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EFFECTIVENESS OF GROUTING MATERIALS FOR WATER SEEPAGE CONTROL

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KEYWORDS: Permeability, grouting materials, grout curtain, dam, SEEP/W

ABSTRACT
One of the major concerns facing dam is the repair of their structures to prevent the seepage under them. In previous years, many existing dams have been treated by grouting, but with varying degrees of success. One of the major reasons for this erratic performance is the unsuitable selection of the grouting materials to reduce the seepage. Grouting is an effective way to strengthen of the permeability of the soil to reduce the seepage. The purpose of this paper is to focus on the efficiency of current available grouting materials and techniques from construction, environmental and economical point of view. The seepage reduction usually accomplished by either chemical grouting or cementious grouting using ultrafine cement. In addition, the study shows a comparison between grouting materials according to their degree of permeability reduction and cost. The application of seepage reduction is based on the permeation grouting using grout curtain installation. The computer program (SEEP/W) is employed to model a dam rested on sandy soil, using grout curtain to reduce seepage quantity and hydraulic gradient by different grouting materials. This study presents a relationship that takes into account the permeability of the soil, grout curtain spacing and a new performance parameter that can be used to predict the best selection of grouting materials for seepage reduction.

INTRODUCTION
Groundwater seepage under dams and other hydraulic structures is a significant problem that geotechnical engineers are facing frequently with hydraulic structures. As dams continue to age, groundwater seepage issues are becoming more current [17]. Recent history has indicated that groundwater seepage under dams and other hydraulic structures can cause significant problems not just for the dam, but to the surrounding communities. Grouting is defined as the procedure of filling or injecting fluid with pressure into the soil, generally via boreholes [18]. Two classes of grouting materials are classified for seepage reduction, 1) suspension-type grouts, 2) Solutions -type grouts [10].

The suspension-type grouts include clay and cement, while solutions-type grouts include a wide variety of chemicals such as acrylamide, N-Methaloacrylamide, acrylate and colloidal silica [9]. The grout is based on cement, silicate, or other materials, selected to suit particular ground conditions and improvement objectives. The grout fills in voids and cracks of the ground and permeates into soil pores to produce a solidified soil-grout mass [2].

GROUTING MATERIAL FOR WATER CONTROL
In order to choose a grout type, several properties of grout should be concerned, such as rheology, setting time, toxicity, strength of grout and grouted soil, stability or permanence of the grout and grouted soil and the penetrability of the grouted soil [12].

SUSPENSION -BASED FINE GROUTS
Cement grout In this type of grouting materials, the micro fine cement is used to permeate between the soil particles. It has an average particle size of 3 to 4 microns [3]. The cement grout decreases the permeability about 5 orders of magnitude as the cement - water mix between (0.5 – 5) [3]. The cement grout would cost about $100 to $ 200 per cubic meter of treated soil [1].
Cement- bentonite grout In this type of grouting materials, the bentonite is used with the micro fine cement to reduce the cost of the grout materials [5]. The permeability of the soil decreases by increasing the percentage of the bentonite [7]. The cement- bentonite grout decreases the permeability about 3-4 orders of magnitude. The cement- bentonite grout would cost about $65 to $ 75 per cubic meter of treated soil [1].
Clay (bentonite) grout This type of grout is used to reduce the cost and also is used to reduce the permeability by increasing the percentage of clay [14]. The permeability of the soil is reduced about 3-4 order of the

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magnitude based on the clay concentration. Clay grout would cost about $35 to $ 45 per cubic meter of treated **soil [1].**

Table (1) k of grouted soil (suspension grout) [1&4]

Grout Type	Characteristics	k (m/sec)
Neat cement	w/c ratio = 0.5 to 5.0	10^{-7} to 10^{-9}
Cement-bentonite	w : c : b = 4 : 1 : 1	10^{-8} to 10^{-10}
Bentonite slurry	20 % solids	10^{-7} to 10^{-10}

CHEMICAL (SOLUTION GROUTS)

Acrylamide grout & NMA grout contractors inject acrylamide to reduce the permeability. It has a viscosity and density similar to water. Acrylamide is considered to be permeant. The acrylamide grout decreases the permeability about 6-8 orders of magnitude [7]. The World Health Organization (WHO) considers acrylamide to be a neurotoxin and a potential carcinogen [9]. The cost of acrylamide grout is about $500 per cubic meter of treated grout [1]. **NMA** (N-Methaloacrylamide) used to reduce the permeability. NMA is not a toxin. So, NMA is better to use than acrylamide grout where drinking water is found. The reduction of permeability is similar to acrylamide about 6-8 orders of magnitude [13]. The cost of N-Methaloarylamide grout is about $550 per cubic meter of treated grout [1].

Acrylate grout In this type of grouting materials, the acrylate grout is used to reduce the permeability of soil. Acrylate gel is used as a less toxic material. It has a high viscosity. Turner 1998 reported the acrylate grout reduce the permeability about 1-3 orders of magnitude [14]. The acrylate grout would cost about $325 per cubic meter of treated soil [1].

Colloidal silica grout (CSG) comprises a mixture of sodium silicate and reagent solution, which change in viscosity overtime to produce a gel. Reagent solution is organic or inorganic materials [11]. CSG has a low viscosity. Yone-kura and Miwa reported that the permeability of the soil is reduced about 4-5 order of the magnitude based on the concentration of colloidal silica [19]. Colloidal silica grout would cost about $60 to $ 180 per cubic meter of treated soil [1].

