JET GROUTING FOR SEEPAGE CONTROL AND GROUND IMPROVEMENT IN SARRATH DAM : A RELIABLE BUT DEMANDING TOOL FOR DAM REHABILITATION

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ABSTRACT

Situated in the north west of Tunisia, Sarrath dam aims to provide both, irrigation and drinking water for the nearby Kef region. With a reasonable capacity of 21hm3, the dam has a main body made up of rolled compacted concrete (RCC) and embankment dykes in right bank and left abutment due to the presence of alluvial material in the foundation. Few days after the first watering of Sarrath dam, an upstream cutoff wall under the right embankment slope made with jet grouting was urgently planned, to address both stability and seepage concerns. The jet grouting test program consists of one set of three over-lapped columns to assess column overlap strength and integrity. Therefore, no further tests regarding columns homogeneity and watertightness were conducted. With a total length of 120m and a target diameter of 1.2m, jet grouting columns were installed using double jet grouting system and extended across the embankment dyke structure to seal the alluvial level until marls at 12m depth. During jet grout operations, an uplift of the overlying ter-rain followed by a tilting of the upstream crest wall of the dam have been observed, which increases considerably fears towards the stability of dam components and jet grout efficiency.

This paper highlights the importance of jet grouting test program by providing a general overview of practices and a back-analysis of empirical evidence for jet columns behavior under a vertical loading through case histories. Finally, a finite element analysis including a representative geological model is presented, in order to discuss additional remedial measures to implement for jet grouting efficiency in Sarrath dam case.

1. GENERAL CONTEXT AND KEY COMPONENTS

1.1 General layout

With climate changing consequences, surface water mobilization became continuously a challenging target, especially for some Mediterranean countries where water is unequally available from the north to the center and southern regions. In Tunisia, an 800 million m3 water transfer capacity system, connecting dams, pumping stations, open channels and pipelines, forms the cornerstone of an integrated water management system that provides an annual average of 1.7 million m3 of surface water.

Sarrath dam, is a newly added dam to the water transfer system. With a total capacity of 21 hm3, a height of 40 m above the terrain level and an uncontrolled spillway of 6000 m3/sec as a maximum flow rate, it provides a source of drinking water and irrigation for the Kef region. the dam has a main body in RCC material, connected to left and right abutments with two embankment dykes due to the presence of alluvial material in foundation. Right view of the dam is shown in Figure 1. The major concerns at the sarrath dam right abutment were both the stability and the seepage that may occur during dam operation lifetime. A cutoff wall using the jet grouting technique under the embankment dike, was urgently planned to set a hardened, relatively impermeable wall of soilcrete columns for ground improvement. This paper highlights the importance of jet grouting test program for providing accurate parameters for jet grout technique effectiveness to address seepage and stability concerns. In addition, a review of empirical evidence for jet grouting columns under vertical loading is analyzed and a finite element model is simulated to confirm jet grouting reliability and performance for ground improvement.

Figure 1 : Right View of Sarrath dam after construction completion (Source : N. Dhiab)

1.2 Right bank context

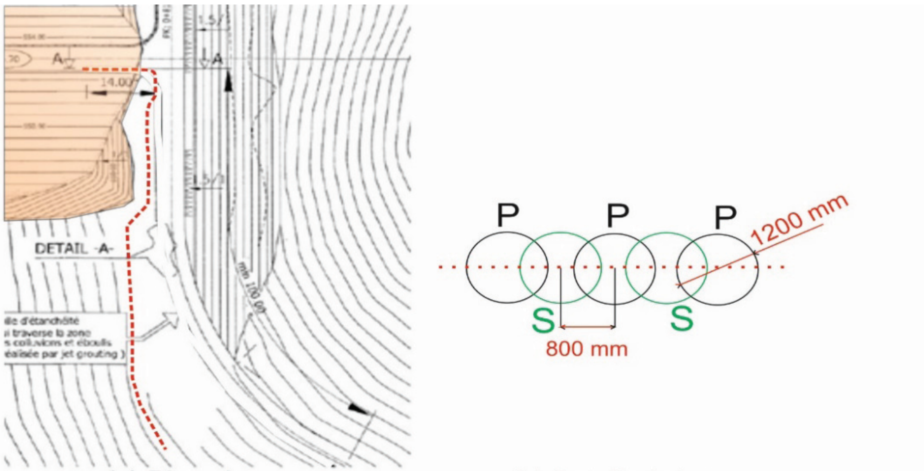
Construction works for Sarrath dam started in February 2007, aiming completion by the end of 2011. Nevertheless, additional geotechnical campaign revealed alluvial material in right abutment that involved the construction of an embankment dike instead of a full RCC dam connecting the main body to the right bank. In fact, the abutment is composed of slope screes and colluviums that are not only instable but also very pervious. Compromising thus both stability and watertightness of the whole dam (Figure 2(c)). Various options of upgrading were evaluated, and a final decision was approved to install a soil-cement jet grouted cut-off wall across the right embankment dam to intercept and cutoff seepage through the pervious foundation layer as shown by the red dotted line in Figure 2(a).

