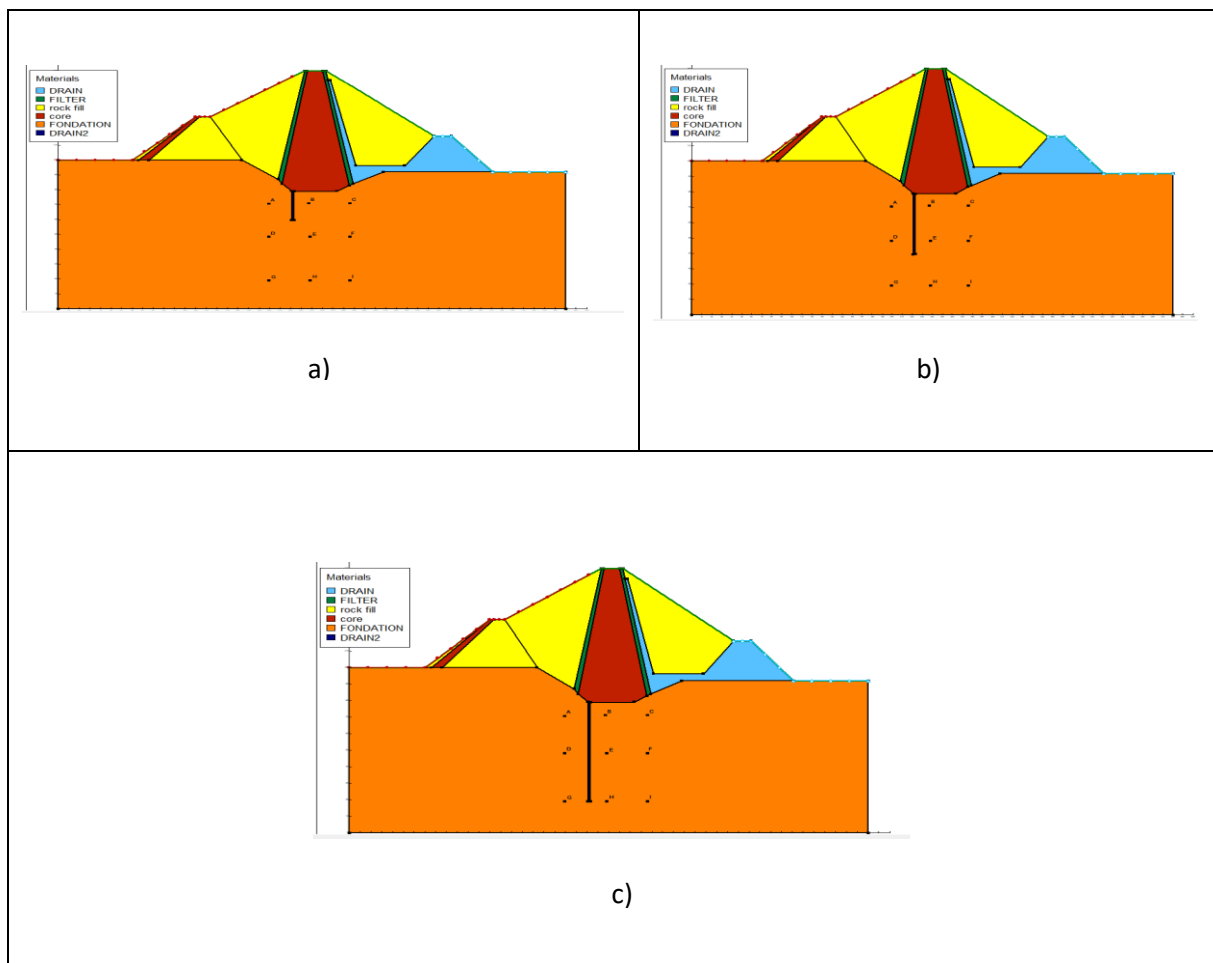


Figure V. 1: Simulation done using Geo Studio with different drain depth

a) L=20m, b) L= 40m, c) L=60m

1. Effects of the length of the drain on seepage flow networks

Figure V.2 shows the behaviour of the seepage flow network in different drain depth (ranging from 20 to 60 m).

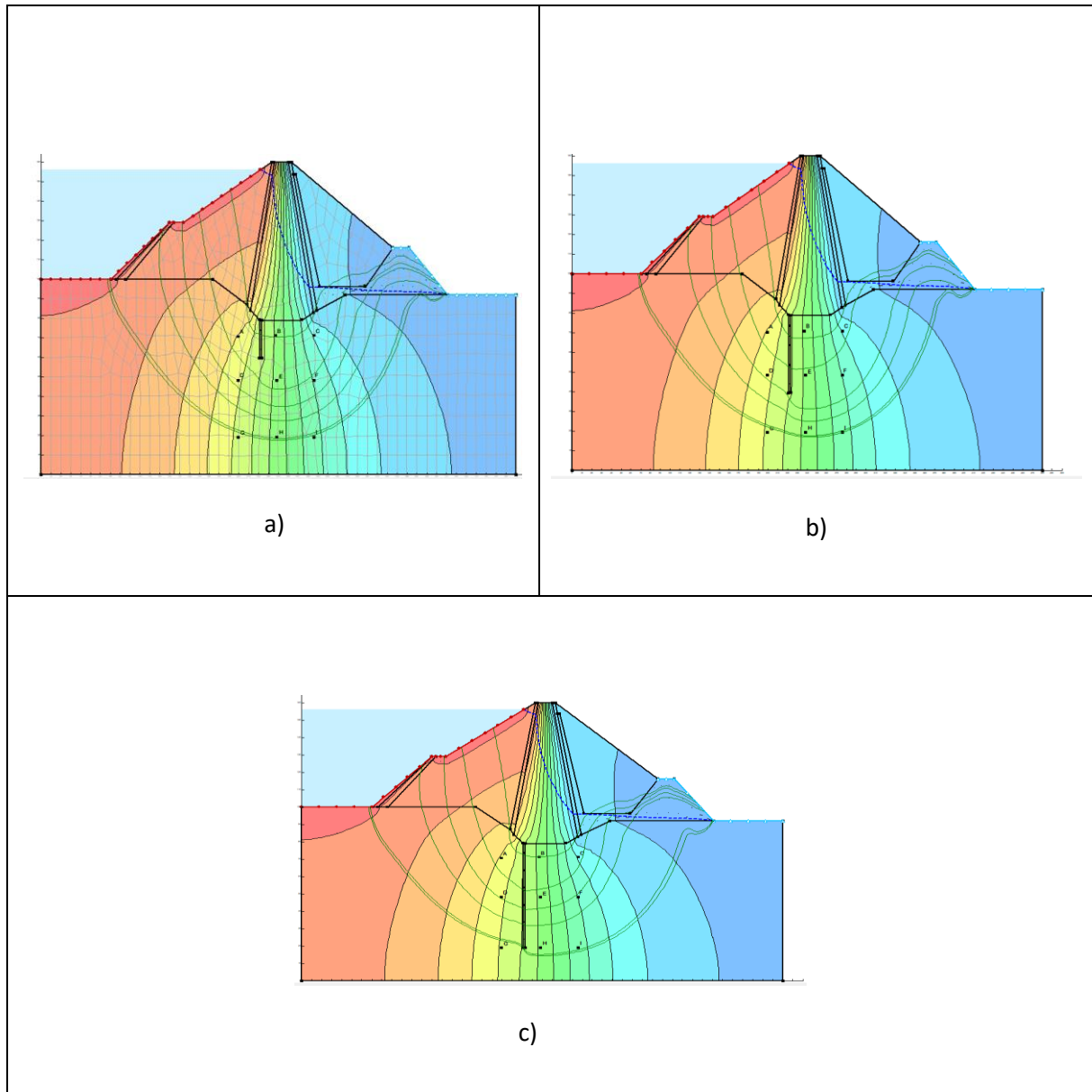


Figure V. 2:Flow network according to the depth of the drain

a) L=20m, b) L= 40m, c) L=60m

The flow network visually represents the routes of seepage water in the dam foundation under different drain depth. With increasing drain depth from 20 m to 60 m, seepage lines become slightly more horizontal and dilute, particularly near the structure bottom. This demonstrates a smoother and more dispersed flow, which results minor reductions in hydraulic pressure and gradient. However, the overall, trend of flow is basically the same and indicates that

individually the drain at even 60 m depth does not seriously alter or restrict the overall amount of seepage. Drains help control the path of flow and possibly reduce the potential for areas of concentrated flow, which are likely to lead to piping. Still, without a cutoff barrier (grout curtain), seepage paths at deeper depth persist.

## 2. Hydraulic parameters studied

In this part, different hydraulic parameters are to be examined in various locations of points in the area that appear to be affected by the drain depth. Figure V.3 illustrates the specific points where the parameters will be measured and analysed:

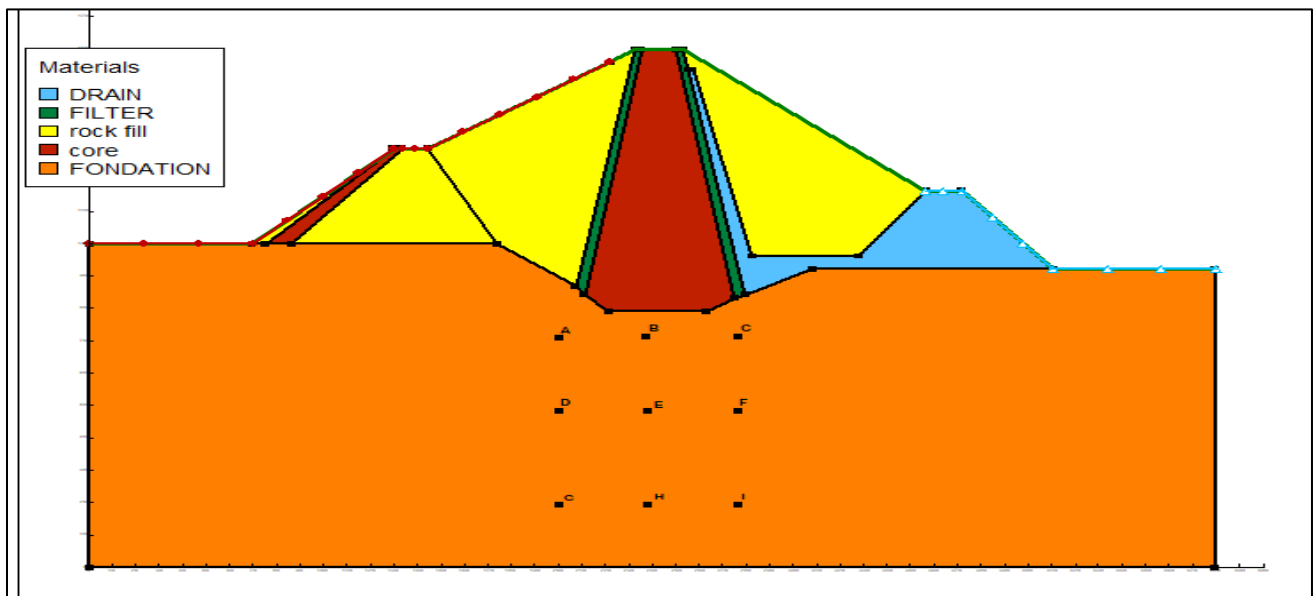


Figure V.3: Different specific studied points

### a. Hydraulic head

Table V.1 Variation of the hydraulic head at the level of the reference points in the indicated zones as a function of different drain length.

Table V. 1: Total hydraulic head with drain depth

Cases	A	B	C	D	E	F	G	H	I
20m	139.52	123.73	104.49	135.73	123.01	109.53	133.58	122.66	111.89
40m	139.44	123.58	104.62	136.03	123.58	109.82	134.16	123.40	112.29
60m	139.19	123.11	104.56	135.83	123.32	109.79	134.35	123.84	112.39

Figure V.4 Comparison between the values of the hydraulic head at the specific selected points with the different drain depth.