Table 2 k of grouted soil (chemical grout) [4&18]

Grout Type	Characteristics	k (m/sec)
Colloidal silica	Non toxic	10^{-9} to 10^{-11}
Acrylamide	Toxic grout	10^{-12}
NMA grout	Non toxic	10^{-12}
Acrylate	Less toxic	10^{-5}

Finally, figure (1) explain the maximum permeability of the soil after being injected by the grouting materials [6].

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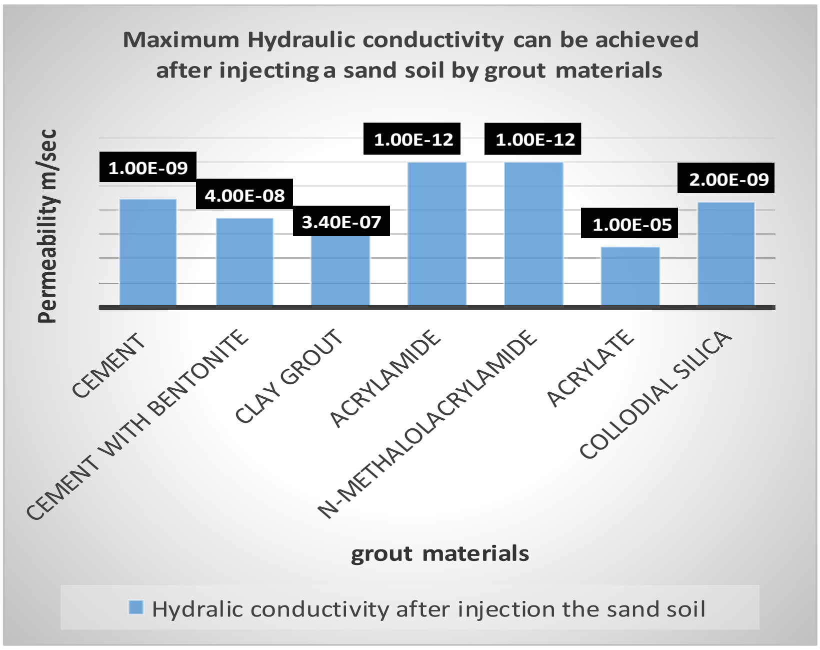

Fig 1: Maximum Hydraulic conductivity can be achieved after injecting a sand soil by grout materials [6].

Permeation grouting for water control includes the injection of a low-viscosity fluid in the soil pores without changes in the soil physical structure. The main goal of this technique is both to strengthen soil and to waterproof ground by filling its pores with injected fluid [17]. This method improves the soil physical and mechanical characteristics and controls the groundwater migration [12]. The process of permeation grouting is schematically shown in Figure (2) [18]. The quality control during permeation grouting is very important to ascertain the effectiveness of the technique.

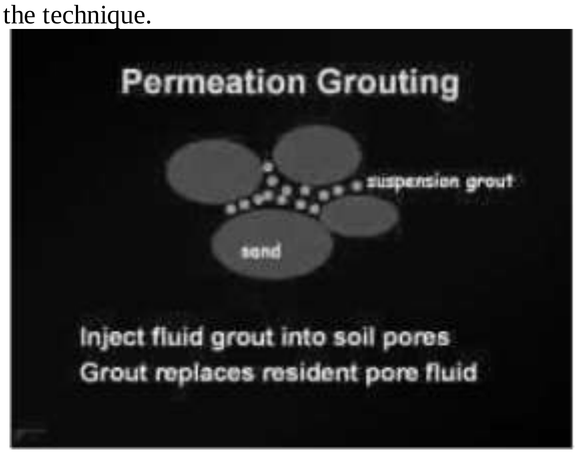

Fig 2: The process of permeation grouting

Repeated cyclic loading and grouting The grouted area is affected by the repeated cyclic loading based on the grouting material used. The suspension grouting is fragile, on the other hand, the chemical grouting is soft and flexible material. It is here known as the impact of the repeated load on fragile material. The effect of cyclic loading can damage a fragile material, but the soft material can withstand against these load [4].

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Grout curtain is a barrier that protects the foundation of a dam from seepage and can be made during initial construction or during repair. It can be single-row or multiple row of curtain. Single-row of curtain grouting is drilled as a widely spaced system of primary holes, subsequently followed by secondary and tertiary holes at a progressively smaller spacing as shown [4]. The depth of the holes is dependent on design considerations as well as the depth of the soil and the head at upstream. For permeation grouting 38mm probe diameter is the most common in use [8]. There are mainly three different types of grout hole patterns used for grouting works [13]. These types are called the random spacing, the fixed spacing and split spacing. Houlsby (1990) proposed another way to construct the grout curtain figure (4) [8]. It is based on three stages of holes (primary, secondary and tertiary) each of them has a different depth, and if necessary, quaternary and quandary holes can also be drilled. The primary spacing used is 12.0 m in most of cases, but can also be less (6.0 m minimum) to reduce the permeability to satisfactory level [16].