2. JET GROUTING PROGRAM

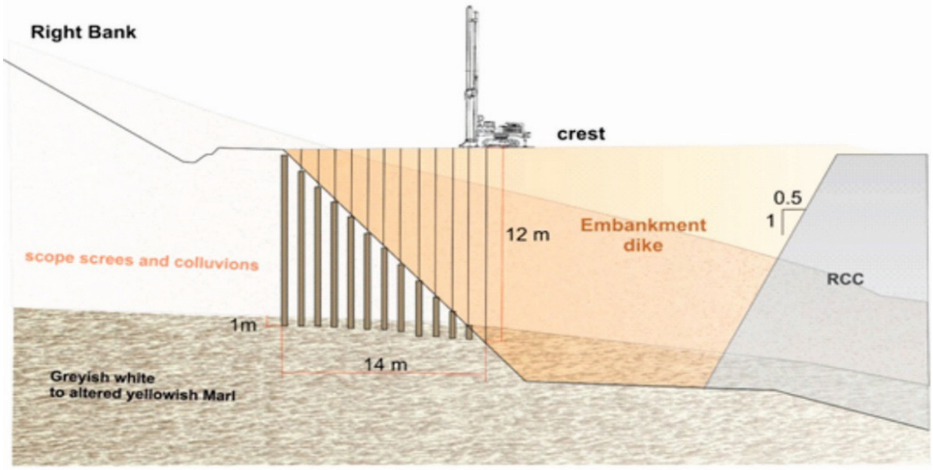
2.1 Test field

Jet grouting is a popular ground improvement technique based on high-speed injection of cement-water mixes within previously drilled boreholes (*Yahiro & Yoshida 1973*) to form pseudocylindrical bodies (columns) of cemented soil. The high pressure/velocity jet fluids erode the existing soil and then mix the cuttings with cement slurry to form hardened, relatively impermeable mass referred to as soilcrete (*Stark & al 2015*). In Sarrath dam case, it consisted of 1200 mm diameter and 12 m deep columns, secant with a center distance of 80 cm and a total length of 120m (Fig. 2b). The curtain grout was made by the double jet procedure. The grout stream is injected under a high pressure of 40 MPa within a cone of compressed air, creating in-situ columns of grouted soil.

In order to calibrate and verify jet grout parameters, a pre-construction test program was performed, depending on soil type, soil density and flow rates of fluid employed (C2) varying with injection pressures and rotation speed. Parameters employed for test program are detailed in the table below.



(a) Plan view (b) Detailed view



(c) Profile view and simplified geology

Figure 2 : The jet grouting cutoff wall: (a) Plan view, (b) Detailed view, (c) Profile view and simplified geology

Table 1 : Jet grouting Test program parameters

Parameters	**Unit**	**Values**
borehole depth	(m)	12
jet grout depth	(m)	12
Injection duration	(s)	9
number of nozzles	(-)	2
nozzle diameter	(mm)	4
air pressure	(bar)	10
grout pressure	(bar)	400
rotation speed	(r/min)	10
cement con-tent	(kg/m^3)	375
bentonite content	(% by weight)	5
C/W	(-)	1

To verify the jet grouting method in the in-situ soils, a few test columns were made in the vicinity of the right abutment. It consists of one set of three overlapped columns, that were partially excavated later to assess column overlap strength and integrity (Fig. 3), which were all found satisfactory. Therefore, no further tests regarding columns homogeneity and permeability were conducted. Moreover, no other installations regarding groundwater conditions were placed in the test area. The three overlapped piles test made in Sarrath dam site was meant to form a unique massive body made of cemented soil, particularly effective where the required performance consists of a strong reduction of settlements and of a high resistance to horizontal loads (*Croce & al. 1990*). However, the main jet grouting program of the dam consisted of one wall of secant primary and secondary piles, which increases questioning of the test program relevance and effectiveness. Geotechnical analysis through numerical simulation has been ruled out while the stability of the right bank and settling seepage issues were expected.

