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Numerical effect of veil injection on a gravity dam using grouting intensity number 'GIN' method

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ABSTRACT

A dam is one of the oldest and largest buildings in the world. This structure is usually constructed to intercept flows, store water, and produce energy. Dams' foundations should really be rocky and robust enough to preserve their rigidity. Despite the great benefits of these structures, they are exposed to the risk of collapse. Two basic problems can confront a gravity dam; the first one is the uplift pressure load that could raise the danger of reversing the dam. The second one is the ground water flow, which can lift the soil under dam. Moreover, cracks are commonly formed in dams after construction. These cracks might produce several complications in the dam structure. Several investigations have shown the influence of the injected veil that made the dams stronger. This study shows the numerical results of the injection influence on a gravity dam. Finite element software is used to check up the best location of the injected veil and the maximum favorable depth. The obtained numerical results show the major effect of the veil injection on the uplift pressure force, the ground water values, and the flows pass under the gravity dam.

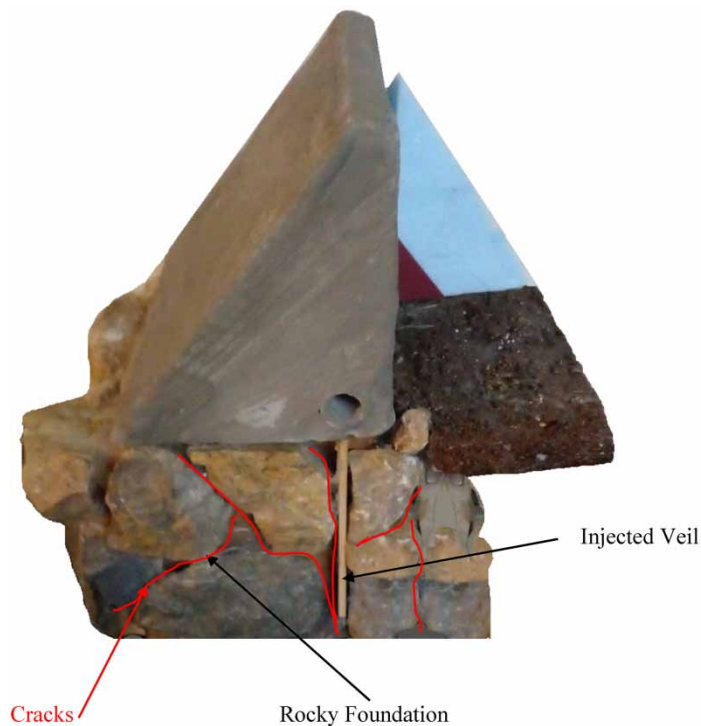
Key words: finite element software, gravity dam, ground water flow, uplift pressure force, veil injection

HIGHLIGHTS

- The impact of this research can be summed up in these points.
- Highlight on one of the major problems that affect the stability of gravity dam.
- Clarify how to solve this problem and prevent the losses in different levels (Humans life and economic way).
- Illustrate in an easy numerical method how to solve such severe problem.
- Encourage the researchers to use the veil injection system in other dam types.

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GRAPHICAL ABSTRACT



1. INTRODUCTION

A gravity dam is considered one of the oldest huge hydraulic structure. It was designed to resist loads by its mass also by resistance to sliding off its foundation and overturning. The uplift pressure force is the most critical pressure of a gravity dam, as it directly affects the stability of such dam. Many researchers had developed different solutions for such issues. According to the Comité Français des Barrages et Réservoirs, [CFGB \(2002\)](#), the solution was introduced by performing an impermeable foundation, robust, and enduring which would assist into reduce this force. The impermeability of the foundation is highly significant as uplift pressure relies mainly upon on the seepage. This treatment may be performed by several methods; veil injection beneath the dam, implementation of a drainage system, jet grout that consolidates the soil and produces a protective layer. A diaphragm wall that was used to construct a waterproof veil in the foundation as the form of a shaped wall and consolidated the supports ([Anton et al. 2019](#)). Injection is a process of closing gaps with solutes that stiffen later ([Silva 2019](#)). The form of the injected veils is connected to the geometry of the boreholes. The purpose of this study is to illustrate numerically the impact of inserting a veil on the stability of gravity dam. This approach provides acceptable alterations to features of the existent soil, and specifically permeability without demand of replaced material. This used technique fundamentally distinguishes it from waterproof screen procedures such as walls resistant to grout, concrete, or plastic concrete.

1.1. Research history and related works

Generally, injection is not only performed in case of the foundation collapse, but also when the dam itself reveals weaknesses. [Boedermann et al. \(1982\)](#) and [Berchten \(1985\)](#) illustrated the performed injection operations in the Zeuzier arch dam, Switzerland. This dam, at his lower base, revealed both cracks, and opened joints. Studies were conducted to discover which form of injection is the most useful in this case. The injection was carried out efficiently in 1988. Since then until now, Zeuzier dam demonstrates excellent conduct.

[Turcotte et al. \(1994\)](#) detailed the injection works of Isle Maligne dam, Canada. The entire degeneration of the structure, mainly at the recovery joints, generated enormous leaks of water and a constant filtration of the concrete. One of the primary repair efforts was the injection of cracks, according to the grouting intensity number (GIN) technology to waterproof the structure.

Silvano *et al.* (1997) reported improvements should be made on the Flumendosa dam, Italy. This dam revealed many cracks in the top part of its upstream side. The rehabilitation task consisted of two steps. Firstly, they made an injection in the cracks and regenerated the joints by the use of epoxy resins. After that, a full dam study related to the internal stresses was conducted. This research shows that the maximum compressive stress remains lower than 5 MPa, while the tensile stress has not been generated.

Several fractures, due to thermal conditions, in Daniel-Johnson dam, Canada, occurred during construction. Lariviere *et al.* (1999) and Bulota *et al.* (2012) explained the treatment method. Therefore, the modified conventional approach used two plunger fracture injections, provided with a steady micro-fine cement solution. After that, the water rise in the plunging fractures was reduced.