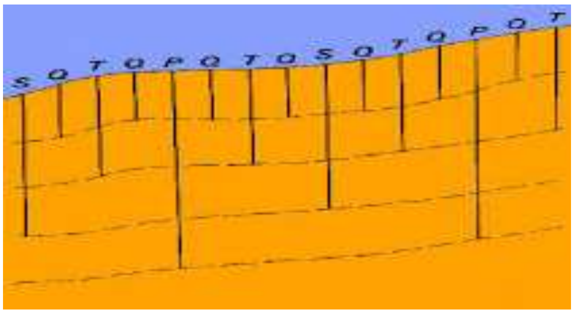

Fig 3: Design of the grout curtain

Grout Intakes The quantity of grout depends on the accuracy required of the work and the volume of the void system of that particular soil to be improved. Understanding the soil porosity is a fundamental to determine the amount of grout that will be required to treat a given volume of soil. To make a serious estimation of grouting materials, it requires a geological study to evaluate the void content and the design of the grout curtain.
volume of grouting materials is given by the following formula (Henn 1996) [6].

$$\mathbf{Vg = Vz\ (\eta\ F)\ (1+L)} \qquad \mathbf{(1)}$$

Where, Vg = Volume of grout intake, V_Z = Volume of grouted soil, η = Porosity of soil. F = Factor of filling (0.85 to 1.0), L = Loss Factor (0.05 to 0.15).
Another method for estimating the quantity of grouting materials depend on the porosity of soil. The expected volume of required material depends on Casagrande formula:

$$\mathbf{K = 1.40\ e^2\ K_{0.85}} \qquad \mathbf{(2)}$$

$$\mathbf{Vg = \eta_{net}\ Vz} \qquad \mathbf{(3)}$$

Where, K = the permeability of the soil, **e** = Void ratio, η_{net} = the net porosity of soil.

COMPARISON BETWEEN THE GROUTING MATERIALS FOR SEEPAGE REDUCTION

In order to choose the best grout type, several properties of grout should be concerned, such as rheology, setting time, toxicity, strength of grout and grouted soil, stability or permanence of the grout, the penetrability of the soil and the cost of each material [12]. Now, the comparison between the grouting materials used to seepage reduction will be explained. It's based on references and pervious experiments according to Gel time, viscosity, and grouting techniques for seepage reduction Figure (4:6).

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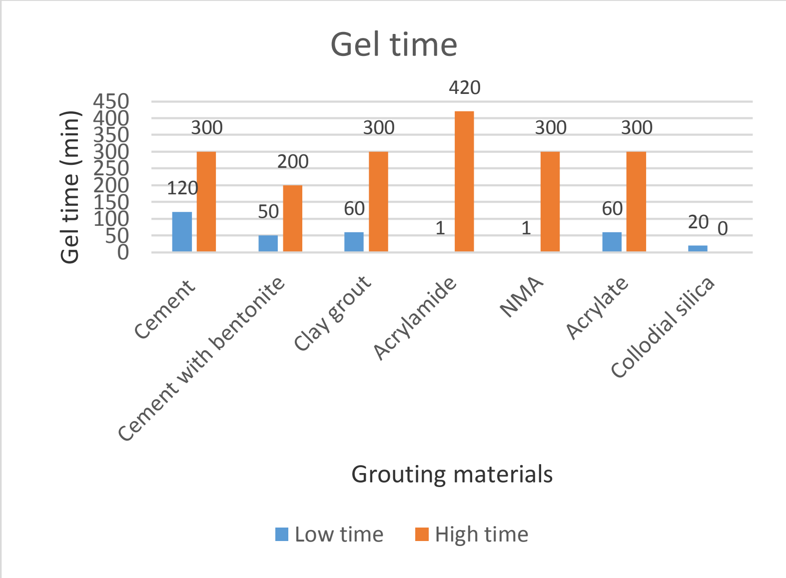

Figure 4: gel time for grouting mix

Permeation Grout	Jet Grout
Used for seepage control(cementious & Chemical grout)	Used for strength of soil and seepage control(cementious grout) not used for seepage control
Compaction Grout	Fracture Grout
Used for strength of soil but not seepage control (cementious & Chemical grout)	Used for strength of soil but not seepage control (cementious & Chemical grout)

Figure 5: grouting techniques for seepage control.

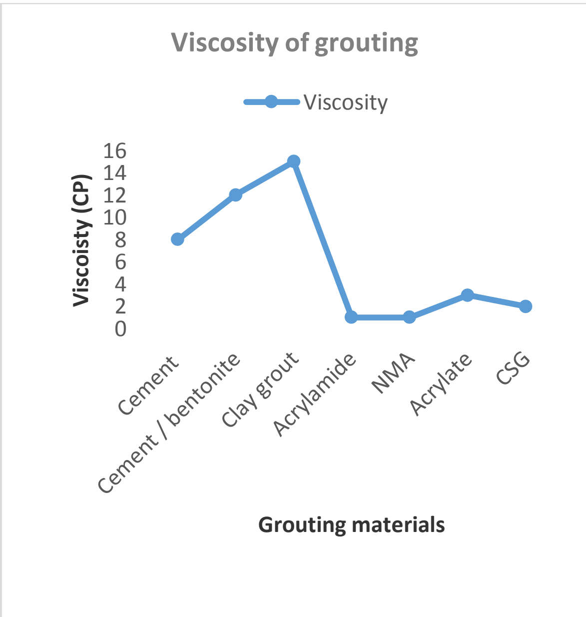

Figure 6: viscosity of grouting mix

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ESTIMATION OF GROUTING MATERIALS (Volume & cost)

the dam rests on the sandy soil with depth 14.0 m and followed by impervious layer. The dam is 18.0 m long, 18.0 m wide and 1.5m buried from the foundation. 6.0 m the head at upstream of the dam.