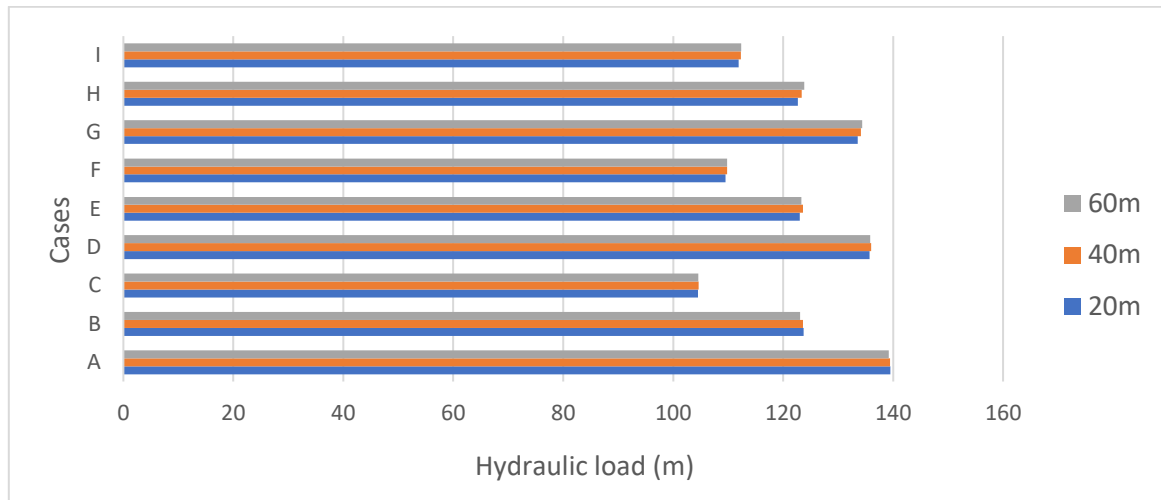


Figure V. 4: Variation of the hydraulic head drain depth influence

**Interpretation**

At all points studied, the hydraulic head varied minimally with the increase in drain depth. Minor decreases were observed at some downstream and mid-core points (e.g., G, H, and I), showing that a deeper drain can be efficient in reducing the internal pressure slightly by depressing the line of saturation. Upstream points (A, B) were unaffected, since the drain is on the downstream and does not influence upstream hydraulic conditions. This confirms that while the drain contributes partially to the stability of the dam foundation, it is not effective in overall load distribution in the absence of other sealing structures.

**b. Pore water pressure**

Table V.2 gives the variation of pore water pressure (Kpa) at the level of the reference points in the indicated zones as a function of different drain depth.

Table V. 2:Variation of pore water pressure in different positions drain depth influence

Cases	A	B	C	D	E	F	G	H	I
20m	677.23	517.78	329.10	859.71	734.97	602.83	1122.43	1015.3	909.69
40m	676.46	516.31	330.45	862.73	740.59	605.68	1128.09	1022.57	913.61
60m	673.98	511.73	329.82	860.72	738.08	605.38	1129.94	1026.89	914.53

Figure V.5. Comparison between the values of the pore water pressure in the specific selected points with the different drain depth.

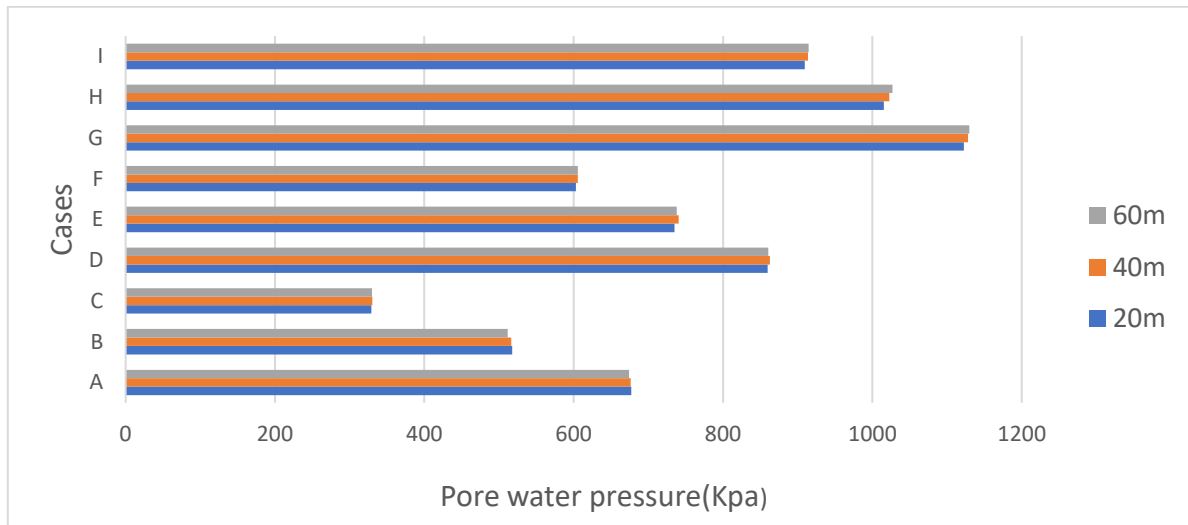


Figure V. 5: Variation of pore water pressure drain depth influence

**Interpretation**

The pore water pressure also followed a similar trend to that of the hydraulic head, with very little reduction with deeper drains. The higher pressures were measured by downstream points (G, H, I) which recorded always high pressures because of the water buildup, while central core points (C, F) measured the lowest. Although increasing the drain depth to 60 m at some points induced small pressure relief, the net impact was low. This implies that drains alone would be insufficient to adequately reduce pore water pressure significantly, particularly at a greater distance away from the path of drain or in materials of low permeability.

**c. Hydraulic gradient**

Table V.3 shows the variation of the hydraulic gradient at the level of the reference points in the indicated zones as a function of different drain depth.

Table V. 3: Variation of the hydraulic gradient in different position

Cases	A	B	C	D	E	F	G	H	I
20m	0.33	0.49	0.56	0.28	0.42	0.32	0.25	0.30	0.26
40m	0.31	0.47	0.56	0.26	0.42	0.36	0.23	0.31	0.27
60m	0.31	0.45	0.55	0.27	0.397	0.33	0.22	0.36	0.27

Figure V.6 shows hydraulic gradient drain depth influence

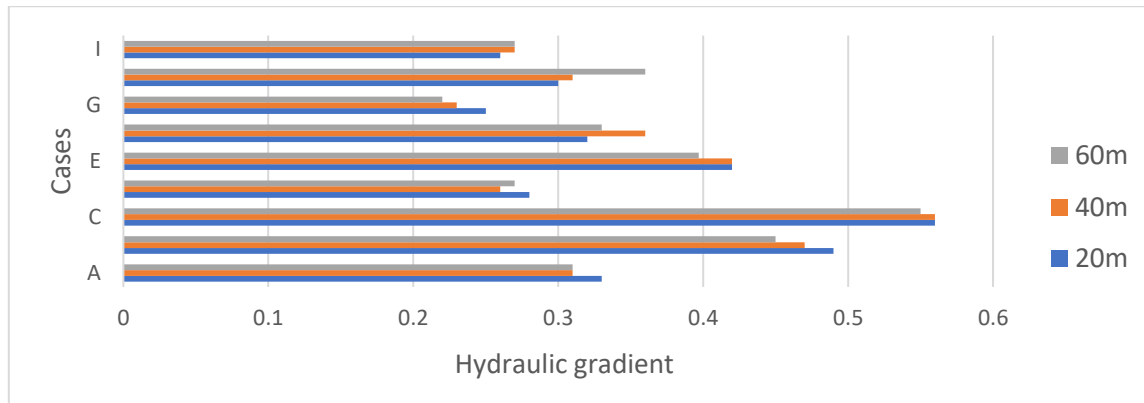


Figure V. 6: Hydraulic gradient drain depth influence

### Interpretation

Hydraulic gradient, which is a measure of water flow steepness and is among the internal erosion parameters, reduced by small values with longer drains, especially in mid and downstream sections such as B, C, F, and G. This suggests that deeper drains extend flow lines, allowing less turbulent water evacuation and lower energy that could be causing piping. Nonetheless, the differences between the 20 m, 40 m, and 60 m drains were not notable, indicating that drain depth in itself does not improve gradient conditions substantially under the tested configuration.

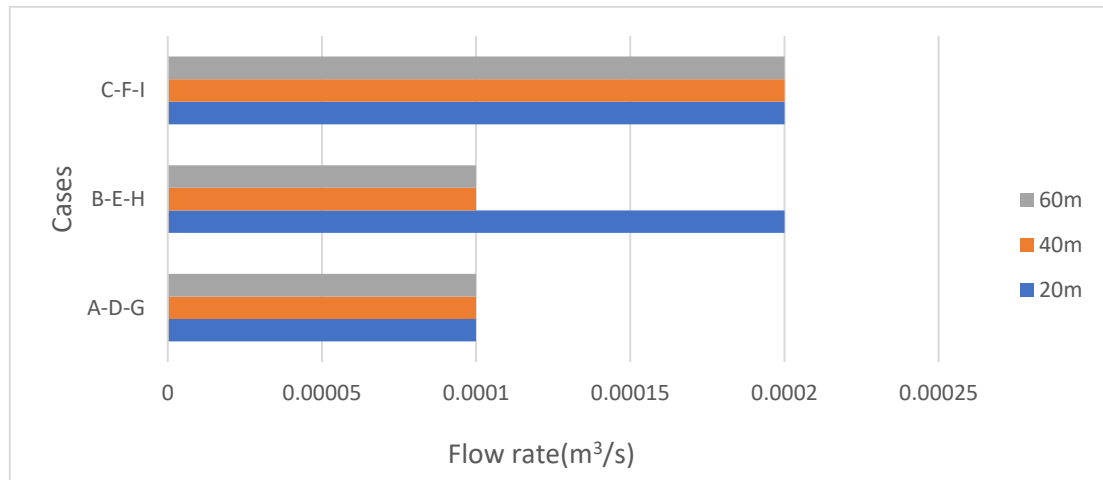
### d. Flow rate

Table V.4 shows the variation of the flow rate at the level of the reference points in the indicated zones as a function of different drain depth.

Table V. 4: Variation of the flow rate

Cases	A-D-G	B-E-H	C-F-I
20m	0.0001	0.0002	0.0002
40m	0.0001	0.0001	0.0002
60m	0.0001	0.0001	0.0002

Figure V.7 Comparison between the values of the flow rate in the specific selected points with the different drain depth



**Figure V. 7:** Variation of flow rate with change of the depth of the drain

The depth of the drain curtain does not affect the flow rate significantly results show that the flow rate is almost constant except on one occasion where the drain depth is 20 m on one specific position B-E-H this is due to the flow network passes through these specific points.

### V.2.2. Analysis of the possible relationship of drain depth with injection curtain

This study aims to analyze the impact of the combination of the most reliable grout curtain results identified in the previous chapter which is 60 m in the beginning of the core with varying drain length on critical parameters influencing dam stability.

Figure V.8 Simulation done using Geo Studio with different drain depth which are:

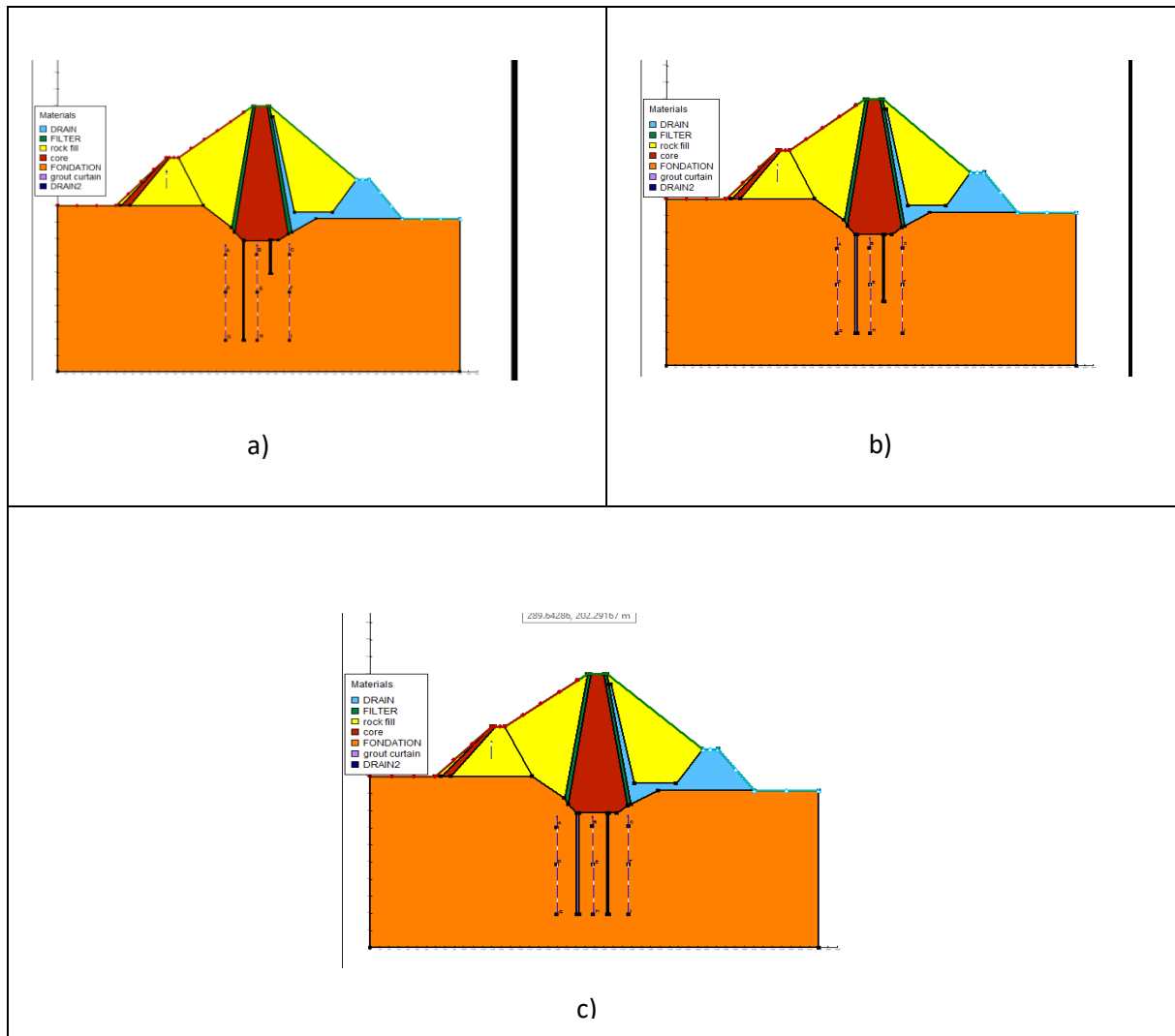


Figure V. 8: Different depth of drain

a) L=20m, b) L= 40m, c) L=60m

1. Variation of saturation line with the depth of the drain

Figure V.9 below shows the variation of the saturation line with the length of the drain.