The Piedra Del Aguila dam, Argentine, revealed significant vertical fractures up to 5 mm, although there was a leak of 300 ℓ/s in specific cracks. Privileggi (2012) discussed the treatment injection works. After repair operations, the leaks were limited to 140 ℓ/s .

Mihoiesti dam (Romania) was mainly constructed to produce electricity. However, due to overload of collected water, besides incomplete works, a consolidation problem appeared and the dam became unsafe in use. Toderaş (2012) presented an optimum solution for this risky situation. Injected drillings were recommended to form veils that penetrate the shield on both slopes. This suggestion forms the solution for sealing consolidation.

Silva *et al.* (2016) analyzed numerically and experimentally the efficacy of small holes in São João dam, Brazil. A cross section steel model used to attain the test. The experience offered an efficient aligned slit dam to eliminate stony-type debris defects. The experience offered an accurate slit dam to eliminate rock debris problems. Following this study, slit dam approaches appear to have a very confined functional/effective range. The numerical results corresponded very well to the experimental ones, and demonstrated a 9% maximum deviation.

Petaccia *et al.* (2016) analyzed the failure mechanics of the Sella Zerbino dam (Italy) especially on its stability. This unexpected failure caused more than 100 victims in 1935. The under pressure load and the poor quality of the foundation rock had a significant effect in the series of events that led in the collapse of the dam.

Hu *et al.* (2017) focused on the leakage effects for gravity dams having penetrating cracks. A research project was conducted on Shimantan Reservoir Dam (China) to analyze the usage of the comprehensive investigation approach. Leakage flows in penetrated cracks has a significant role in the dam groundwater flow. The specific hydrostatic-seasonal-time approach was introduced to address the effect of leaked flow in actual micro-cracks through concrete dams based on the Navier–Stokes formula. The outcome indicates that the suggested models can provide adequate accuracy in interpreting such data.

Bazarov & Mavlyanova (2019) reported numerically the approach for the final estimation of spillway dams, concerning flood and the feasibility of maintain a particular level in the upstream. A waterfall of hydro-technical works on the Chirchik river basin, Uzbekistan, has been chosen for the numerical investigation. The acquired results proved feasibility, mathematically, by usage of highly established equations and techniques of hydraulics. The compatibility of the attained results were also compared with that collected by other researchers.

Tahar *et al.* (2020) assured that the injection method is the most suited procedure to treat most problems in the most varied soils. Concerning a foundation, the application of this treatment makes it feasible to avoid or eliminate karst dangers by considering the geological aspects of each area. A numerical study of existing karst inconsistencies was conducted out on the foundation of El Ghrass dam (Morocco) to define an acceptable distribution of these karsts. This study was considered extremely important for the determination of injection configuration (drilling spacing, alignments) and quantities.

Hu *et al.* (2020) proposed numerically to anticipate and simulate the full process of waterfall reservoir dam-break. A cascade reservoir breaching simulation (CRBS) at Tangjiashan barrier lake, China, relies on a special dam-break model by connect the hydraulic parameters of upstream and downstream basins with flood routing simulation (FRS) and flood regulating calculation (FRC). This numerical prediction model proves the great advantage of structural applications in the risk computation and flood control of waterfall reservoirs.

Magdalena *et al.* (2021) presented a numerical study of flood risk flow near an obstacle. A momentum-conservative finite technique depends on a mismatched grid system to resolve on modified non-linear shallow water equations. To validate this numerical model, various tests were performed. The application, to multiple deformation forms of the model channel, was also examined. Validation of the computed outputs analytically and experimentally indicates that the flow depicted with excellent accuracy. Moreover, the impact of the barrier size on the height of water was also analyzed.

2. METHODS

The model requirement is to specify the boundary conditions for the soil and the dam. Furthermore, it is needed to detect the depth for the veil, and the best location to install it, using a particular procedure to find its limitations. Different steps should be performed to manage this injection and model it.

2.1. Equations

The proportions of the veil wall depend on grade of the rock and height of the dam. The depth should be appropriate to minimize of both percolations and uplift. Generally, the veil depth will estimated to be 35% to 100% of the overall height of the dam. To be more specific, the United States Bureau of Reclamation (Anton *et al.* 2019) provides a formula for calculating it (Figure 1) as follows:

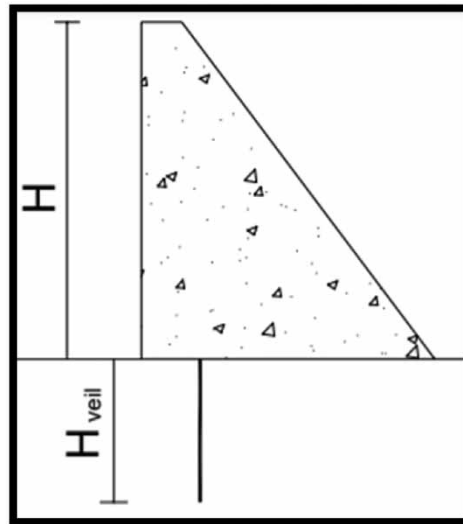


Figure 1 | Depth of the veil.

$$H_{\text{veil}} = \frac{1}{3} \times H + C \text{ with } C = 8 \text{ to } 25\text{m} \quad (1)$$

Three forces will be applied at the dam: upstream water pressure Q1, uplift pressure force Q2, and downstream water pressure Q3 (Figure 2).

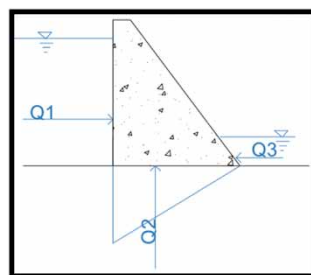


Figure 2 | Exerted forces at the dam.

2.2. GIN method

The GIN method was applied in the procedure of the veil injection. The purpose of this procedure is to limit injection volume and pressures. It proposed to use grout with low water-cement ratio. This aims to avoid the injection of a huge quantity of water (Lombardi & Deere 1993). The fundamental concept is to utilize an intensity specified as follows:

$$\text{GIN} = p \times V \left[\text{bar} \cdot \frac{\ell}{\text{m}} \right] \quad (2)$$

where: p represents the final pressure of the injection (in bar) and V is the final volume of the injected grout (in ℓ/m). A limit curve GIN is defined by taken into consideration three factors; P_{\max} , V_{\max} and GIN intensity limit. To find the limit curve, Lombardi (1993) proposed a standard limit GIN (Figure 3).