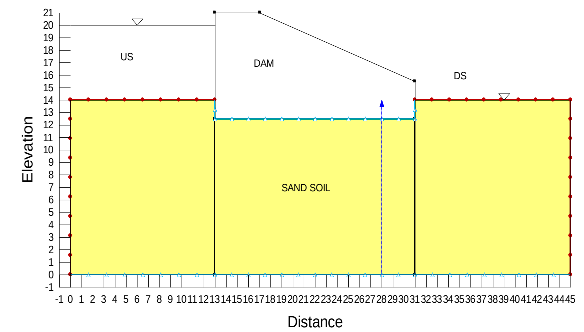

Figure 7: Geometry Model for 2D SEEP/W Analysis

Grout curtain used in the case of study The curtain effectiveness may be increased by using multiple grout lines. In curtain grouting, the grout holes are arranged in a series of lines to form a grout curtain perpendicular to the direction of seepage with length 24.0m at upstream of the dam. The initial spacing of primary holes starting with 6.0 m based on the grouting materials to achieve the best design for seepage reduction. In our case of study, two rows of the grout curtain are used to define the cost of each material based on the quantity of grout injection and installation as shown in figure (8).

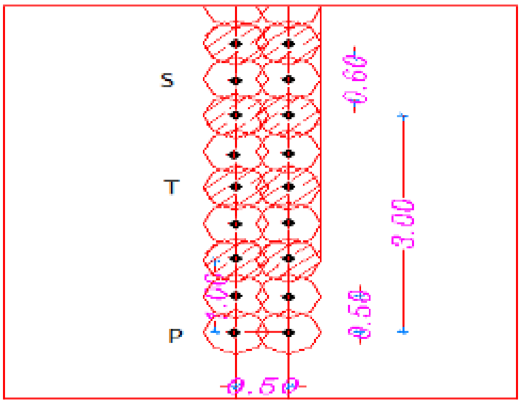

Figure 8: Layout of holes

Injection pressure The pressure, which is measured at the entry of a grout hole, is always higher than the overburden pressure at the level of injection. Injection pressure criteria have generally been set relative to the vertical overburden pressure. Available injection pressure equals five times of overburden pressure (European code). In permeation grout, the injection rate for suspension grout is 6 L/min, while the chemical grouting is 8 L/min [1].

Case (1) estimating the Total quantity of each material. According to the case of study, the expected volume of grouted soil and grouting materials depends on the permeation technique for grout curtain installation. The split hole is the best choice for seepage control and the two rows of the hole can achieve the seepage control to a satisfactory level. The expected volume of grouted soil equals 108.06 m3 as shown in the figure (9).

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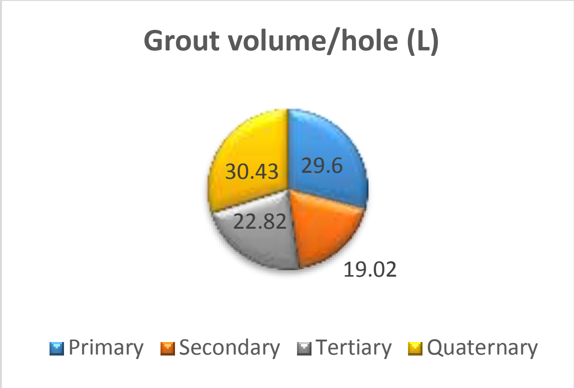

Figure. 9 the grout volume for hole of grout curtain.

Based on the volume of grouted soil, the volume of grouting materials can be calculated according to (Henn 1996) equation (1) and presented in table (3) [6]. Figure (10) shows the comparison between the grouting materials by the total cost of grouting materials with permeation grout installation. Where the cost of permeation grout for suspension grouts is about $ 130 per meter of grouted soil, while the chemical grouts is about $ 200 per meter of grouted soil [1].

Table (3) the expected volume of grouting materials (Henn1996)

Material type	Void filling factor %	Grout loss factor %	**Total quantity**
Water-cement	90	5	35.74
Cement-bentonite	85	5	33.75
Clay grout	85	10	35.36
Acrylamide Grout	95	15	41.32
NMA Grout	95	15	41.32
Acrylate Grout	85	10	35.36
Colloidal silica	90	10	37.44

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Figure 10: Total cost for each grouting material.

Case (2) estimation the grouting materials to achieve the permeability 10-7 m/Sec: Based on the data of the model and figure (1), the required volume of each grouting material can be calculated to reduce the permeability of soil from 10-4 m/sec to 10-7 m/sec as shown in table (4). To achieve this permeability of soil, it depends on the porosity of the soil before and after grouting process. The porosity of the model for the case study is 35 % at the permeability of soil 10-4 m/sec. From Casagrande formula can calculate the new porosity at the permeability 10-7 m/sec. Finally, the new porosity is 1.65 %.