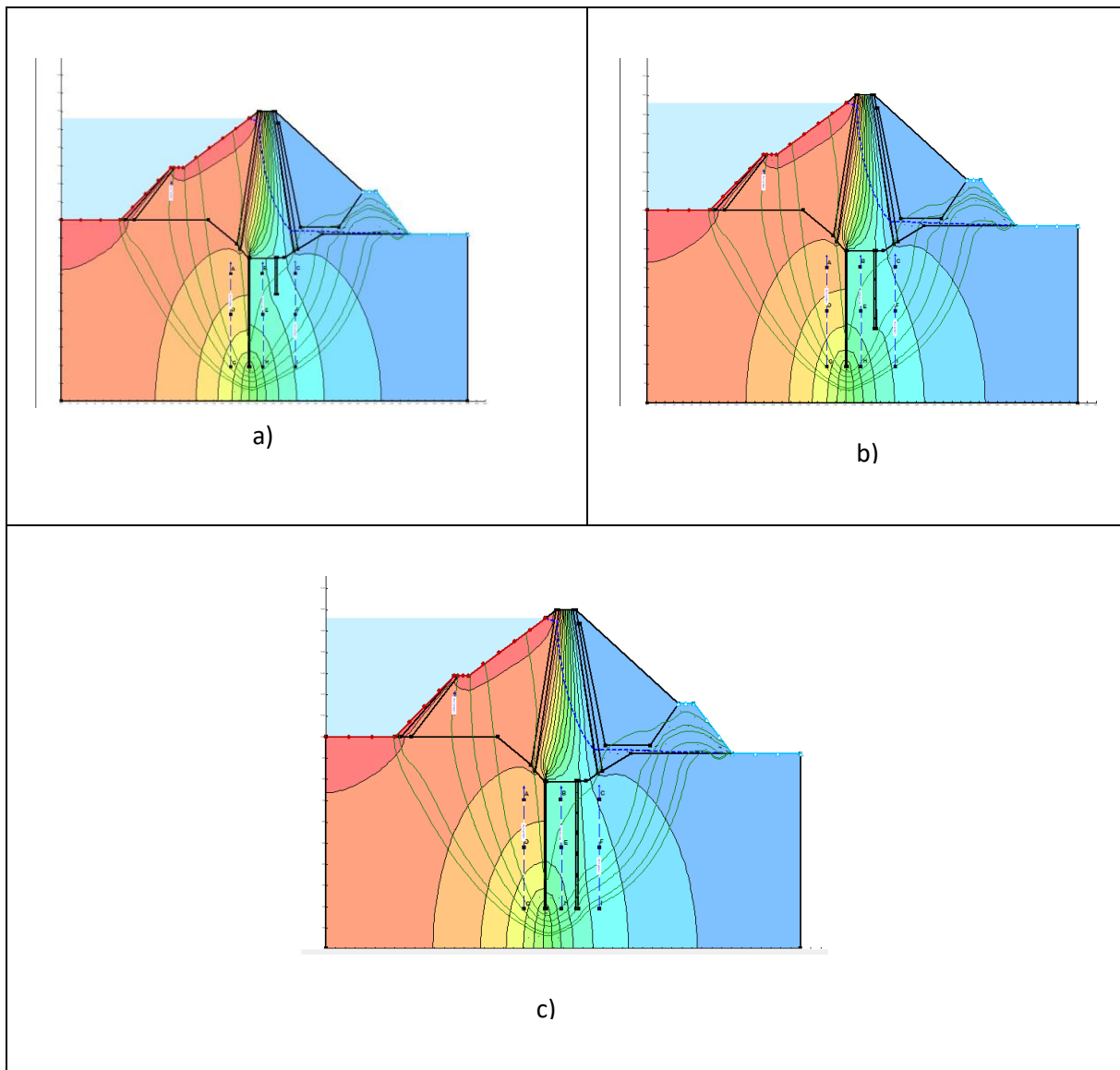


Figure V. 9: Influence of drain depth

a) L=20m, b) L= 40m, c) L=60m

A longer drain more effectively lowers the water table because when the drain length is 20m the saturation line is high but when the drain length is 60m the saturation line is lower meaning it brings down the water table.

## 2. Hydraulic parameters studied

In this part, we are going to examine different hydraulic parameters in various location of points in the area that appear to be affected by the existence of drainage system with different depth in front of the grout curtain. The locations of the points are illustrated by A, B, C, D, E, F, G, H, I.

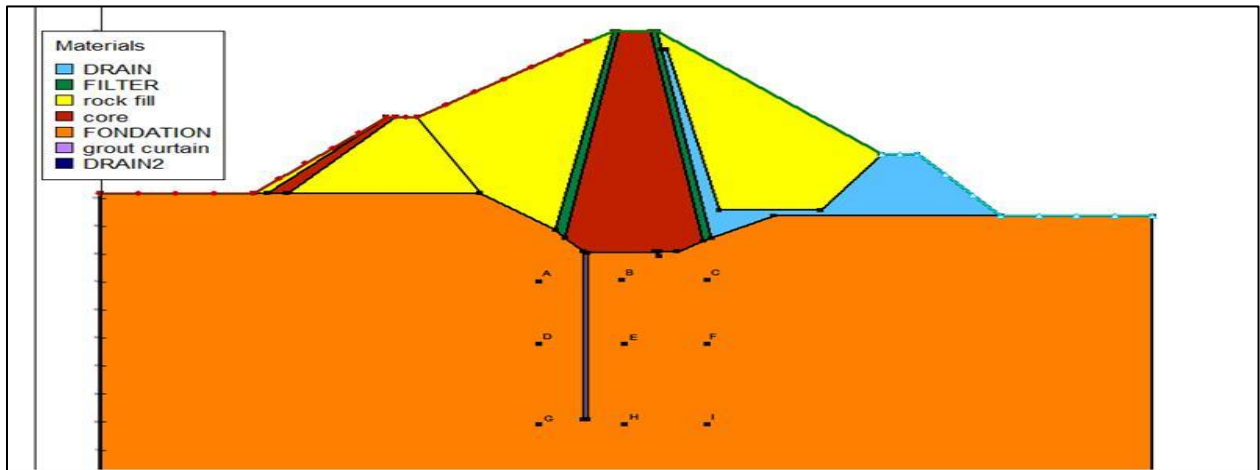


Figure V. 10: Analyzed areas

All the points to be studied are located under the core area to observe the effect of the drain depth on the hydraulic parameters.

### a. Hydraulic head

Table V.5 shows the variation of the total hydraulic head (m) at the level of the reference points in the indicated zones as a function of different drain depth.

Table V. 5: Variation of hydraulic head in different areas

Cases	A	B	C	D	E	F	G	H	I
20 m	147.76	105.48	98.76	143.5	107.73	102.09	137.29	114.25	104.77
40 m	147.66	106.12	99.09	143.34	107.49	101.99	136.96	113.65	104.29
60 m	147.47	107.02	99.42	143.05	107.99	102.23	136.54	112.62	103.62

Representation of results of total hydraulic head are shown below in figure V.11.

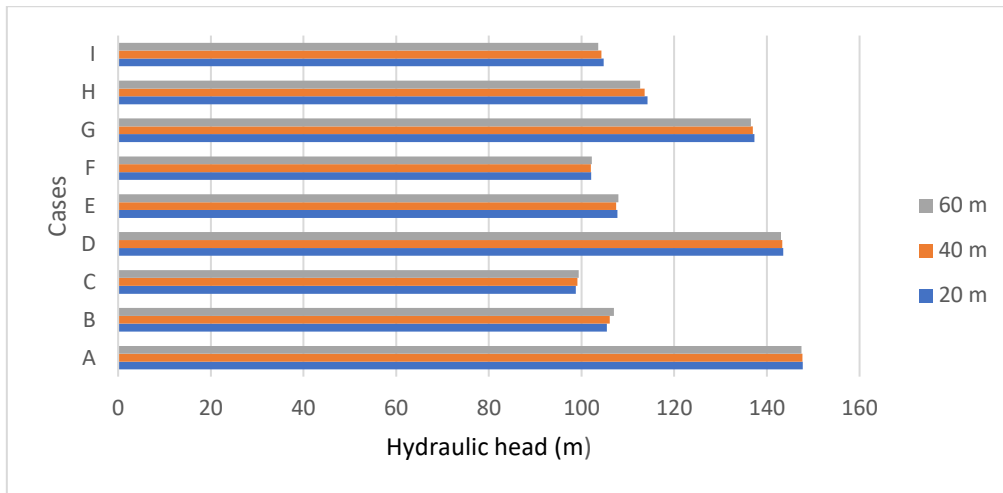


Figure V. 11: Variation hydraulic head with drain depth

### Interpretation

Increase of the length of the drain from 20 to 60 m has less effect on the total hydraulic head. The reduction is not notable, i.e., the drain has little direct effect on total head, which is more a function of boundary conditions (inlet/outlet water levels). Points A, D, G have higher hydraulic head compared to points C, F, I because the points are close to the outlet. Relative point ordering remains unchanged with drain length, meaning load is a function of location but only mildly a function of drain length. Drainage mainly aids pressure relief, not head reduction.

#### b. Pore water pressure

Table V. 6 the variation of pore water pressure (Kpa) at the level of the reference points in the indicated zones as a function of different drain depth.

Table V. 6: Variation of pore water pressure in different positions

Cases	A	B	C	D	E	F	G	H	I
20 m	758.06	338.78	272.99	935.92	585.28	529.88	1158.15	932.81	839.8
40 m	757.04	345.11	276.14	934.37	582.83	528.90	1155.80	927.00	835.21
60 m	755.18	353.86	279.37	931.5	587.69	531.14	1151.45	916.78	828.58

Figure V.12 shows the comparison between the values of the pore water pressure in the specific selected points with the different drain depth.

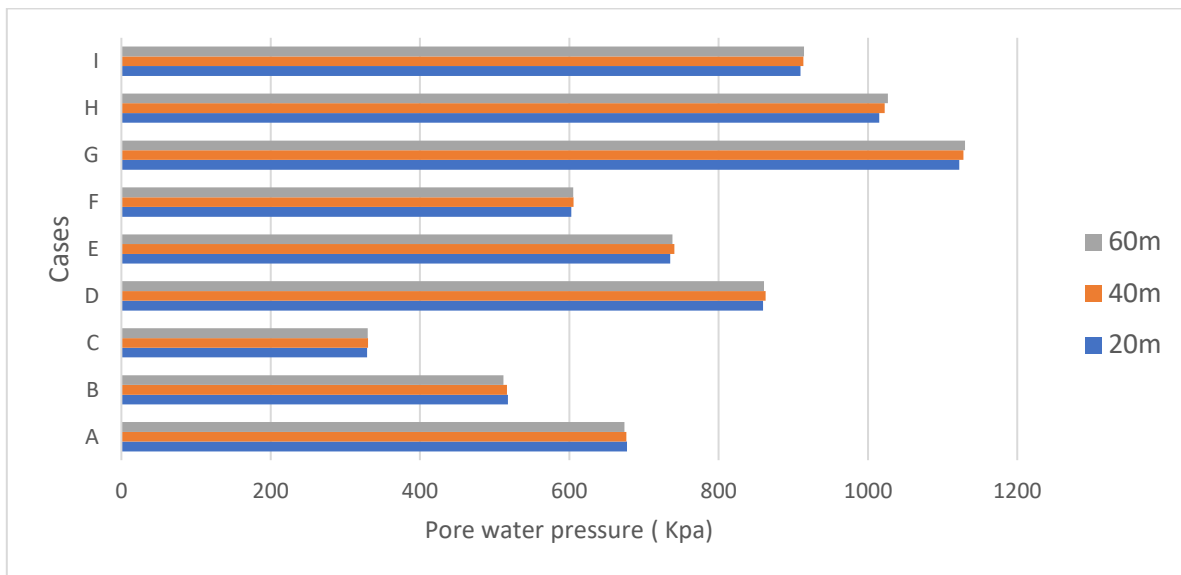


Figure V. 12: Variation of pore water pressure with the depth drain influence.

### Interpretation

As drain length increases, the pore pressure reduces minimally at all points. But the big changes happen in the middle and the downstream areas because of the position of the drain (the drain is located in the downstream area). Maximum pressures occur at Points G, D, H these could be areas of weaker drainage effect or near the sources of water. Pore water pressure is highly affected by drain depth.