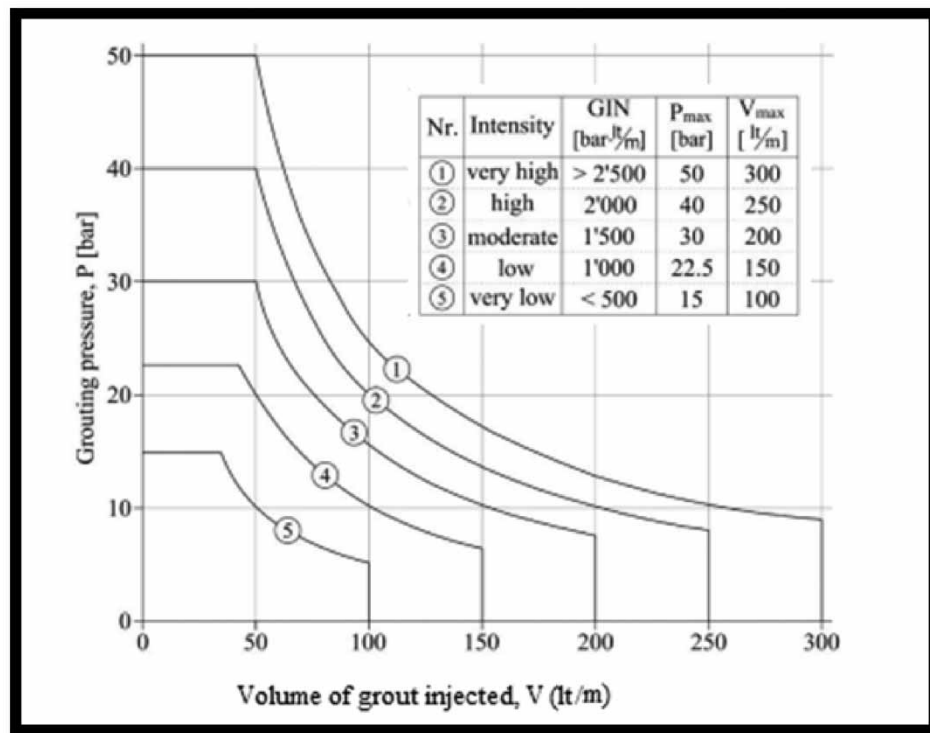


Figure 3 | Typical ranges of GIN values, as well as corresponding maximum pressures and volumes.

The standard limit defined by the GIN method presents the maximum values of both pressure (P_{\max}) and volume (V_{\max}) based on the tests (Table 1).

Table 1 | Maximum pressure and volume based on the intensity

N	Intensity	GIN (bar. ℓ/m)	P_{\max} (bar)	V_{\max} (ℓ/m)
1	Very high	> 2,500	50	300
2	High	2,000	40	250
3	Moderate	1,500	30	200
4	Low	1,000	22.5	150
5	Very low	<500	15	100

2.3. Dam modelling and simulation parameters

The gravity dam analyzed has the following dimensions: height of 25 m, upper base of 3 m, and lower base of 21.75 m. These dimensions were obtained behind the proportion of the downstream inclination that is suggested by French Committee for Dams and Reservoirs (Comité Français des Barrages et Réservoirs; CFGB 2002).

By the end of the 20th century, the introduction of computer technology had allowed portable computers sufficient to run complex finite element software. PLAXIS is considered as one of many geotechnical programs released in the early 1990s.

PLAXIS 2D program performed a finite element geotechnical analysis (BENTLEY 2021). By using this software, flow distribution, uplift pressure force, and water dissipation beneath the dam can be obtained.

The study using PLAXIS 2D is accomplished through the following processes. The first phase is pre-processing, where the FE model and the external conditions are established. The second phase is the simulation. The third and final phase is post-processing, where the outcomes are evaluated.

Several models were prepared to show the important effect of the injected veil. Two main parameters were taken into consideration, the depth of the injected veil and its location.

- The model is defined as a plane model (2D) on a strip of 1 meter thick. One-meter thickness is enough for the calculation of the gravity dam because the same function will be repeated every one meter.
- Related literature for estimating parameters can be found in the studies of Rowe & Davis (1982), Bowles (1997), and the Canadian Foundation of Engineering (2006). Since the Flow type alone is used, the soil permeability (flow parameters in Figure 4) and the injected veil properties are introduced in Table 2. The material model was considered as linear elastic, although the groundwater model was set as saturated and impermeable. The thermal effect was ignored.