Table (4) Calculation of grouting materials based on Casagrande formula [17]

Material type	The permeability reduced	The volume of required materials to achieve 1 % of porosity m^3	**Total quantity required**
Water-cement	$1X10^{-09}$	1.02	34.21
Cement-bentonite	$4\ X10^{-08}$	0.994	33.15
Clay grout	$3.4\ X10^{-07}$	1.03	34.68
Acrylamide	$1\ X10^{-12}$	1.18	39.38
NMA Grout	$1\ X10^{-12}$	1.18	39.38
Acrylate	$1\ X10^{-5}$	Cannot reach	—
Colloidal silica	$2\ X10^{-09}$	1.07	35.92

DATA ANALYSIS

The most important soil property used in seepage analysis is the hydraulic conductivity. In a saturated soil, all the voids are filled with water, and the volumetric water content is equal to the porosity of the soil. All data used in the model mentioned in the table (5).

Table (5) Property of Soils.

Parameter	**Name**	**Unit**	**Soil**
Material model	Model	-	Sandy soil
material behavior	Type	-	Drained
Soil unit weight	γsat	KN/m^3	15
Permeability	K	M/s	.0001
Young's Modulus	E	KN/m^2	20000
Void ratio	e	-	.53
Poisson's ratio	ν	-	0.3
Porosity	n	%	35
Cohesion	c	-	0
Friction angle	Φ	-	35

Case (3) changes in the depth of curtain grout This case shows the seepage analysis to assign the seepage quantity under the dam based on the change of curtain depth and different grouting materials where the curtain grout equals (50 cm).

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Case (4) changes in the width of curtain grout The width of curtain grout depends on the number of lines. So based on seepage analysis and different grouting materials, the effect of the number of the rows of the grout curtain can be defined. In the case of study, the depth of grout curtain is 9.0 m and the width of the of grout curtain changes.

RESULTS AND DISCUSSION

Case (3): change in the depth of curtain grout The result of the seepage analysis of the modeled dam (Cement - Bentonite and acrylamide grout), shows a seepage quantity and exit gradient under the dam based on the change of curtain depth and different grouting materials for the seepage reduction as shown in Figures (11&12). In addition to the uplift pressure under the dam that can be extracted from the seepage analysis due to increasing the depth of the grout curtain as shown in figure (13).

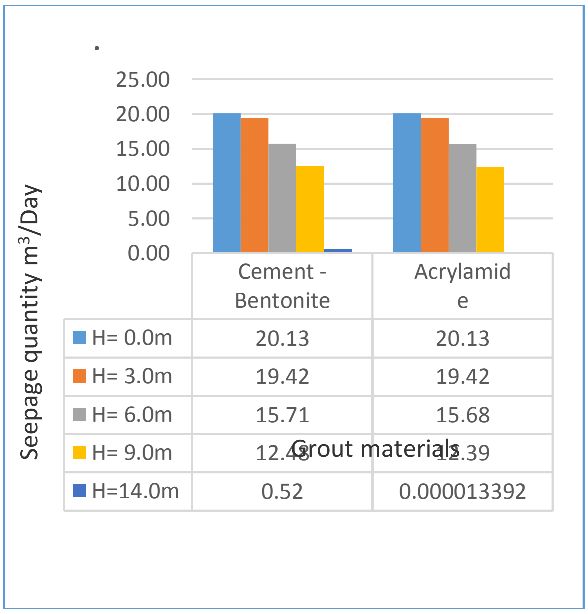

Fig 11: Effectiveness of grouting material for seepage quantity based on depth of grout curtain.