### c. Hydraulic gradient

Table V.7 shows the variation of the hydraulic gradient at the level of the reference points in the indicated zones as a function of different drain depth.

Table V. 7: Variation of the hydraulic gradient in different position

Cases	A	B	C	D	E	F	G	H	I
20 m	0.185	0.086	0.298	0.23	0.21	0.19	0.34	0.40	0.20
40 m	0.187	0.065	0.312	0.23	0.17	0.175	0.35	0.40	0.185
60 m	0.192	0.049	0.34	0.24	0.13	0.19	0.36	0.47	0.15

Figure V.13 Comparison between the values of the hydraulic gradient in the specific selected points with the different drain depth.

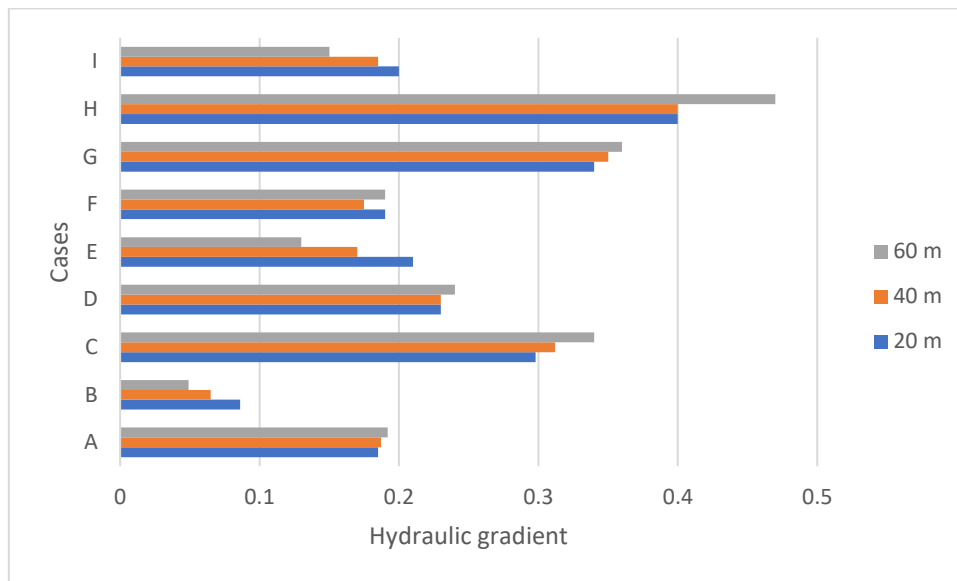


Figure V. 13: Variation of hydraulic gradient drain depth influence.

**Interpretation**

Hydraulic gradient becomes lower with increased drain depth. At some points (e.g., H), gradient increases, potentially due to redistribution of flow and localized effect. Points B, E are of lowest gradients, showing steady, well-drained regions.

**d. Flow rate**

Table V.8 shows the variation of the flow rate at the level of the reference points in the indicated zones as a function of different drain depth.

Table V. 8: Variation of the flow rate in different positions with drain depth influence.

Cases	A-D-G	B-E-H	C-F-I
20 m	6.68E-5	1.31E-5	9.59E-5
40 m	4.30E-5	7.81E-6	9.71E-5
60 m	6.92E-5	2.82E-5	0.00001

Figure V.14 Comparison between the values of the flow rate in the specific selected points with the different drain length.

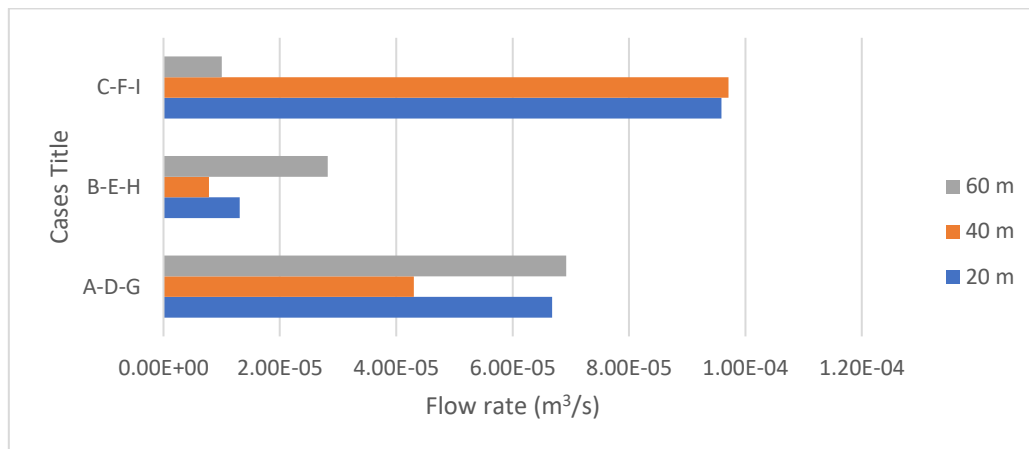


Figure V. 14: Variation of flow rate with change of drain depth

**Interpretation**

The results show that increasing drain depth affects flow rates differently across zones. While zone C–F–I shows a clear reduction at 60 m, zones A–D–G and B–E–H display mixed behavior, indicating that drainage efficiency depends on local seepage conditions.

**e. Final comparison**

The study indicates that while a deeper drain can deliver some marginal hydraulic performance advantages, a little reduction in pressure and gradient, for instance the overall effect is small. With deeper drains, the flow network is more stable and uniform, which is desirable, but seepage paths still develop through the foundation. Therefore, a drain system alone is not an effective means of significantly reducing piping risk or seepage amount. In order to attain both good hydraulic performance and dam safety, the drain system should be augmented by a grout curtain or other form of impermeable barrier to limit water entry and reduce seepage energy.

Table V.9 provides a comparative overview of the impact of different drain length on hydraulic head, pore water pressure, pressure load, hydraulic gradient, and flow rate to establish the most appropriate configuration.

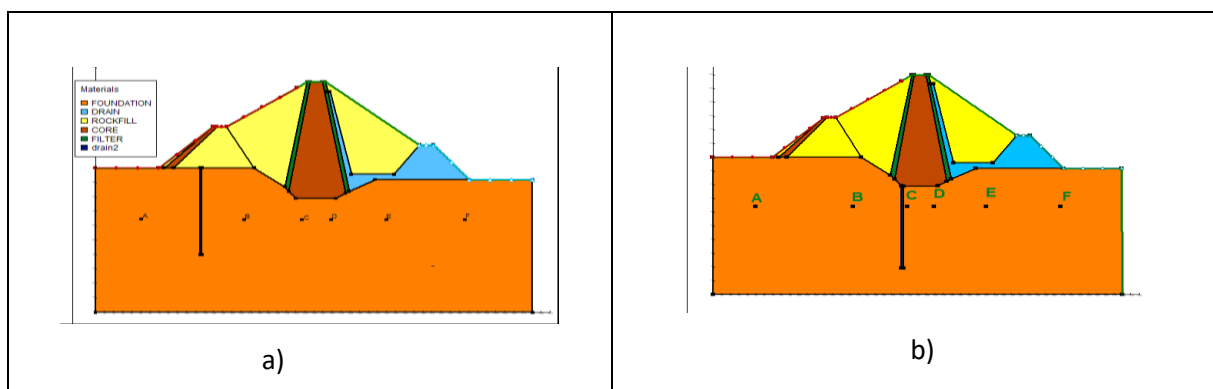
Table V. 9: Final comparison between the cases studied

Parameters	Effect When Increasing Drain Length (20 → 60 m)	Best Performing Length	Notes
Hydraulic head	Slight decrease; not sensitive to length	No significant difference	Controlled by boundary conditions (not strongly drain-dependent)
Pore Pressure	Clear and consistent reduction, especially in downstream zones	60 m	Longer drain reaches further downstream better relief
Pressure Load	Slight decrease with increasing length	60 m	Follows same trend as pore pressure
Hydraulic Gradient	Mostly decreases; some local increases (e.g., at Point H)	60 m	Better control in critical areas; exceptions due to flow shifts
Flow Rate	Mixed trend: some decrease, some increase	40 m (more stable flow)	60 m may increase flow in certain zones due to channelling

**V.2.3. Effect of changing the drain position**

This study aims to analyse the impact of changing the position of the drain on critical parameters influencing dam stability. Specifically, we will investigate how varying the position of the drain affects these parameters and assess their role in enhancing the overall stability of dams.

Figure V.15 Simulation done using Geo Studio with different drain positions.



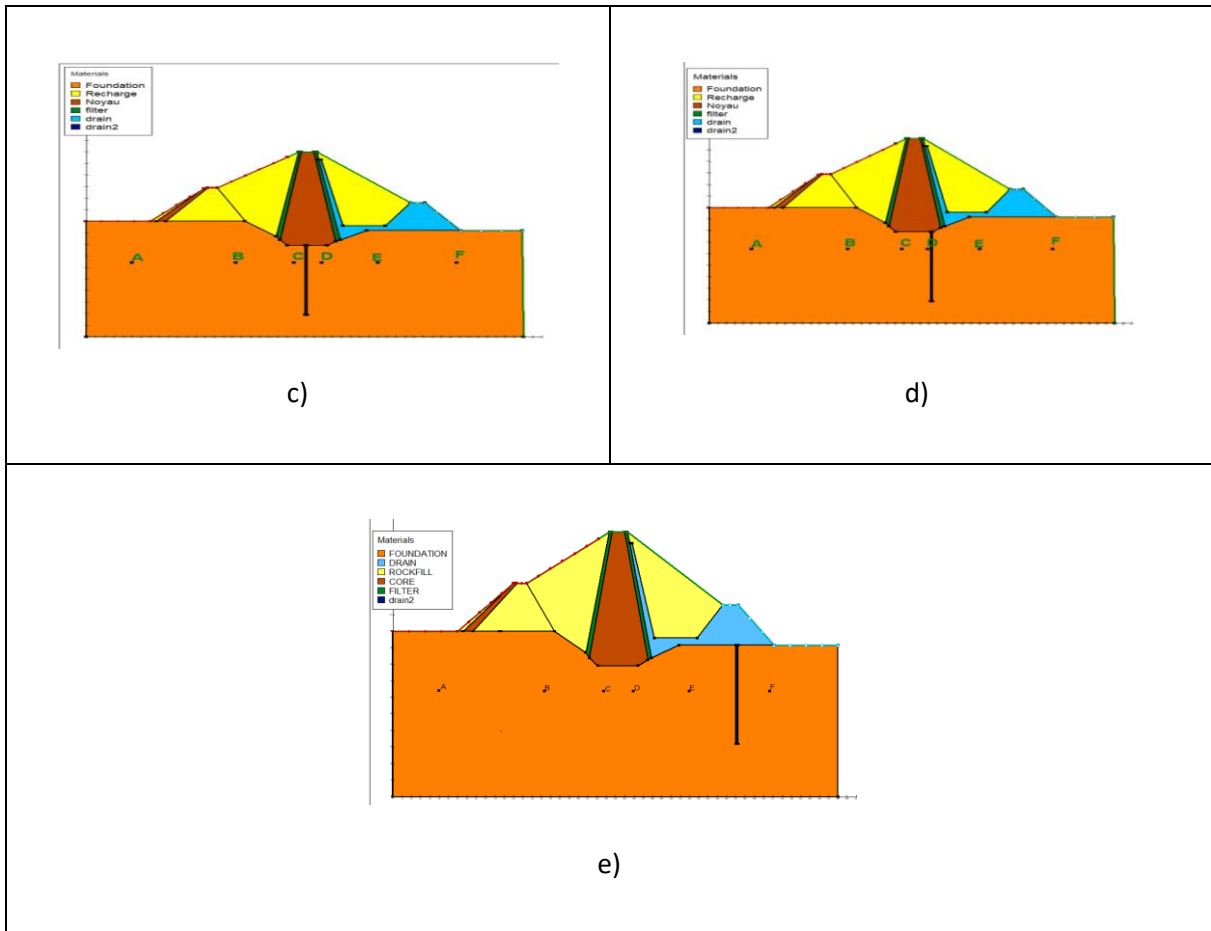
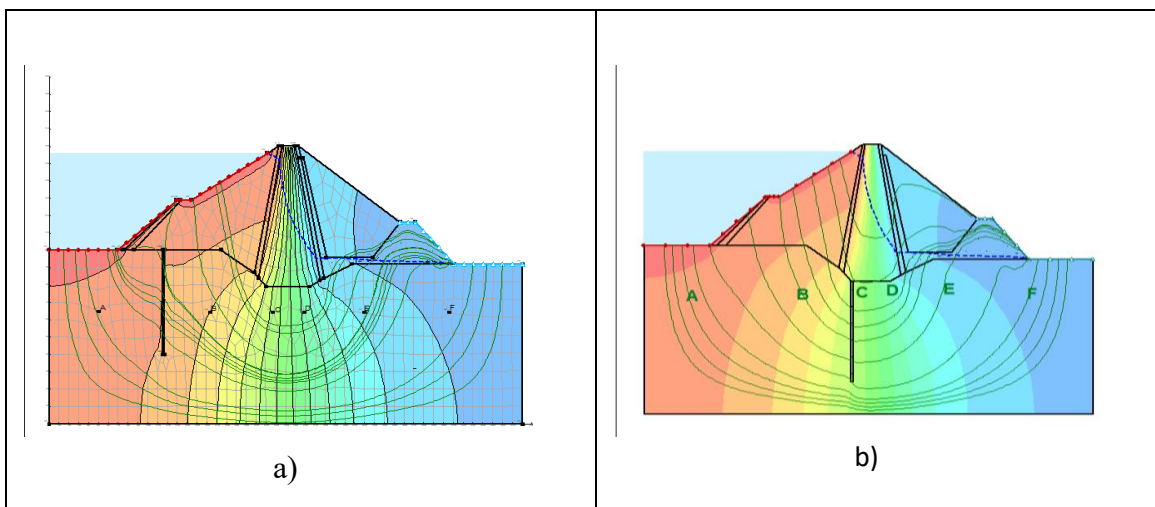


Figure V. 15: Different positions of the drain

a) Upstream b) Start of the core, c) Middle of the core d) End core, e) Downstream

**1. Flow network variation with changing drain position**

Figure V.16 below shows how position of the drain impacts the stability of the dam in general. Also, how the position of the drain affects the flow network.