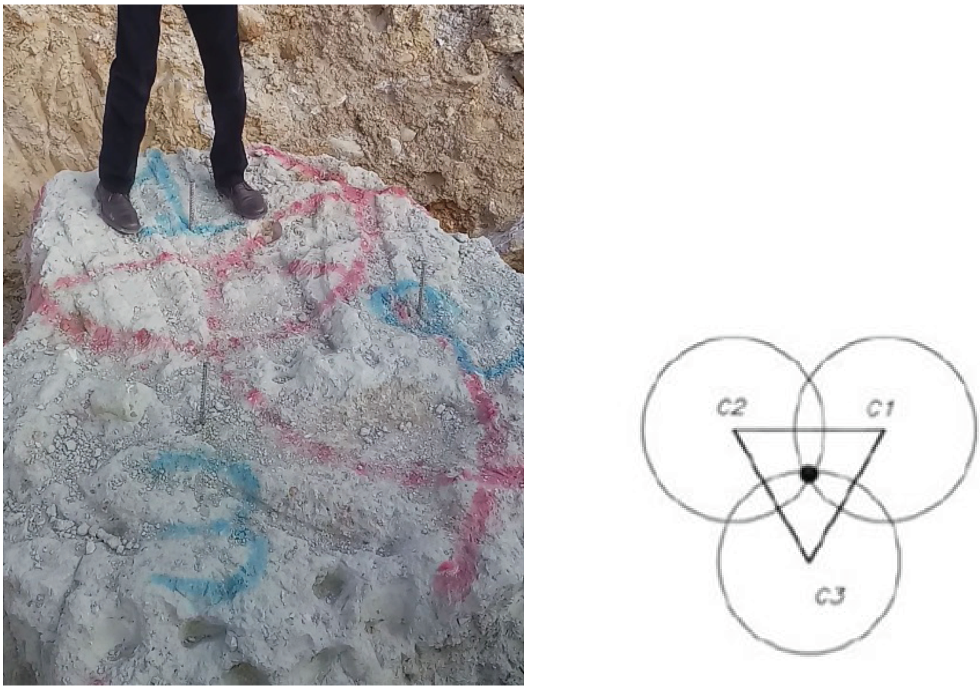


Figure 3 : Pre-construction test program (Source : N.Dhiab)

2.2 Jet grouting works

Once the test program has been completed, 12 m deep holes were made drilled using a rotary with a C8 type machine with using a tricone of 101 mm in diameter Considering the junction between the embankment structure and the right abutment, jet grouting columns were carried out between 12m and the low level of the embankment dyke. The portion of the drilling located in the embankment material have been filled with cement grout (Fig. 2).

Drillings started at the crest of the embankment dyke, 1 m behind the parapet wall that is anchored 1 m in the ground. Barely after 7 injected columns, cracks and 1 cm tilting were observed in the upstream crest wall, exposing joints. Furthermore, a slight uplift of the terrain accompanied by the appearance of air holes and bubbles were observed during the grouting works. Accordingly, urgent measures were taken including the installation of 3D- fissuremeters and topographic marks to monitor horizontal and vertical displacements caused by the jet grouting works. However, those degradations may have suggested that the cohesive compacted materials of the embankment material at the contact with the foundation, could have been damaged, resulting in a change in the active seepage condition of the dam, and even though no remedial works were taken.

3. COLUMN-SOIL INTERACTION, A REVIEW OF EMPIRICAL EVIDENCE FOR JET COLUMNS BEHAVIOR UNDER A VERTICAL LOADING

According to Modoni & al. (2006), the jet-grouting has three types of mechanical interaction with the surrounding soil, depending on their type, namely, grout seepage for gravels, penetration for sandy soils and erosion process for clayey soils. According to the presence of detrital deposits of silt, clay and rock sediments characterizing the colluvium material, the mechanical phenomenon induced by jet grouting could be considered as both erosion and seepage on the basis of the theory of submerged flows.

3.1 Column diameter reduction by depth

According to experimental observations, column diameters may range from a few decimeters to more than 2 m depending on the combinations of injection systems and original soil properties (*Xanthakos & al. 1994*) and unconfined compressive strength of cemented soil varies between 1 and 20 MPa depending on the original soil type and on the grout compositions (*Croce & al. 2001*). Although, it must be considered that the subsoil conditions may be particularly heterogeneous and that, even when large average values can be optimistically expected, the diameters and strength of columns may suffer from particularly severe local reductions affecting the overall column resistance (*Croce & al. 2002*). Figure 4 shows the relationship between measured cross-sectional dimensions as a function of depth for three trial columns injected in the same soil with different jet energies. The experimental data are compared with trends predicted by means of theoretical relations of Modoni et al. in 2006.