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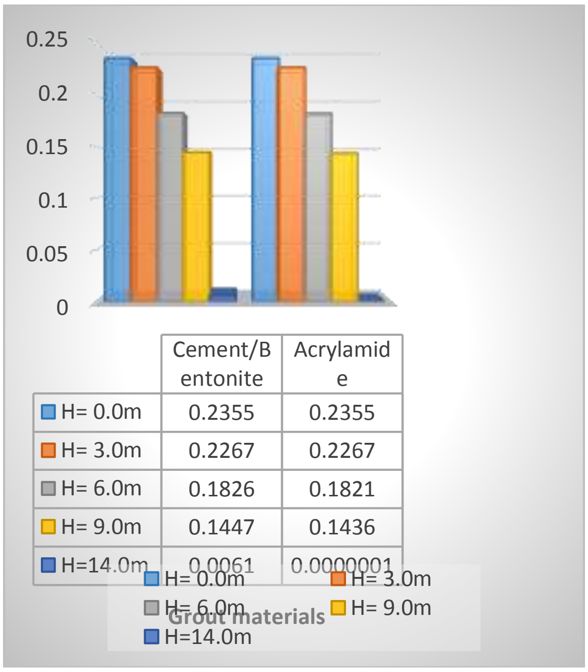
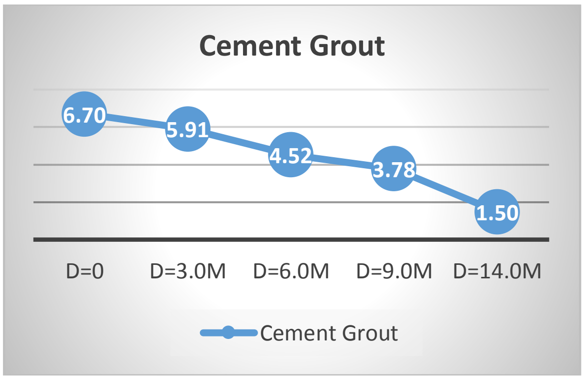
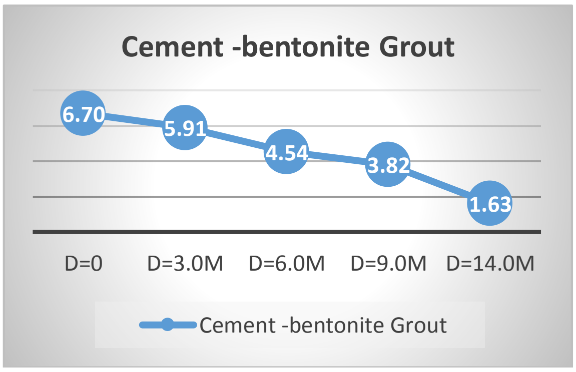
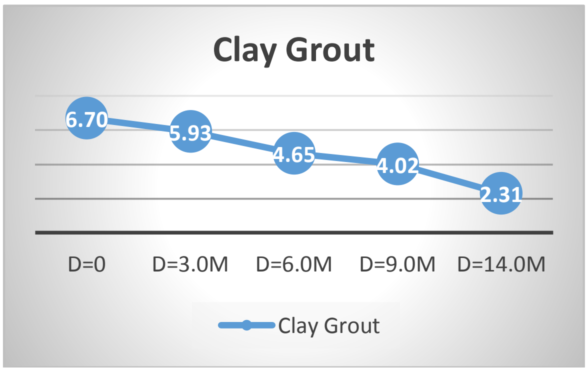
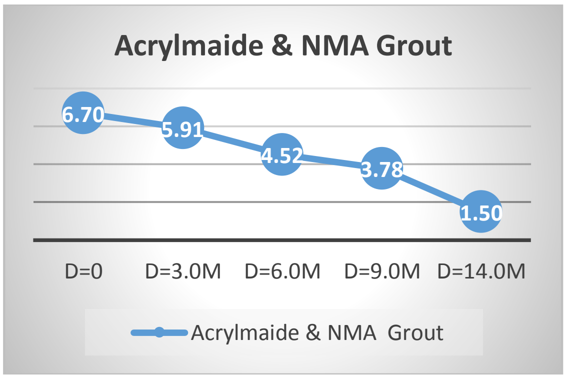


Fig 12: Effectiveness of grouting material for exit gradient based on depth of grout curtain









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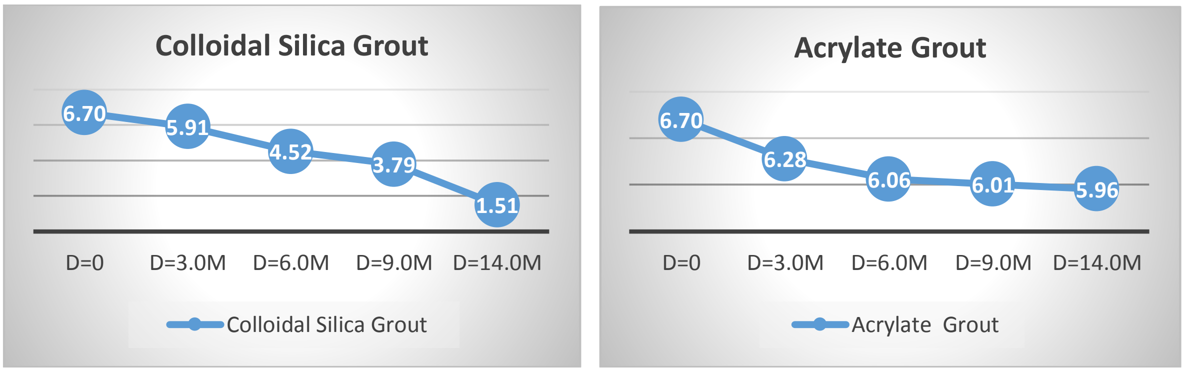

Figure 13: maximum uplift pressure due to the increasing the depth of the grout curtain.

Case (4): Change in the width of curtain grout The width of curtain grout depends on the number of lines either single or multiple row. In this case of study, the depth is constant (1.5H = 9.0m) and width of the grout curtain equal (0.5 & 1.0 & 1.5m). Figure (14) shows the effect of changing width of the cementious grouting on seepage control.