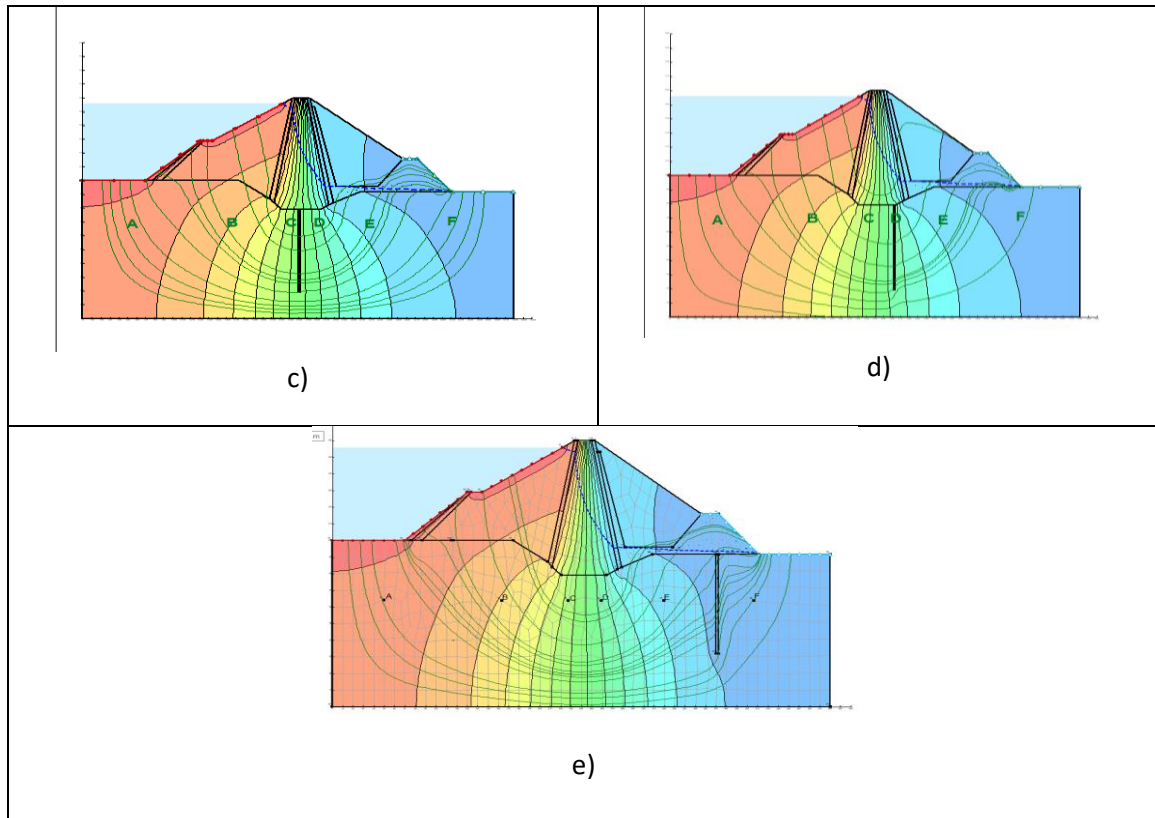


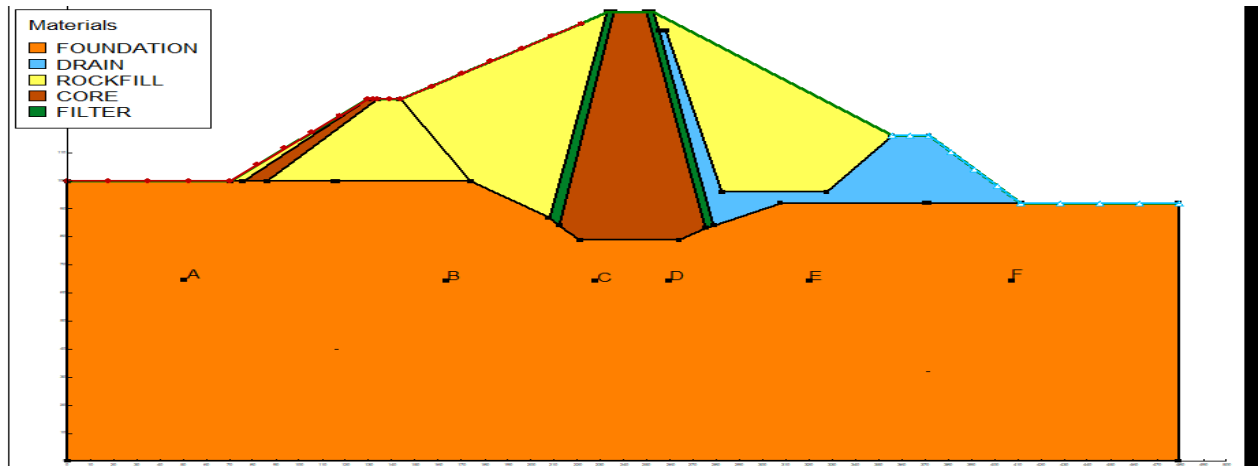
Figure V. 16: Variation of flow networks

a) Upstream b) Start of the core, c) Middle of the core d) End core, e) Downstream

The flow net results across different cases clearly illustrate how drain positioning affects seepage behaviour and dam safety. In the case of drain in the upstream with no effective drainage, flow lines are nearly stagnant, leading to high saturation and pore pressures posing serious stability risks. Case (drain at the start of the core) shows slight improvement, but drainage remains insufficient. In Case (drain in the middle of the core) where the drain is placed at the core base, flow lines converge more actively, indicating efficient seepage interception and reduced pressure. Case (drain at the end of the core), with the drain just downstream of the core, proves the most effective; flow is actively directed toward the drain, reducing saturation and relieving hydraulic pressure early. in Case, the drain is at the downstream toe, forcing water to traverse the entire dam body before interception, making it a poor standalone solution. Overall, Cases (drain in the middle of the core) and (drain at the end of the core) strike the best balance.

**2. Hydraulic parameters analyses**

In this study, the impact of changing the position of the drain is observed on the hydraulic parameters. Figure V.17 below illustrates the specific studied points.



**Figure V. 17:**Positions of the analysis points

All the points to be studied are located under the foundation area to observe the effect of the drain position on the hydraulic parameters.

**a. Hydraulic head**

Table V .10 shows the variation of the hydraulic head (m) at the level of the reference points in the indicated zones as a function of upstream and downstream position.

**Table V. 10:**Hydraulic head in relation to position of the drain.

Cases		A	B	C	D	E	F
Upstream		153.63	144.82	128.09	113.60	98.72	93.85
Core	Start	153.47	144.66	127.94	113.77	98.91	93.92
	Middle	153.39	144.46	127.67	113.59	98.76	93.88
	End	153.32	144.21	127.55	113.54	98.58	93.81
Downstream		153.38	144.42	127.71	113.21	98.14	93.10

Figure V.18 Variation of hydraulic head in function of different position of the drain.

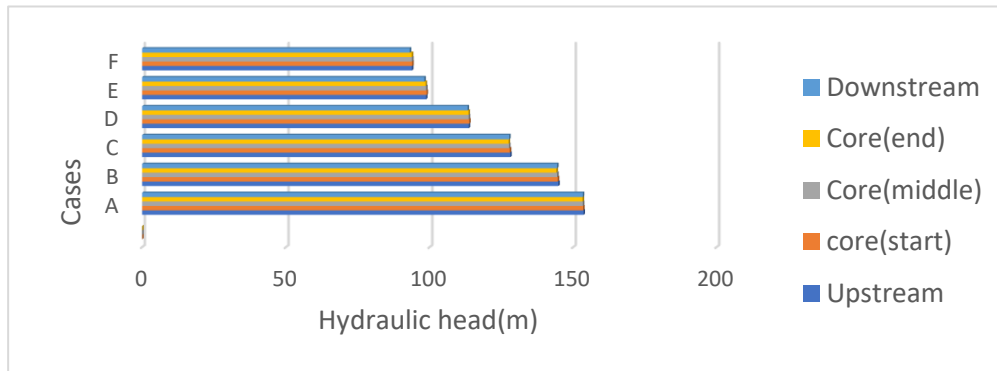


Figure V. 18:Variation of hydraulic head in relation to drain position

### Interpretation

Slightly higher near the upstream side and core start lowest at downstream toe. The drain position affects slightly hydraulic head the most effective places to place the drain is on the downstream side of the dam as the result indicate low hydraulic head when the drain is placed on the downstream of the dam.

### b. Pore water pressure

Table V.11 Variation of the pore water pressure (Kpa) at the level of the reference points in the indicated zones as a function of upstream and downstream position.

Table V. 11 Pore water pressure in relation to drain position

Cases		A	B	C	D	E	F
Upstream		874.12	792.64	628.56	486.45	340.52	292.82
Core	Start	877.43	791.10	627.07	488.13	342.42	293.45
	Middle	876	789.14	624.46	486.37	340.90	293.01
	End	876.05	786.68	623.23	485.91	338.90	292.38
Downstream		871.71	788.64	624.85	482.60	334.83	285.41

Figure V.19 Variation of pore water pressure in function of different position of the drain.

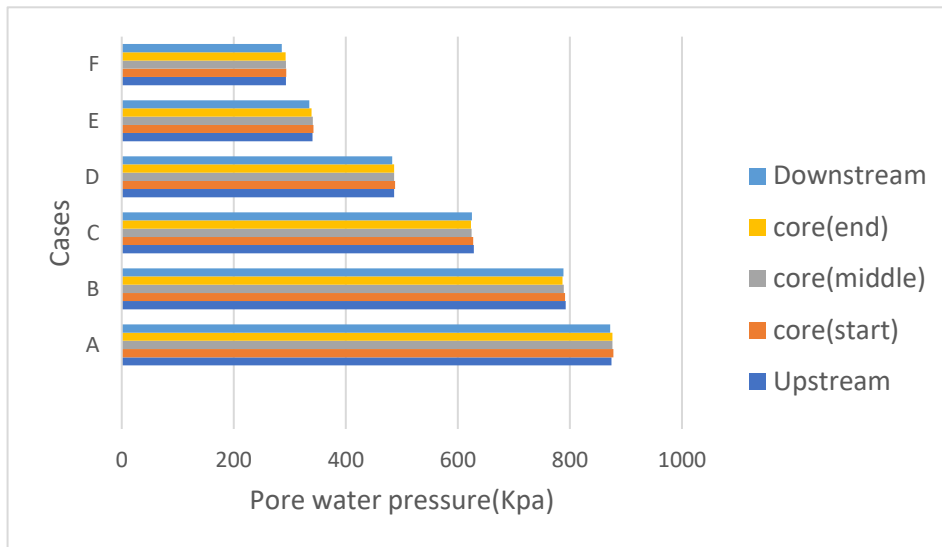


Figure V. 19: Variation of pore water pressure in relation to drain position

**Interpretation**

The graph shows almost constant pore water pressure this is because the drain only is not that effective to reduce the pore water pressure. But generally, the downstream position of the drain is more effective it has relatively lower pore water pressure.

**c. Pressure load**

Table V.12 shows the variation of the pressure load at the level of the reference points in the indicated zones as a function of upstream and downstream position.

Table V. 12 shows pressure load in different cases

Cases		A	B	C	D	E	F
Upstream		89.13	80.82	64.09	49.60	34.72	29.85
Core	Start	89.47	80.62	63.94	49.77	34.91	29.92
	Middle	89.39	80.46	63.67	49.59	34.76	29.87
	End	89.32	80.21	63.55	49.54	34.55	29.81
Downstream		88.88	80.41	63.71	49.21	34.14	29.10

Figure V.20 Variation of pressure load with different position of the drain.