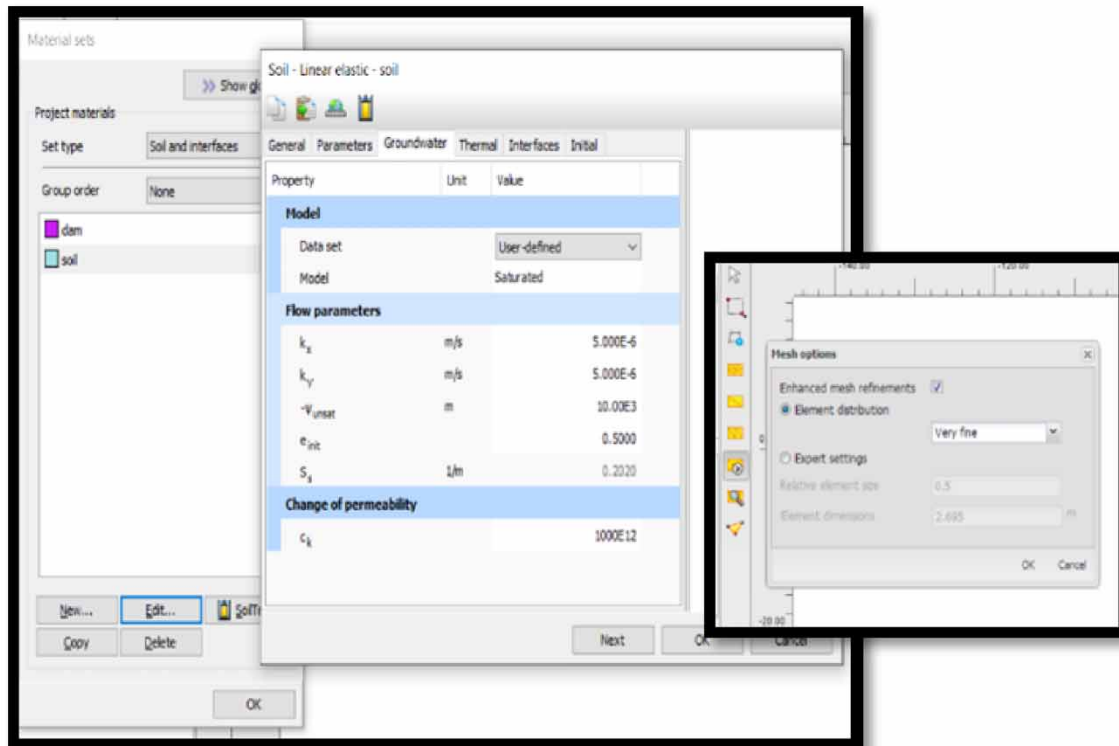


Figure 4 | Characteristics of the soil.

Table 2 | Properties of soil and anchor used in FE modelling using PLAXIS-2D

	Name	Value
Soil properties	Unit weight (unsaturated), γ_{unsat}	0 kN/m ³
	Unit weight (saturated), γ_{sat}	0 kN/m ³
	Drainage conductivity, d_k	0 m ³ /s/m
	Dilatancy cut-off, e	0.5
	Flow x direction, k_x	5*10 ⁻⁶ m ³ /s
	Flow y direction, k_y	5*10 ⁻⁶ m ³ /s
	Interface roughness, R_{inter}	1
Injected veil properties	Material	Concrete
	Water-cement ratio	0.67:1
	Relative cohesion	0.2 kN/m ²
	Poisson's ratio, ν	0.2

- The dam is drawn on the defined soil, with the same dimensions as demarcated below.
- the upstream water pressure Q1 is added. The uplift pressure force Q2 will be added automatically.

- The suitable mesh for the soil and the structure is generated (Figure 5(a) and 5(b)). The purpose of the mesh is to simplify the structure in order to facilitate computation, by use of finite elements to make a geometrical model (Clough 1960). Variations of the elements are illustrated in Figure 5. To get high accuracy, a very fine mesh type in a triangular form with three node elements was picked from the default menu of PLAXIS-2D. The elements around the injected veil were maintained denser than the other ones. The number of mesh elements in the case of gravity dam without injected veil was 763 elements; while in the case of adding injected veil to a similar gravity dam, the number reached up to 2123 elements.
- Finally, the finite element for the PlaxFlow type (Flow only) is computed. In order to emphasize the importance of its existence, we have studied 56 models. As a reference model, there is absence of injected veil ($x = 0$ and $h = 0$), unlike all the other 55 cases. Two parameters were studied, the depth and the location of injected veil. The obtained results show the variations of the uplift pressure force, and the ground water flow below the dam.

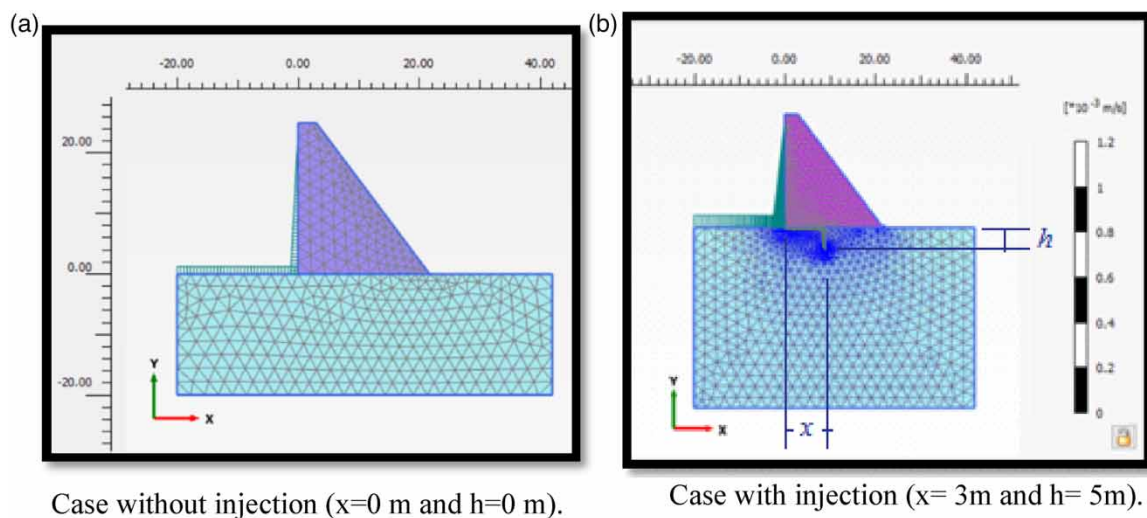


Figure 5 | The suitable mesh. (a) Case without injection ($x = 0$ m and $h = 0$ m). (b) Case with injection ($x = 3$ m and $h = 5$ m).