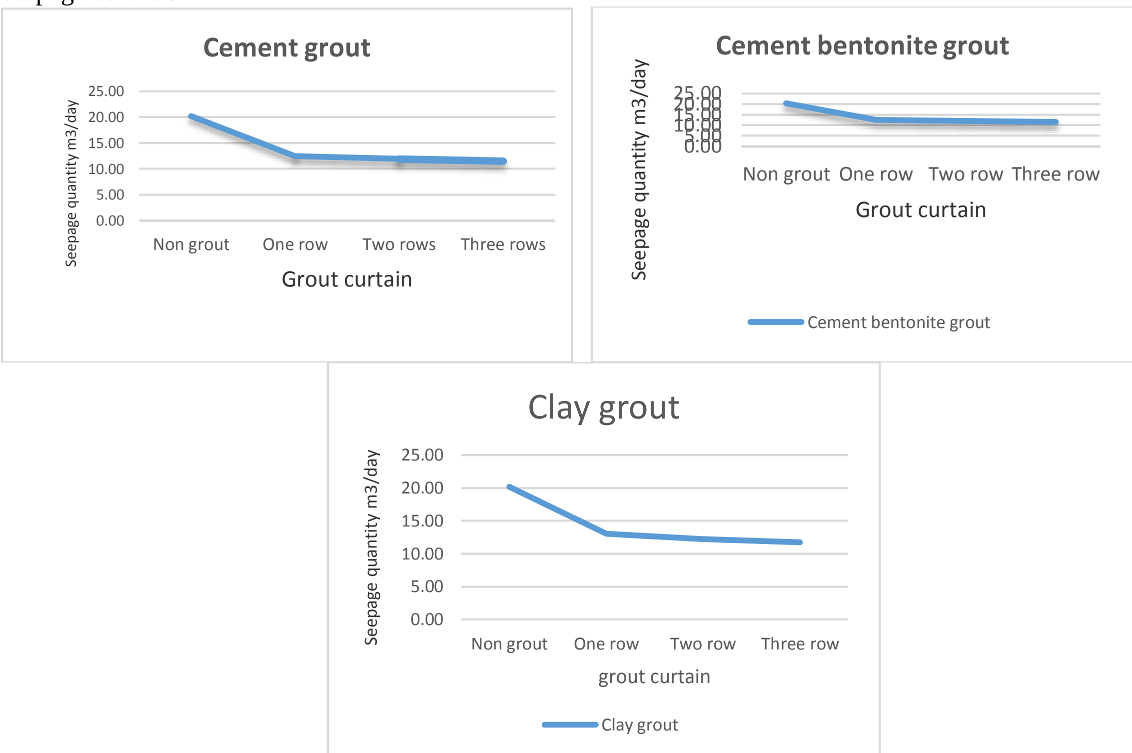

Figure 14: The Result of width effect of suspension grout where (D = 1.5H & width = 1, 2, 3 rows.

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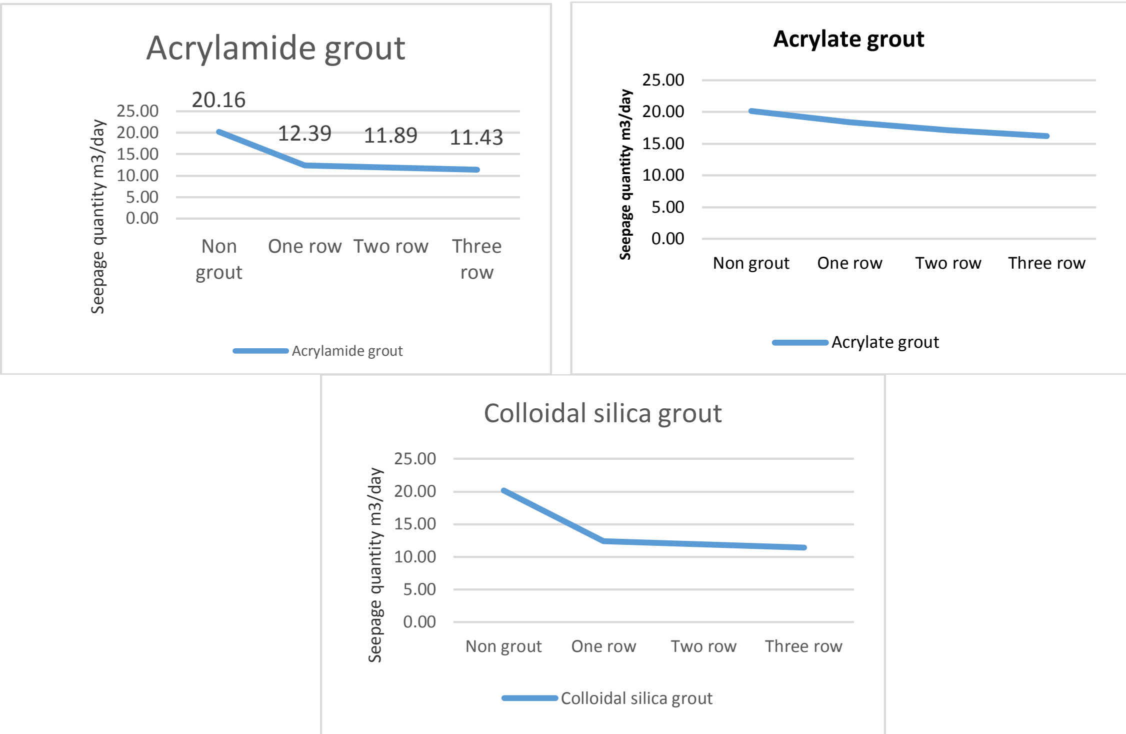
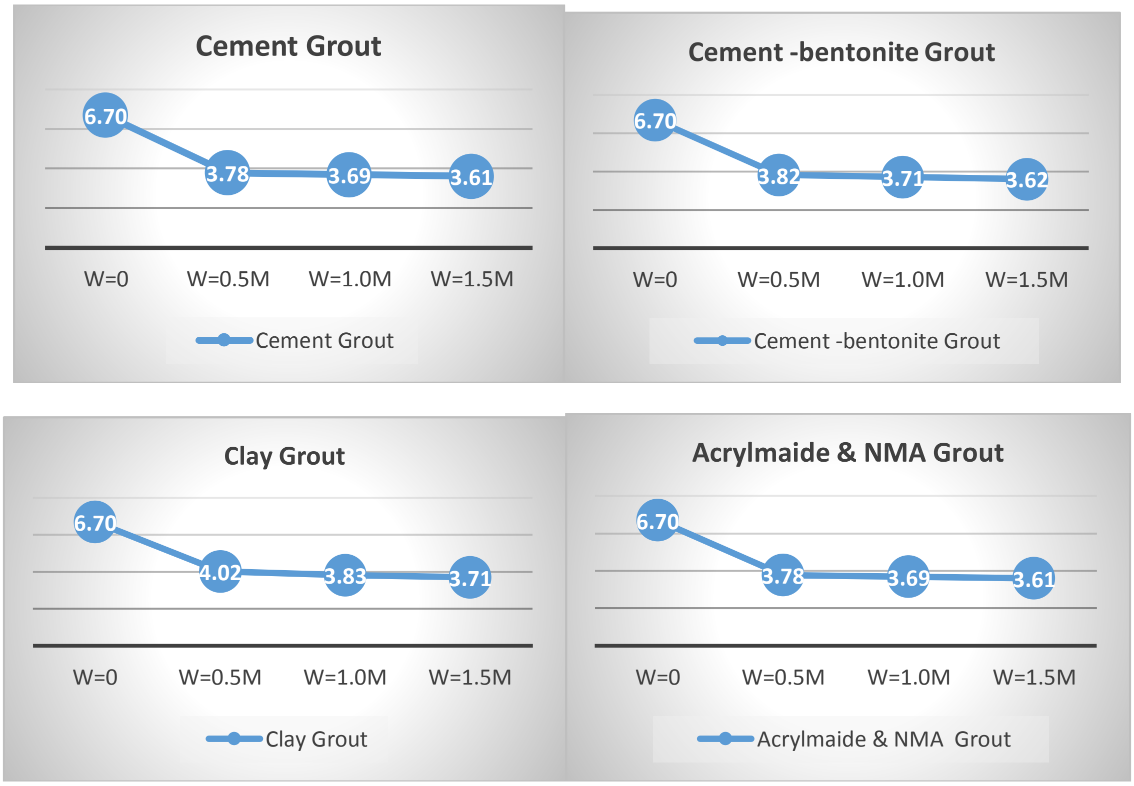