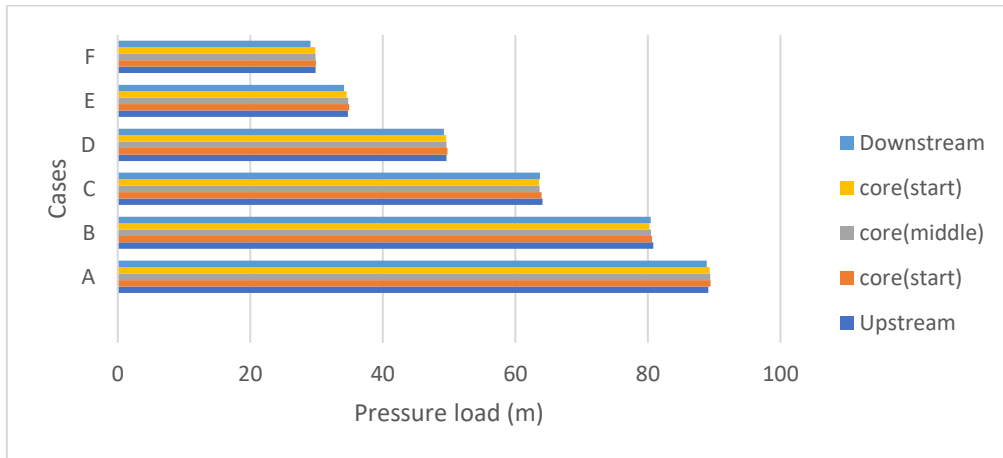


Figure V. 20: Variation of pressure load with drain position

The downstream positioning of the drain still remains the most effective drain position. The pressure load decreases slightly as the drain position changes towards the downstream.

**d. Hydraulic gradient**

Table V .13 shows the variation of the hydraulic gradient at the level of the reference points in the indicated zones as a function of upstream and downstream position.

Table V. 13 Variation of hydraulic gradient with influence of drain position

Cases		A	B	C	D	E	F
Upstream		0.06	0.18	0.49	0.49	0.17	0.05
Core	Start	0.06	0.18	0.44	0.50	0.17	0.05
	Middle	0.07	0.17	0.50	0.48	0.17	0.05
	End	0.06	0.17	0.49	0.43	0.15	0.05
Downstream		0.065	0.17	0.48	0.48	0.16	0.026

Figure V.21 Variation hydraulic gradient with different position of the drain.

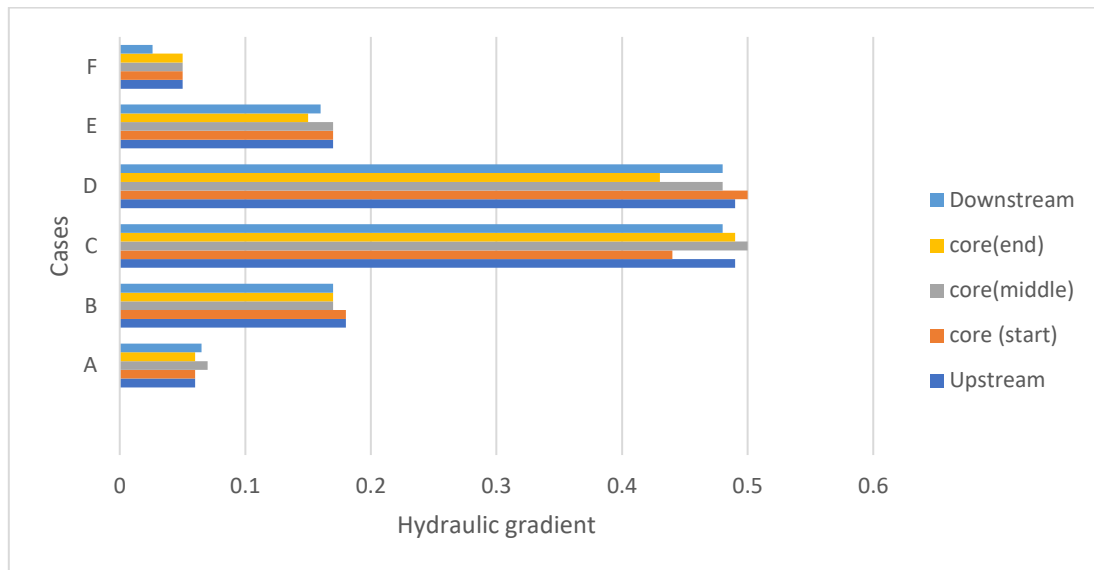


Figure V. 21: Variation of hydraulic gradient drain position influence

**Interpretation**

Hydraulic gradient remains relatively stable across most positions, with slight decreases toward the downstream area. The most significant reduction occurs at point F. This suggests that the drain placement is most effective in reducing seepage forces at the downstream end, especially near point F.

**e. Flow rate**

Table V.14 shows the variation of the flow rate at the level of the reference points in the indicated zones as a function of upstream and downstream position.

Table V. 14 Variation of flow rate drain position influence

Cases	A	B	C	D	E	F	
Upstream	0	9,84 <sup>E</sup> -6	0	2.54 <sup>E</sup> -5	6.32 <sup>E</sup> -6	4.25 <sup>E</sup> -6	
Core	Start	1.014E-5	8.51E-6	0	4.017E-5	6.26E-6	5.64E-6
	Middle	1.013E-5	8.51E-6	0	4.02E-5	6.25E-6	5.64E-6
	End	1.37e-5	2.90E-5	0	1.11E-5	8.47E-7	0
Downstream	2.39E-6	0	0	2.97 <sup>E</sup> -5	2.69E-6	2.68E-6	

Figure V.22 Variation of flow rate in relation to drain position.

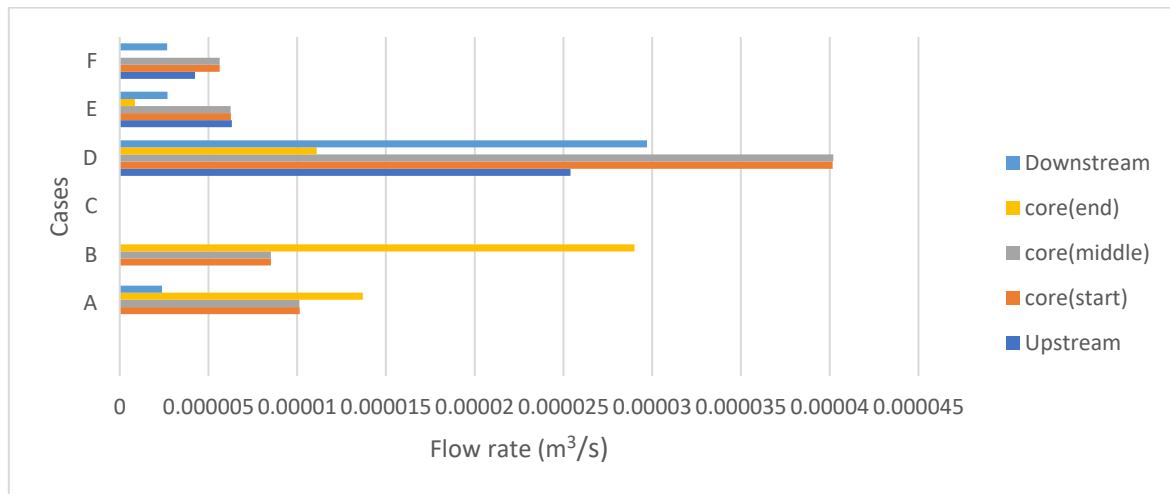


Figure V. 22: variation of flow rate in relation to drain position

The data shows that where you place the drain makes a big difference in how well the system captures flow. Drain position D stands out as the most effective overall, pulling in a strong flow through the core, though it does let some of it slip through downstream. Position A also performs well, capturing most of the flow within the core and barely allowing any to escape. Position B is particularly good at drawing flow from the end of the core and manages to prevent any flow from continuing downstream. Meanwhile, positions E and F do a decent job at the start and middle of the core, but they don't fully prevent some of the flow from leaking out.

#### V.2.4. Analysis of the positioning of drain with the grout curtain

This study aims to analyze the impact of drain on 4 critical parameters influencing dam stability: hydraulic head, pore water pressure, hydraulic gradient and flow rate. Specifically, we will investigate how changing the position of the drain. affects these parameters.

Figure V.23: Different positions of drain upstream and downstream position.

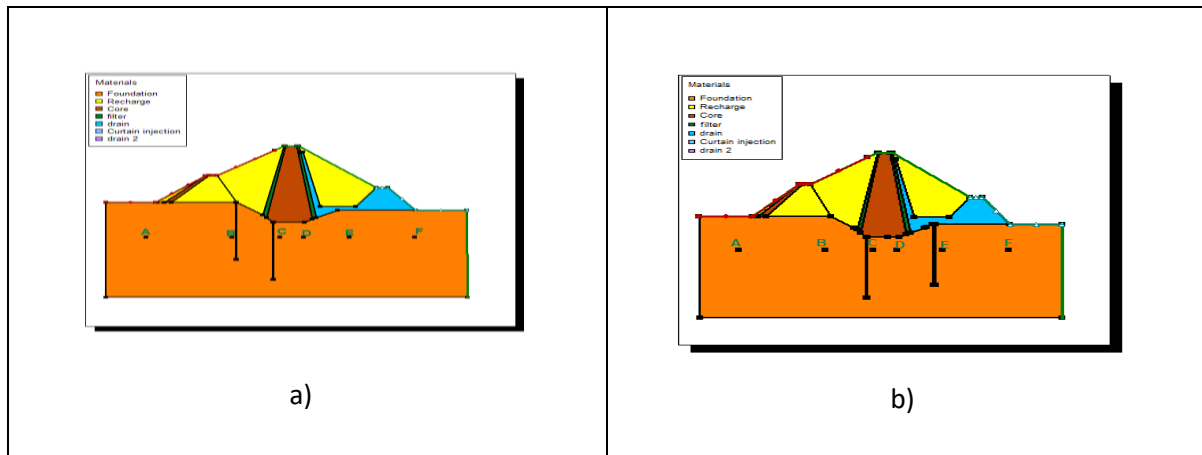


Figure V. 23: Different positions of the drain

a) Upstream drain b) Downstream drain

### 1. Effects of different positions of the drain on seepage flow networks

Figure V.24 Influence of the drain position on the flow networks.

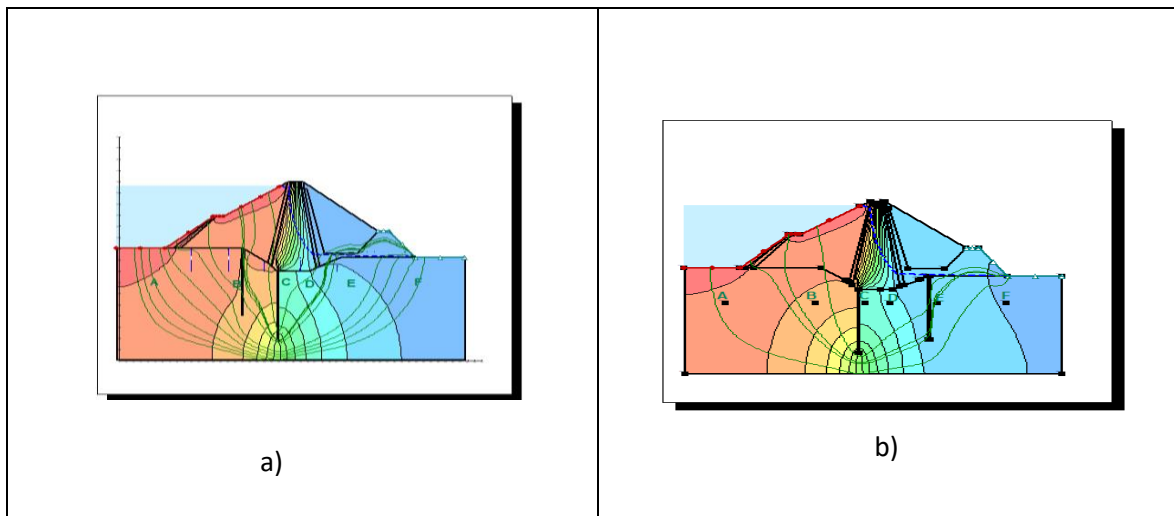


Figure V. 24: Flow network with respect to the position of the drain

a) Upstream drain b) Downstream drain

Upstream Position: Flow lines looked more compressed indicating high rate of flow. Water is entering the system with more energy, and there are more closely spaced equipotential lines while in the downstream position: Flow lines are more spread out near the downstream face. The equipotential lines are less steep suggesting a reduced hydraulic gradient.

## 2. Hydraulic parameters studied

In this study, the position and the length of drainage system is going to be changed to observe the most effective position to place the drainage system. The drain was placed in the upstream and the downstream and the certain points were observed as shown below in Figure V.25.