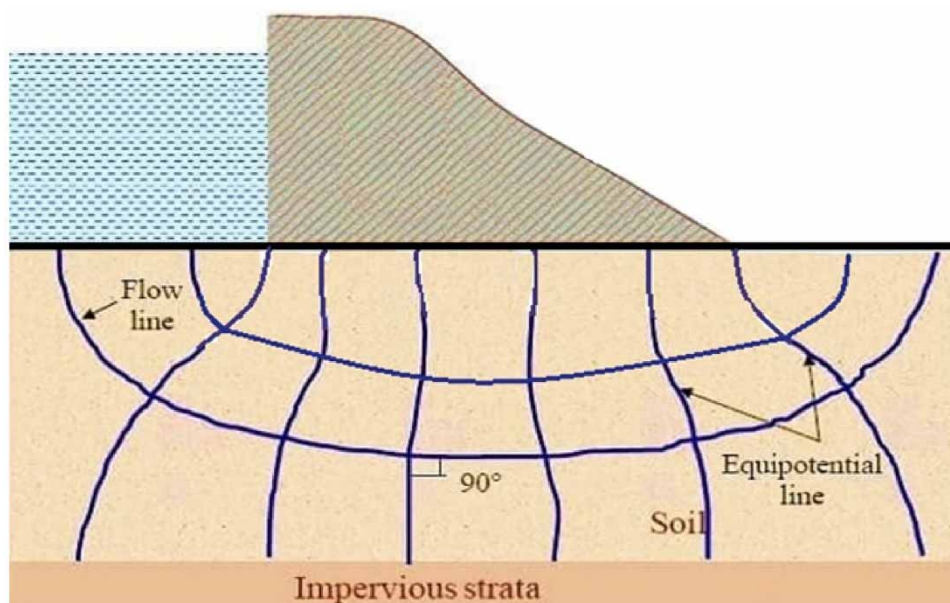


Figure 6 | Uplift pressure.

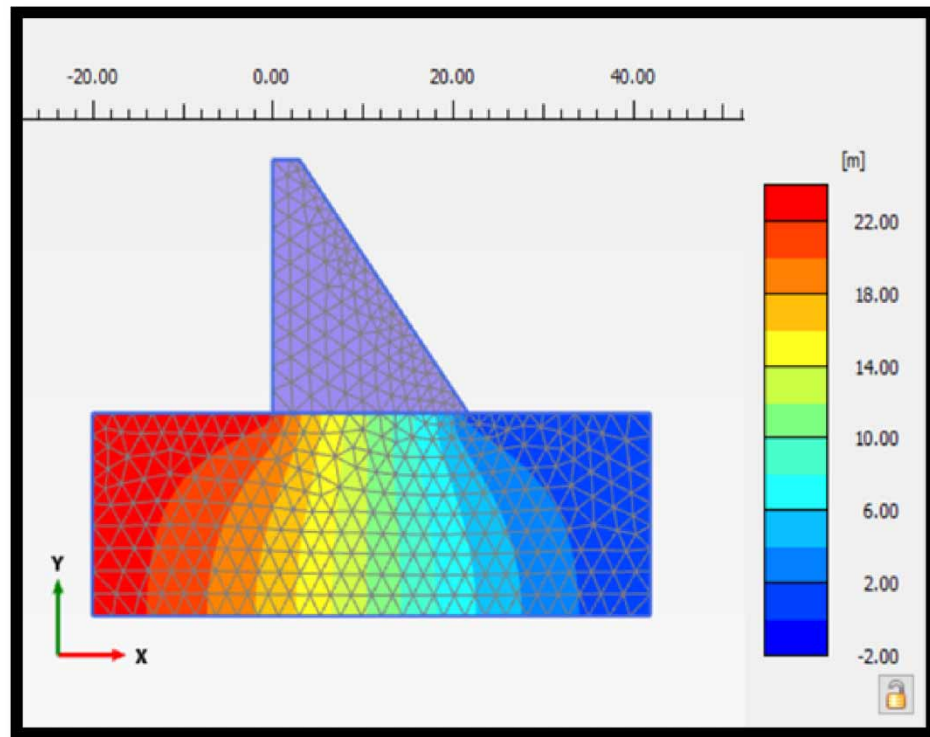


Figure 7 | Uplift pressure load without injection.

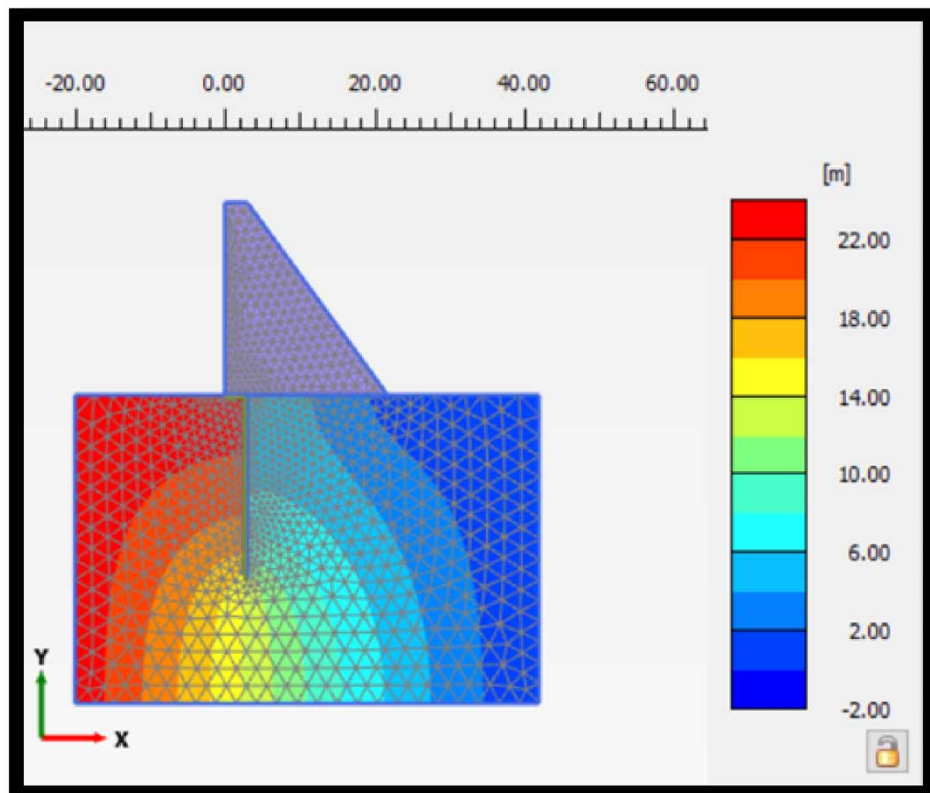


Figure 8 | Uplift pressure load with injection.