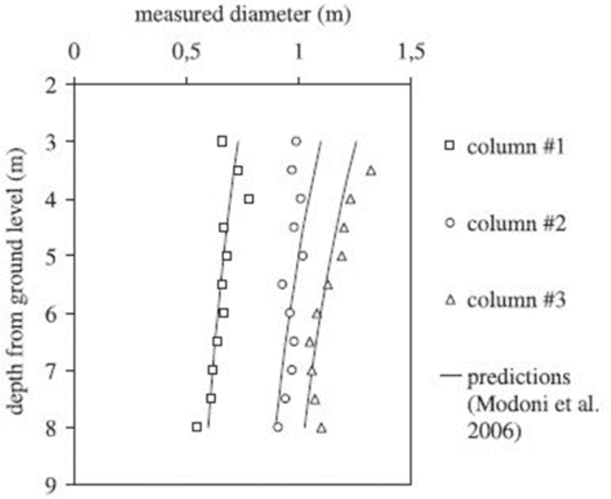


Figure 4 : Sample of results and predictions from field trial (Modoni et al., 2012)

The results shown in Figure 4 shows that even with homogeneous soil composition, columns can be barely considered as perfectly cylindrical bodies. Increasing depth leads to increasing soil strength, therefore leading to a decrease of column diameter, which yields a conical shape to jet grouting columns.

3.2 Stress-strain response reliability

Results of compression tests on samples cored from jet columns (*Croce & Flora 1998*) typically show a much stiffer response than natural soils. When the prefailure stress strain response of a cemented soil is approximated with a linear elastic model, it may be quantified with the Young Modulus E_c and the compressive strength σ_c , that can be obtained from uniaxial compression tests and depend on the composition of the injected grout and the original soil. Values obtained in three different soils show similar dependency of E_c and σ_c on the properties of the original soil and injected grout where a simpler linear relation (Eq. 1) can be established among these two parameters as supported by the experimental correlations reported in Figure 5. β represents correlation coefficient and is relative to soil type and origin.

$$E_c = \beta \, . \, \sigma_c \quad (1)$$

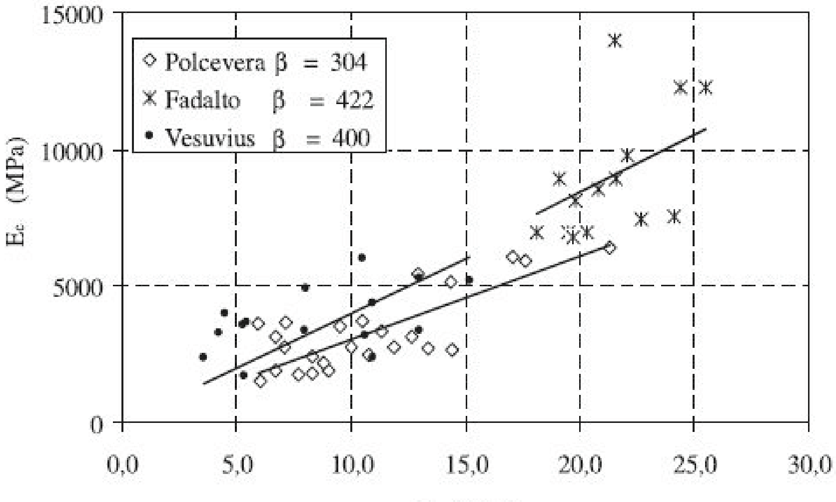


Figure 5 : Experimental correlations between E c and σ c (Bell, 1993)

This approximation can be used to predict foundation settlements with negligible errors if the prefailure stress-strain response of cemented soil is approximated with a linear elastic model, according to results of compression tests on samples cored from jet columns (Croce and Flora, 1998).

3.3 Load- Settlement curve

The reduction of settlements is considered as the most important requirement for the design of reinforced foundations. It is a nonlinear load-settlement response that is modeled with a load-transfer curve. The basic principle of the load-transfer curve method is that the load is transferred to the surrounding soil by vertical stresses increasingly mobilized on the side and the base of the column. Field and laboratory full-scale tests performed by Maertens and Maekelberg (2001), observed sudden collapse in the upper part of axially loaded columns, well in advance of a global failure of the soil-column complex. In fact, structural collapse may locally occur because of a sudden narrowing of their cross sections and/or poor soil cementation *(Modoni & al. 2012)*.