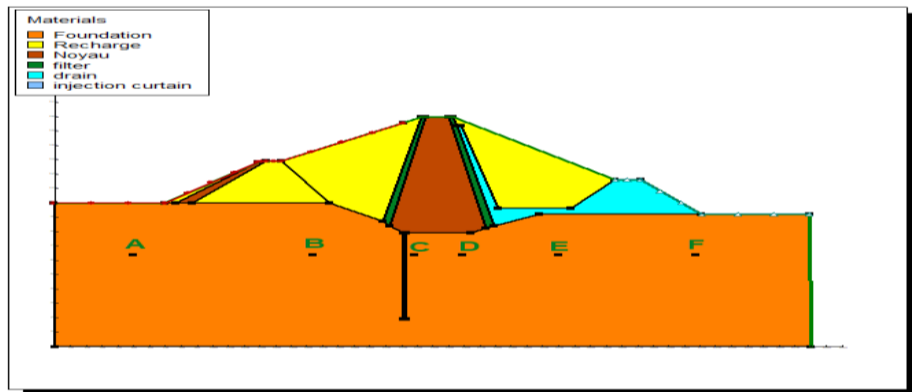


Figure V. 25: Different specific study points

All the points to be studied are located under the foundation area to observe the effect of the grout curtain position on the hydraulic parameters.

### a. Hydraulic head

Table V.15 Variation of the hydraulic head at the level of the reference points in the indicated zones as a function of different positioning of the drain.

Table V. 15: Variation of the hydraulic head drain position influence

Cases	A	B	C	D	E	F
Upstream	154.43	149.94	107.34	103.24	96.46	93.38
Downstream	154.09	148.19	102.07	98.03	91.00	89.83

Figure V.26: Comparison between the values of the total hydraulic head in the specific selected points in different positions.

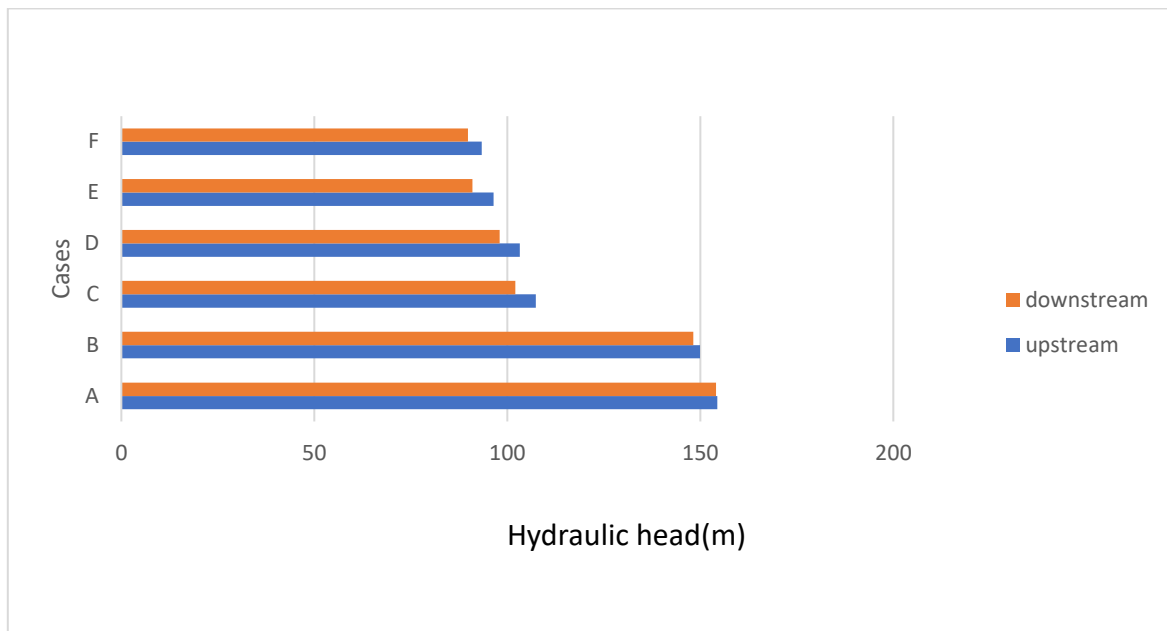


Figure V. 26 Hydraulic head of drain positioned upstream and downstream

Hydraulic head is reduced slightly when the drain is at every point in a downstream position. The most notable difference appears at Point D, representing the downstream drain to be better in middle paths of flow.

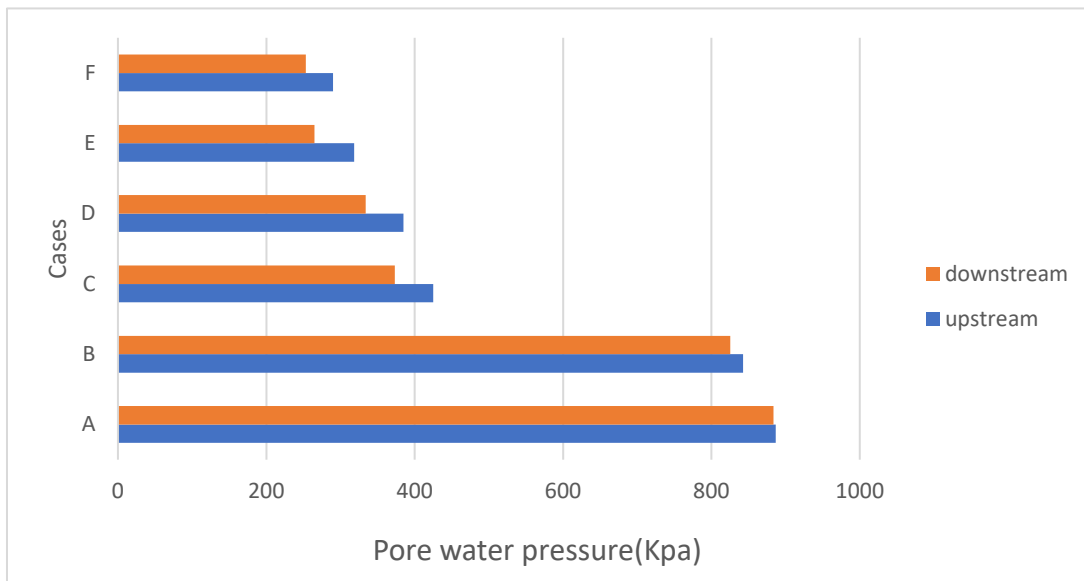
**b. Pore water pressure**

Table V.16 Variation of the pore water pressure at the level of the reference points in the indicated zones as a function of different position of the drain.

Table V. 16: Variation of the pore water pressure drain position influence

Cases	A	B	C	D	E	F
Upstream	886.90	842.87	425.11	384.85	318.35	289.88
Downstream	883.51	825.63	373.39	333.78	264.85	253.32

Figure V.27 Comparison between the values of the pore water pressure in the specific selected points with different positions upstream, downstream respectively.



**Figure V. 27:** Pore water pressure in relation to upstream and downstream drain position

Downstream drain significantly reduces pore water pressure, in every position except the point in the upstream. Such a pressure reduction leads to increased dam stability and seepage force reduction.

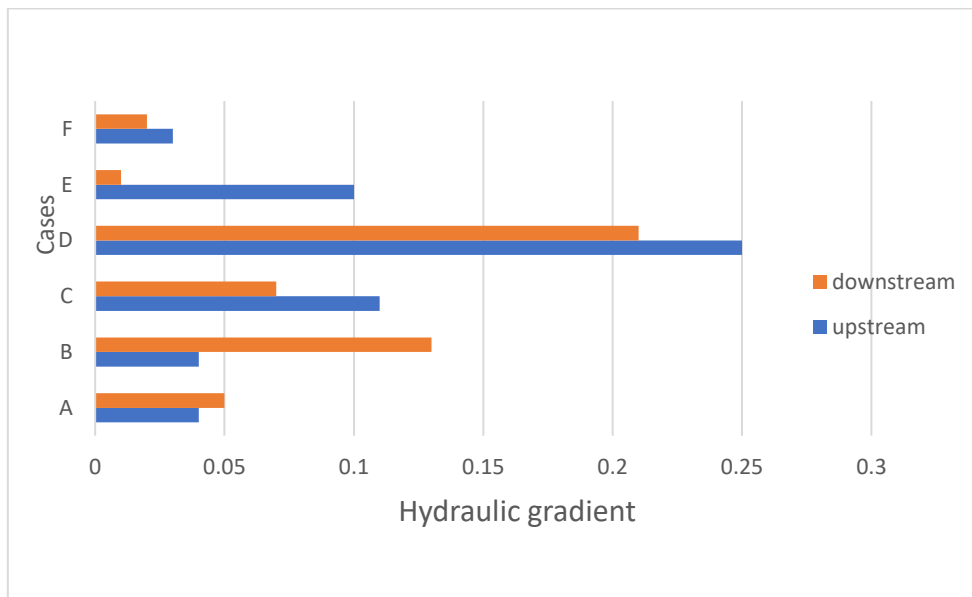
### c. Hydraulic gradient

Table V.17 shows the variation of the hydraulic gradient at the level of the reference points in the indicated zones as a function of upstream and downstream position.

**Table V. 17:** Variation of the hydraulic gradient drain position influence

Cases	A	B	C	D	E	F
Upstream	0.04	0.04	0.11	0.25	0.10	0.03
Downstream	0.05	0.13	0.07	0.21	0.01	0.02

Figure V.28 Comparison between the values of the hydraulic gradient in the specific selected points with the different positions.



**Figure V. 28:** Difference of hydraulic gradient in the upstream and downstream drain position

For Points A through D, the hydraulic gradient is slightly lower with the downstream drain possibly due to pressure drop accelerating flow. However, at Point E, the gradient is much lower with the downstream drain, which signifies localized pressure relief. This is to say that drain placement is very important in dam stability.

**d. Flow rate**

Table V .18 Variation of the flow rate at the level of the reference points in the indicated zones as a function of upstream and downstream position.

**Table V. 18:** Variation of flow rate influence of upstream and downstream drain position

Cases	A	B	C	D	E	F
Upstream	2.08E-6	1.87E-6	2.07E-3	0	1.67E-6	1.88E-6
Downstream	7.10E-6	9.92E-6	0	0	2.01E-6	1.78E-6

Figure V.29 Comparison between the values of the flow rate in the specific selected points with the different drain positions.

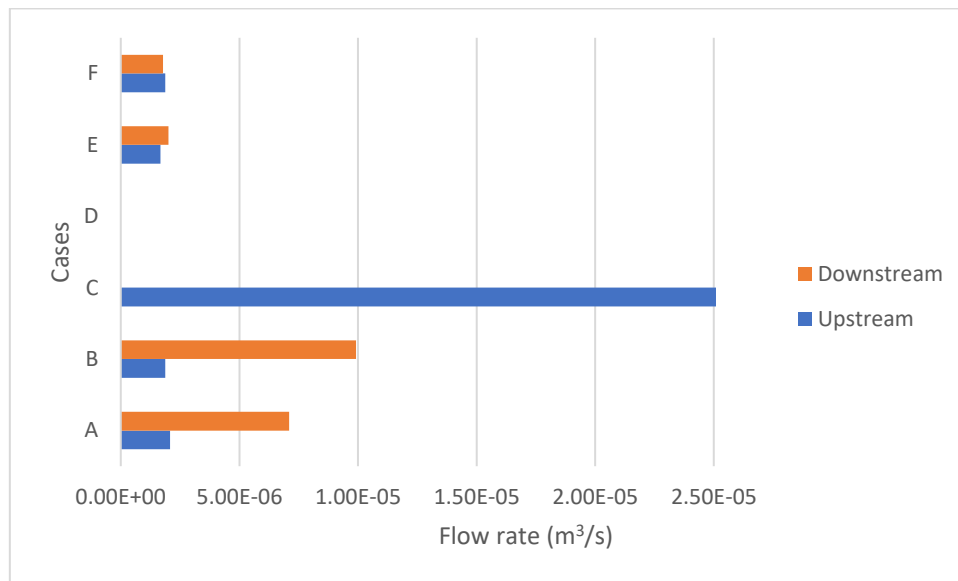


Figure V. 29: Flow rate in relation to downstream and upstream position of the drain.

The drain at the downstream has a zero-flow rate indicating the drainage system is effectively capturing seepage within the embankment.

**e. Final comparison**

The following table provides a comparative overview of the impact of different drain position (upstream or downstream) on hydraulic head, pore water pressure, pressure load, hydraulic gradient, and flow rate to establish the most appropriate configuration.

Table V. 19: Comparison of upstream and downstream drain effect.

Parameter	Comparison between upstream and downstream	Better Position	Notes
Hydraulic head	Slightly lower in downstream, but difference is minimal	Equal	More dependent on dam geometry and head difference
Pore Pressure	Significantly lower downstream	Downstream	Maximum pressure relief occurs downstream (especially in lower zones)

Pressure Load	Follows same pattern as pore pressure	Downstream	Downstream drainage helps unload hydraulic pressure
Hydraulic Gradient	Mixed: slightly higher in some points downstream, lower in others	Depends on zone	Local effects vary needs monitoring (e.g., H shows higher gradient)
Flow Rate	Downstream reduces overall seepage in upper/mid points	Downstream	Downstream drain intercepts flow effectively

**V.3. conclusion**

The study conducted on the Boughrara Dam using GeoStudio simulations examined the influence of both drain length (20 m, 40 m, 60 m), change of position without the drain and drain position (upstream and downstream of the grout curtain) on key hydraulic parameters such as hydraulic head, pore water pressure, hydraulic gradient, and seepage flow. Results showed that increased drain length, particularly up to 60 m, has a noticeable reduction in pore water pressure and improved control over hydraulic gradients, leading to increased dam stability. Although there was little impact on overall hydraulic head, longer drains reduced pressure more efficiently, especially in downstream regions. Additionally, downstream positioning of the drain (downstream of the grout curtain) proved to be more effective compared to upstream positioning in that it both decreased pore pressures and total seepage considerably in critical sections of the foundations. There were certain local hydraulic gradient increases that were observed, which demanded cautious design. Generally, the most effective setup for maximum safety and performance is a 60 m drain downstream of the grout curtain that offers the best compromise of pressure relief, gradient control, and seepage reduction.