Figure 14: d, e, f the Result of width effect of chemical grout where (D = 1.5H & width = 1, 2, 3 rows.

Now, based on the SEEP/W analysis, the effect of increasing the width of the grout curtain about the uplift pressure can be extracted to each grouting materials. Figure (15) indicates the increase of the grout curtain width that decrease the uplift pressure for each grouting materials.



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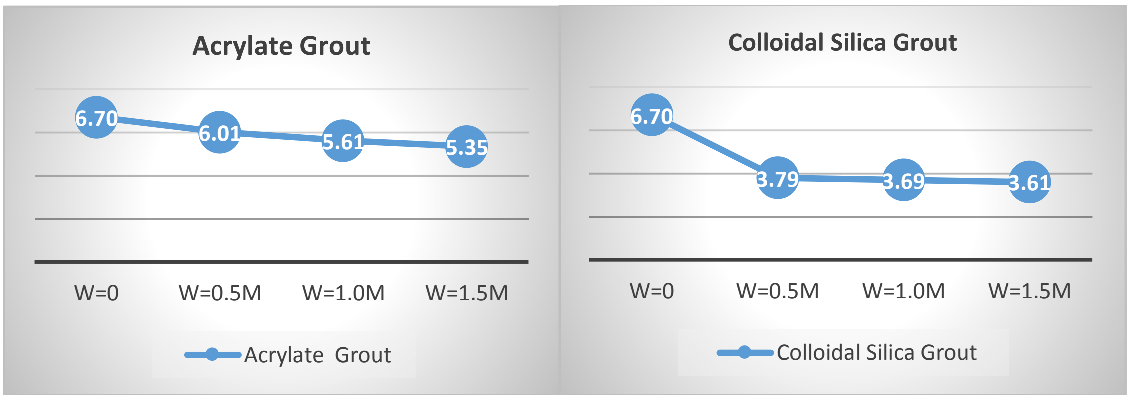

Figure 15: maximum uplift pressure due to the increasing the depth of the grout curtain.

CONCLUSION

The efficiency of grouting depends mainly upon the penetration of grouting material through the pores of the soil and the percentage of fine particles. Based on the case of study and references can extract the following:

1)With acrylamide grout, creep can occur nearly 20 % so, the use of acrylamide grouts should be limited to seepage reduction.

2) NMA grout will be stable, but it absorbs water up to 200 % of its original volume, so the use of these grout should be limited to seepage reduction because of swelling.

3) Under repeated cyclic loading, chemical grouting is better in use than the cementious grouting because of its fragile behavior. The destruction of bond for chemical grouting would be partial, while the destruction of bond for cementious would be full.

4) In our case of study, the acrylamide grout can reduce the permeability up to 40 % at one row of curtain grout and the exit gradient up to zero. Acrylamides effect on F.O.S against piping more efficient than other materials, but it is toxic and expensive.

Recommendation: the best type of grouting materials in Egypt is a cement/ bentonite grout for seepage reduction. Cement/bentonite grout could be excellent grout, available alternative material and also less expensive than other materials

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