3. RESULTS AND DISCUSSION

For each studied case, three mainly results will be discussed: the under pressure load, the ground water flows under the dam, and the flows pass under the dam. The uplift pressure was represented by both of equipotential and flow lines (Figure 6). It presented the piezometers that give us the water pressure on each line.

Using the visualization module, numerous outcomes may be examined by showing the results, such as meshed coloured contour plots. Colours ranged from maximum pressure (red part), until reaching its minimum value 0 m (dark blue part). It was noticed that, from the obtained results and the deformed coloured contour shapes, there was an important variation of the uplift pressure load (Figures 7 and 8) and the ground water flow.

All the obtained results concerning the variation of the uplift pressure are summarized in Table 3 and in Figure 9. Knowing that, x is the distance between the left edge of the dam and the location of injected veil. However, h is the depth of injected veil.

Referring to the obtained results (Table 3), there is an important decrease in the uplift pressure values compared to the referred model (actual data) due to the insertion of veil. The maximum decrease will be observed at the maximum chosen depth (30 m). The maximum reduced values of the uplift pressure will be deduced, and summarized in the following table (Table 4).

These important reductions in the uplift pressure values give the dam more stability and safety.

Other results were summarised in Table 5 and Figure 10, concerning the variation of the ground water flow under the dam (Q).

Table 3 | Variation of the uplift pressure load P (kN/m^2)

	h (m)	x (m)							
		0	3	6	9	12	15	18	21
Without injection	0	240	200	160	180	100	180	160	120
With injection	5	140	140	140	100	140	120	100	160
	10	120	120	120	80	120	100	80	140
	15	100	100	100	60	100	80	60	120
	20	80	80	80	40	80	60	40	100
	25	60	60	60	20	60	40	20	80
	30	40	40	40	0	40	20	0	60

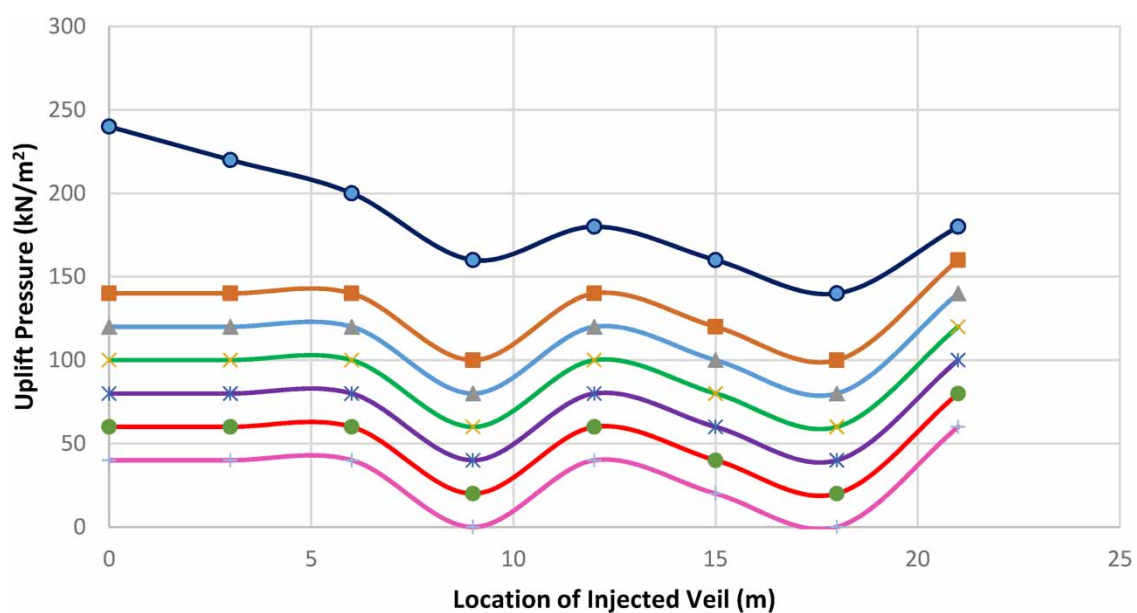


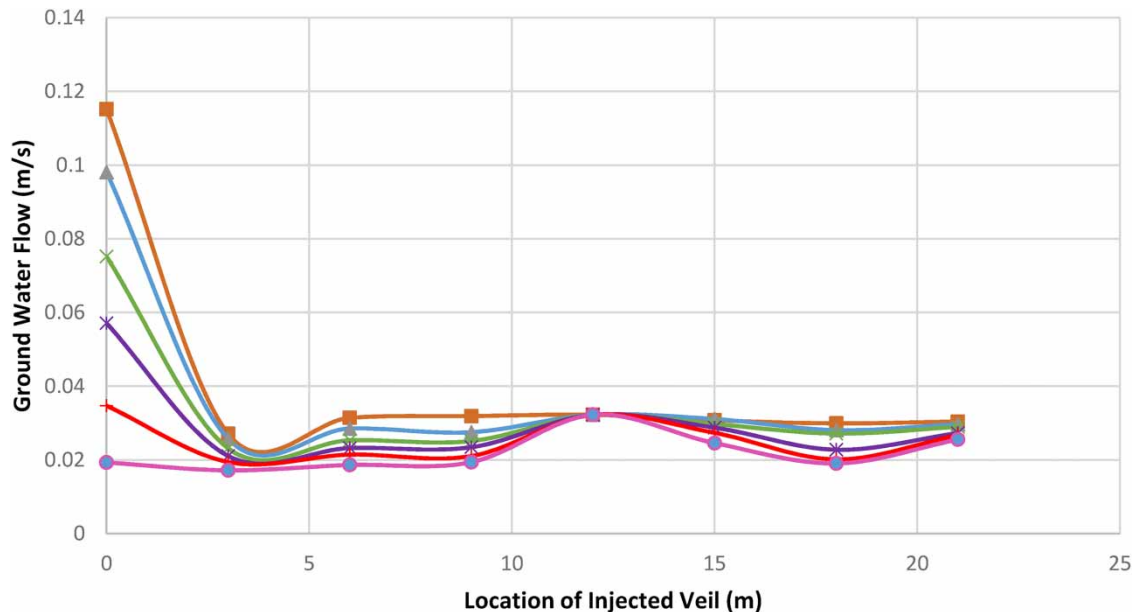
Figure 9 | The effect of the location of injected veil on the uplift pressure.