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## General conclusion

This comprehensive study underscores that while dam failures remain relatively rare, their consequences can be catastrophic, affecting human lives, infrastructure, and ecosystems. Statistical analysis reveals that most failures are concentrated in embankment dams, especially within the first five years of operation, and are primarily caused by overtopping, internal erosion (piping), foundation issues, and inadequate drainage systems. Notably, the failure probability decreases with increased dam height and improved construction standards.

This study has demonstrated, through advanced numerical modeling with GeoStudio, the critical influence of waterproofing and drainage design on the hydraulic behavior and safety of embankment dams. The simulations carried out for the Boughrara Dam allowed for a detailed evaluation of different configurations of grout curtains, drainage systems, and core base lengths to identify the most effective combinations for controlling seepage and enhancing structural stability.

The core base length being one of the waterproofing systems its width of the impermeable central clay core was identified as a key factor in the overall hydraulic behavior of the dam. Among the lengths studied, base widths of 43 meters and 50 meters yielded the most favorable outcomes. These dimensions provided a balanced distribution of impermeability and structural stability, significantly reducing seepage rates while maintaining the dam's mechanical equilibrium. They also contributed to better control of the saturation line and an overall decrease in flow velocity within the embankment.

Similarly, the other type of waterproofing which is the grout curtain, a fundamental element for reducing seepage through the foundation, exhibited its highest performance at a depth of 60 meters, when positioned centrally beneath the clay core. This configuration effectively intercepts deep seepage paths, significantly decreases hydraulic conductivity, and results in lower hydraulic gradients and pore pressures. The 60 m depth proved to be the most efficient in terms of reducing total hydraulic head and minimizing the risk of internal erosion and piping two major failure mechanisms in earth dams.

Moreover, the drainage system was found to be most effective when extending 60 meters downstream of the core. This configuration ensures the rapid evacuation of infiltrating water, efficiently lowers the phreatic surface, and controls uplift pressure in the downstream body of

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the dam. This helps maintain the structural integrity of the embankment, especially during periods of high reservoir levels or rapid drawdown conditions.

In combination, the configuration of a core base length of 43 to 50 meters a 60-meter-deep central grout curtain and a 60-meter downstream drain, and represents the most hydraulically and structurally stable scenario modeled in this study. This setup delivered the lowest values of total hydraulic head, pore water pressure, and flow rate, while also ensuring a safe and efficient seepage control strategy.

These findings underscore the importance of a carefully integrated design approach in dam engineering, where the interplay between waterproofing, drainage, and core geometry must be optimized to enhance safety and durability. The results serve as a strong recommendation for future dam projects, especially in geologically complex or permeable foundation conditions, and offer a validated reference for improving design standards and risk mitigation strategies in embankment dam construction.

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## References

- Al-Ansari, N., Adamo, N., Sissakian, V., Laue, J., & Knutsson, S. (2020). Dam safety problems related to seepage. *Journal of Earth Sciences and Geotechnical Engineering*, (vol 10(6)).
- Albergel, J., Nasri, S., Boufaroua, M., Droubi, A., & Merzouk, A. (2004). *Small dams and hill reservoirs: Innovative management for water conservation and for protecting downstream infrastructures*. Sécheresse, (vol 15(1)).
- Amara, N., & Dib, G. (2020). *Contribution à la conception des barrages en zones sahariennes* [Master's thesis, Tlemcen University].
- Associates-Wahler. (1978). Kelly Barnes dam failure: Hydrological and structural analysis. *Dam Safety Journal*.
- Asthana, B., & Khare, D. (2022). Embankment dams. In *Recent advances in dam engineering*. Springer.
- ASTM. (2012). Standard Proctor test. ASTM D698-12. *American Society for Testing and Materials*.
- ASTM. (2015). Marshall stability and flow test standard. *ASTM D6927-15*.
- Bencherrat, N., & Mostefa Kara, M. (2018). *Analyse paramétrée pour l'optimisation des dimensions des drains des barrages en terre* [Master's thesis, Tlemcen University].
- Bendjema, L., & Benbarek, N. (2015). *Les techniques de diminution des débits de fuite dans les barrages* [Master's thesis, University of Biskra].
- Bentaher, L. (2012). *Parameters for embankment dams using fuzzy logic and artificial neural network techniques* [Master's thesis, Cairo University].
- Cambridge Press., & Gokap, Z. (2009). Engineering characteristics of sand-clay mixtures. *Clay Minerals Journal*.
- Cazzuffi, D., Giroud, J. P., & Scuero, A. (2009). Geosynthetic barrier systems for dams. In *9th International Conference on Geosynthetics*, Guarujá, Brazil.
- Charrak, H. (2022). *Parameterized analysis of injection and drainage parameters in dam foundations: Case of El Izdihar dam* [Doctoral dissertation, Tlemcen University].
- Charrak, H. (2023). Influence of cutoff wall and horizontal drainage on seepage in earth dam foundations. *Indian Geotechnical Journal*.
- Coleman, F. (2004). Lessons from Teton dam failure. *Dam Safety Journal*.
- Dam Management. (2022). Water: Japan's experience. *Japan International Cooperation Agency (JICA)*.
- Do Rocio Marconcin, L. (2018). *Monitoring structures with optical fibers: Infiltration detection* [Master's thesis, University of Innsbruck, Austria].

- 
- Duncan, W. (1987). *Design of small dams* (3rd ed.). University of Iceland.
- Erlingsson, S. (2009). Analysis of a geomembrane faced rockfill dam during earthquake. In *17th ICSMGE*, Egypt.
- Fakhari, G., & Gambari, A. (2013). A simple method for calculating seepage from earth dams with clay core. *Journal of Geoengineering*.
- FEMA. (2017). Risk reduction measures for dams: Technical advisory 1. *Federal Emergency Management Agency*.
- Fell, R., MacGregor, P., Stapledon, D., Bell, G., & Foster, M. (2015). *Geotechnical engineering of dams* (2nd ed.). *CRC Press*.
- Freeman, M., Jones, C., & Elwood, B. (2018). Considerations for embankment dam toe drain design. *Dam Safety Insights*.
- Genevois, R. (2005). The 1963 Vajont landslide: Geological aspects. *Engineering Geology*.
- Ghaderi, M. (2023). Advanced materials for smart protective coatings. *Advances in Colloid and Interface Science*.
- Guosheng, H. (2019). Reservoir dam body structure capable of preventing water seepage. *Patent*.
- Hariri-Ardebili, M. (2014). Concrete dams: From failure modes to seismic fragility. In *Encyclopedia of Earthquake Engineering*.
- Horsin Molinaro, H. (2016). Phénomènes de boulangerie et d'érosion régressive dans les barrages. *Ministère de l'Éducation française*.
- Houlsby, A. C. (1990). *Construction and design of cement grouting: A guide to grouting in rock foundations*. Wiley Interscience
- ICOLD. (1999). Embankment dams with bituminous concrete upstream facing. *International Commission on Large Dams*.
- ICOLD. (2010). Asphalt concrete cores for embankment dams. *ICOLD*.
- ICOLD. (2013). Dams and reservoirs under changing challenges. *CRC Press*.
- ICOLD. (2019). Statistical analysis of dam. *ICOLD*.
- India, Government of. (1980). Machchhu dam disaster report. *Government Press*.
- John, E., & Costa, R. (1987). The formation and failure of natural dams. *US Geological Survey Open-File Report*.
- Lemos, J. (2011). Discontinuum models for dam foundation failure analysis. In *Rock Engineering Conference*.
- Lian, J., Wang, H., & Dong, X. (2013). *A kind of steel membrane rock*. Article in University of Tianjin, China.
- Limin, Z. (2024). *Managing landslide dam failure risks*. Hong Kong University, China.

- 
- Londe, P. (1987). Malpasset dam failure: Geological and geotechnical aspects. *Engineering Geology*.
- Mahmoud, M., & Zhen, S. (2023). Numerical study of drainage systems in earth dams. *Journal of Hydraulic Structures*.
- Messaid, B. (2009). *Étude de la position efficace des drains dans le barrage en terre* [Doctoral dissertation, University of Annaba].
- Micha, W., & Yassir, M. (2024). Dams at increasing danger of collapse. *UNESCO – Institute of Water Education*.
- Mioduszewski, W. (2012). Small water reservoirs: Function and construction. *Journal of Water and Land Development*.
- Mirali, M. (2011). Effect of impervious clay core shape on embankment dam stability. *Conference Paper*.
- Nahyan, M. (2022). Global statistics of dam failures. *Earth-Science Reviews*.
- Narita, K. (2000). *Design and construction of embankment dams*. Aichi Institute of Technology.
- Nasser, R., Dimitris, T & Yiliu, L. (2024). *Statistical analysis of global dam accidents in the 21st century*. Research report. Norwegian University of Science and Technology.
- Ouandjeli, A. (2018). *Étanchéisation d'un barrage: Souk Tlata* [Master's thesis, University of Tizi Ouzou].
- Outland, C., & Arthur, H. (1977). Man-made disaster: The story of St. Francis Dam. *Clark Company*.
- Payam, S. (2019). Utilizing fiber reinforced concrete for rockfill dams. *Engineering Journal*.
- Pougatsh, H., Schleiss & Anton, J. (2011). *Les barrages : Du projet à la mise en service*. (vol 17) *Traité de Génie Civil de l'École polytechnique fédérale de Lausanne* publié sous la direction de René Walther et Manfred A. Hirt
- Renolit, A. (2025). *Adhered system*. Renolit UK Ltd., Cramlington.
- Salmasi, F. (2020). Effect of inclined clay core on seepage and stability. *Geotechnical and Geological Engineering*.
- Sazzad, M. (2015). FEM based seepage analysis through earth dam. *International Journal of Advances in Engineering & Technology*.
- Shaofei, X. (2018). Water construction and waterproofing in dams. *Technical Report*.
- Sirwan, S. (2013). *Effect of structural geometry on earth-fill dam stability* [Master's thesis, University of Nottingham].
- Skutnik, Z. (1997). Evaluation of geotechnical parameters using DMT. *Technical Journal*.

---

Smail, N. (2014). *Suivi du comportement des barrages : Étude de cas* [Doctoral dissertation, Tlemcen University].

Terzaghi, K. (1943). *Theoretical soil mechanics*. Wiley Interscience.

US Army Corps of Engineers. (1972). Analyzing effects of dam failures in design studies. *Government Report*.

US Army Corps of Engineers. (2023). Mean time to failure of dams. *Engineering Manual*.

USSD. (2011). Materials for embankment dams. *United States Society on Dams*.

Xuanying, L. (2018). Anti-seepage water-stopping structure. *Chinese Patent CN105625264A*.

Zhang, L. (2007). Analysis of earth dam failures: A database approach. *Georisk, The Hong Kong University*.

Zhao, X. (2021). Leakage detection in rockfill dams using flow field fitting. *Earth and Space Science, 8. AGU Journals*.

Liu, H., Shi, Z., Li, Z., & Wang, Y. (2023). Experimental investigation on reinforcement application of newly permeable polymers in dam engineering with fine sand layers. *Henan University of Urban Construction in China*.

---

## Webiography

Association de la sécurité des barrages. (2019). Dam Failures and Incidents.

[https://damsafety.org/dam-failures?Utm\\_source=](https://damsafety.org/dam-failures?Utm_source=)

BBC News. (2023). *Libya's deadly floods: What went wrong?*

<https://www.bbc.com/news>

Ministère de la Transition écologique. (2023). Rupture de barrage écologique, Ministère de la Transition. Géorisques :

[https://www.georisques.gouv.fr/minformer-sur-un-risque/rupture-de-barrage.](https://www.georisques.gouv.fr/minformer-sur-un-risque/rupture-de-barrage)

Seepage pressure. (2024, SEPTEMBER 4). Retrieved from MADE EASY:

<https://study.madeeasy.in/ce/soil-mechanics-foundation-engineering/seepage-pressure/>

Trapbag. (2024). Trapbag . Retrieved from Trapbag vs Tiger Dam Erosion Protection Bags:

<https://trapbag.com/blog/trapbags-vs-tiger-dams/#:~:text=trapbags%20are%20innovative%20and%20versatile,sediment%20containment%20in%20various%20settings>

Jines Construction Co. (2020). Double packer grouting method:

<https://www.jines.com/en/double-packer-grouting/>