Table 4 | Percentage reduction values of the uplift pressure load P

	x (m)	0	3	6	9	12	15	18	21
% Reduction	0	83.33	80	75	100	60	88.88	100	50

Table 5 | Variation of the ground water flow $Q \cdot 10^{-3}$ (m/s)

		x (m)							
	h (m)	0	3	6	9	12	15	18	21
Without injection	0	0.3191							
With injection	5	0.1152	0.0271	0.0314	0.0319	0.0322	0.0308	0.0299	0.0304
	10	0.0981	0.0258	0.0285	0.0275	0.0322	0.0311	0.0281	0.0297
	15	0.0752	0.2314	0.0253	0.0251	0.0322	0.0297	0.0271	0.0290
	20	0.0571	0.0211	0.0232	0.0235	0.0322	0.0288	0.0228	0.0273
	25	0.0347	0.0194	0.0214	0.0211	0.0322	0.0273	0.0201	0.0267
	30	0.0193	0.0172	0.0186	0.0194	0.0322	0.0246	0.0191	0.0255

**Figure 10** | The effect of the location of injected veil on the ground water flow.

By comparing all the previous results obtained, it was clear that the greater (h), the less effect of ground water flow on dam. However, with the increase of (x), the uplift pressure decreases as summarized in Table 3. The ground water flow (Q) was constant ($0.3191 \cdot 10^{-3}$ m/s.) in the absence of injected veil. However, for the other 55 cases, there were many changes depending on the depth of the injected veil (h) and its location (x).

Backing to the collected data in the previous table (Table 5), there is an effective drop in the variation of the ground water flow values compared to the referred model (actual data) due to the insertion of veil. The maximum efficiency will be at the maximum chosen depth (30 m). The percentage reduction values at 30 m depth, for the variation of the ground water flow, will be summarized in the following table (Table 6).

Table 6 | Percentage reduction values of the ground water flow Q

	x (m)	0	3	6	9	12	15	18	21
% Reduction	0	93.95	94.61	94.17	93.92	89.91	92.29	94.02	92

Based on all the previous results, the better performance of the injected veil on this gravity dam will be at $x = 0$ m and $h = 30$ m. As a summary, the uplift pressure, in the absence of injected veil, was 240 kN/m^2 , with corresponding ground water flow $0.3191 \times 10^{-3} \text{ m/s}$. However, after using the injected veil with $h = 30$ m, the uplift pressure becomes 40 kN/m^2 , with corresponding ground water flow equals to $0.0193 \times 10^{-3} \text{ m/s}$. Therefore, there is a reduction in the uplift pressure around 83.33% (Table 4), and 93.95% in the ground water flow (Table 6).

The passage of the flow under the dam without veil injection, accord to the showed arrows, is high and fast as seen in subsequent figures (Figures 11 and 12). While insert the injection, the veil will block those arrows, so they will go down to the deepest point of the veil, and almost disappear (Figures 13 and 14).

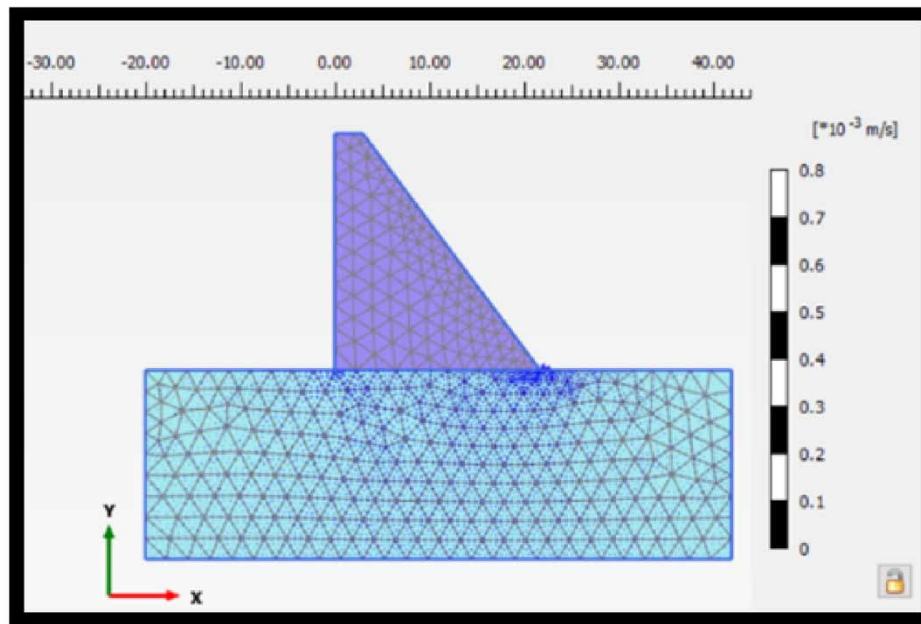


Figure 11 | Obtained results for flow paths under the dam (Without injection case).

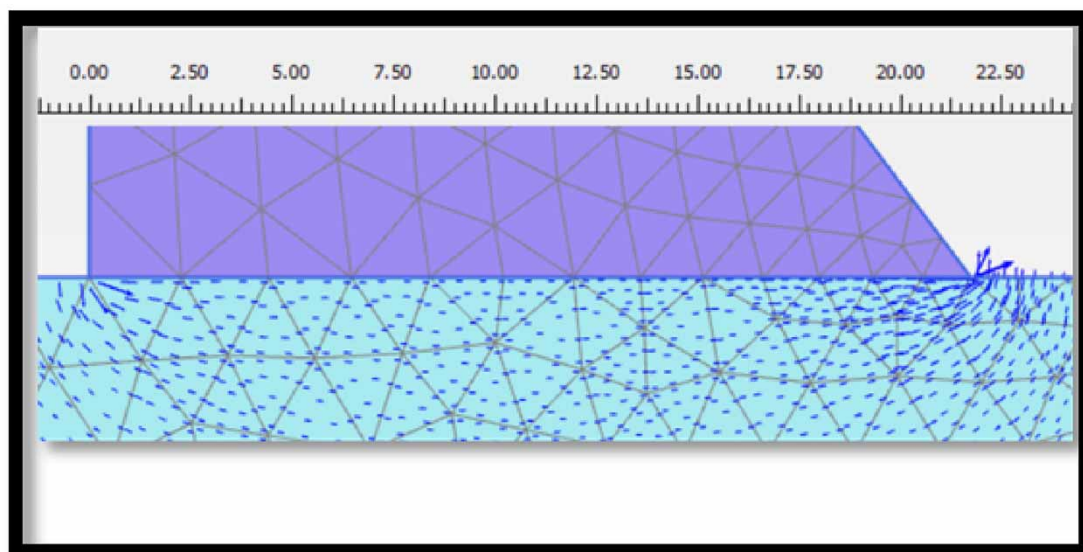


Figure 12 | Zoomed view for obtained results for flow paths under the dam (without injection case).

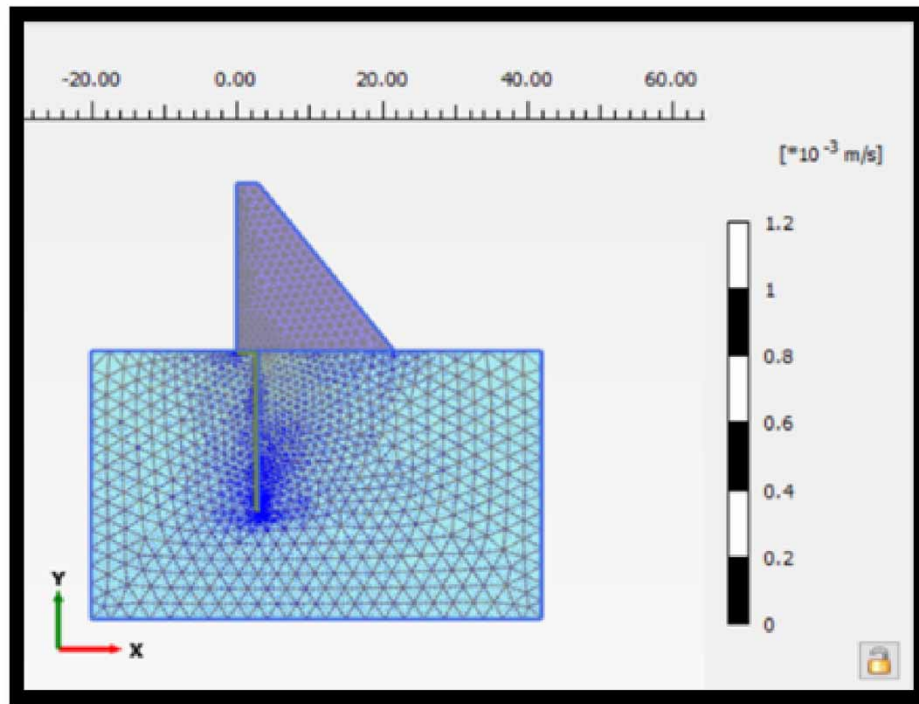


Figure 13 | Obtained results from the flow pass under the dam (Injection case).

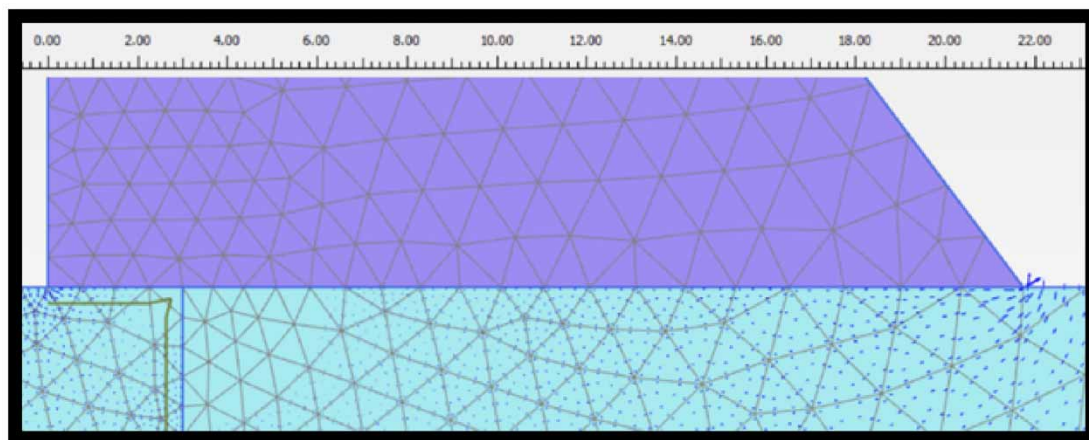


Figure 14 | Zoomed view of obtained results from the flow pass under the dam (injection case).

4. CONCLUSIONS

The major causes of dam failure are cracks found in the foundation. Different studies were made to find the best solution to repair the foundation and make it more resistant. Injection is the most effective solution to fix this problem in the dams. Proper injection based on the studies and using the GIN method can be very effective.

In this research, several conditions of gravity dam were studied (56 models). The first one was chosen to be as a reference model (without injected veil). Whereas, all the other models were provided with injected veil. The injected veil was displaced under the gravity dam in eight locations (x). In addition, at each location, seven tests with variable depths (h) were studied. The finite element software, PLAXIS 2D, has been used and applied for this study. The 2D model is realized on the PLAXIS 2D software based on Marcy's law to show the uplift pressure force, the ground water flow, and the flows arrows under the dam. Besides that, the effect of chosen the best location and depth of injection were discussed.

In these studied cases, for a gravity dam, a comparison was taken place to show the effect of insertion an injected veil using GIN method. The obtained uplift pressure load reduced by 83.33%, while the ground water flow under the dam showed a reduction by 93.95%. The injected veil also blocks the flow arrows passed under the gravity dam, and almost disappeared.

Future research studies should be investigated for other dam types to clarify the effect of injected veil on them.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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