The entire load-settlement function q-w can be calculated with the distribution of axial loads S at different sections. The column's integrity can be continuously verified by comparing axial loads with their limit values S_{lim} expressed by the following function (*Coyle and Reese 1966*):

$$S_{lim} = \sigma_c . \pi . D^2/4 + \sigma f \tag{2}$$

Where σ_c is the uniaxial compression strength, D the column diameter, *af* and *σf* represent respectively the cross-sectional area and the strength of a reinforcement that could be possibly included into the column. Considering Equation (2), when S is constantly lower than S_{lim} for all sections, the load settlement curve is entirely dictated by the soil response and a typical hyperbolic q-w curve is obtained (case A Figure 6). If S becomes equal to S_{lim} in at least one section, settlements proceed without any further increase of q (case B Figure 6). Even more, this condition does not necessarily imply collapse of the whole column-soil system, because further loads can be transferred from the side of the column located above the collapsed section.

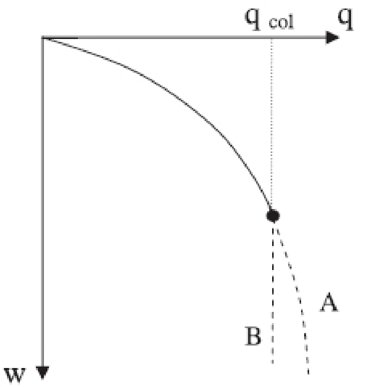


Figure 6 : Load-settlement curve

3.4 Intact soil and void inclusions compromising strength and impermeability

A relevant case history is developed in the current section regarding the astonishing results of the jet grout test program at Tuttle Creek Dam that shows unforeseen problems that can occur with the jet grouting technique. Tuttle Creek Dam is a U.S. Army Corps of Engineers project located on the Big Blue River, 200 km west of Kansas City. In 2005, aiming to address the seismic stability concerns, an upstream cutoff wall to bedrock was to be constructed by jet grouting. A test program, downstream the dam, was conducted to develop appropriate parameters and prove the viability of the technology. It included not only construction and full-scale excavation of the 27 columns performed, but also sectioning, visual inspection, coring and testing.

The main observations revealed that when the eroded soil is not completely mixed with slurry, the resulting columns had soil inclusions which can reduce the strength of the column and/or increase its permeability. In fact, sectioned columns showed that more than 40 to 50% of the column contains native soil that was not broken up and mixed in the jet grout process. Furthermore, external appearance of the excavated columns in addition to the results of the core drilling, mostly satisfying, were not representative enough of the amount of soil inclusion in the completed column. Even more, large chunks of intact soil were found in the bottom of many columns suggesting the periodic collapse of material of the column's roof into the unhardened grout slurry.

As the chunks became dislodged and because they are heavier than the slurry mix in the column below, they sink through the unhardened fluid grout and are not broken up and mixed by the action of the jets (*Stark & al. 2012*).

4. FINITE ELEMENT MODELLING OF SARRATH DAM CASE

4.1 Phase 1: At the end of embankment dam construction

Calculations of a 3D model were made first for the colluvium-marl foundation prior to jet grouting works to consider load-settlement behavior at the end of the embankment dam construction. Using basic information of soil layers materials detailed in Table 2, FEM calculations on *Plaxis 3D Foundation* were applied for a specified length (the equivalent length of 5 secant columns), according to the studied case. The geological model of the Sarrath right abutment case was schematized as shown in Figure 7(a). The embankment-colluvium interface was considered as the reference level. The water table was calculated according to the normal level of operating dam, located at 546 m from Normal Ground Level, just below the reference level by 2.7 m. Since the marl-alluvium interface varies between 0 m and 12 m NGL, an average value of the interface has been interpolated to 6 m. The active load materialized by the embankment dam weight was calculated considering an approximate triangular section of a 6 m height and a length according to the number of piles simulated further in Phase 2. Considering a saturated soil weight $\gamma sat = 19.3$ kN/m^2 for compacted embankment dam, total load applied equals to 1765 kN.

3D mesh properties and distribution of relative shear stresses are shown in Figure 8(a,b).Total deformations obtained equals to -26,98 .10^{-3} m, representing the vertical settlement due to the embankment load for the studied length section (4,4m). Deformations mostly occur in the upper part of soil layer because of soil strength increase by depth (Figure 8-c). The load-settlement curve (Figure 10) shows the soil behavior under axial load in one single point, which represent a value of 353 kN.

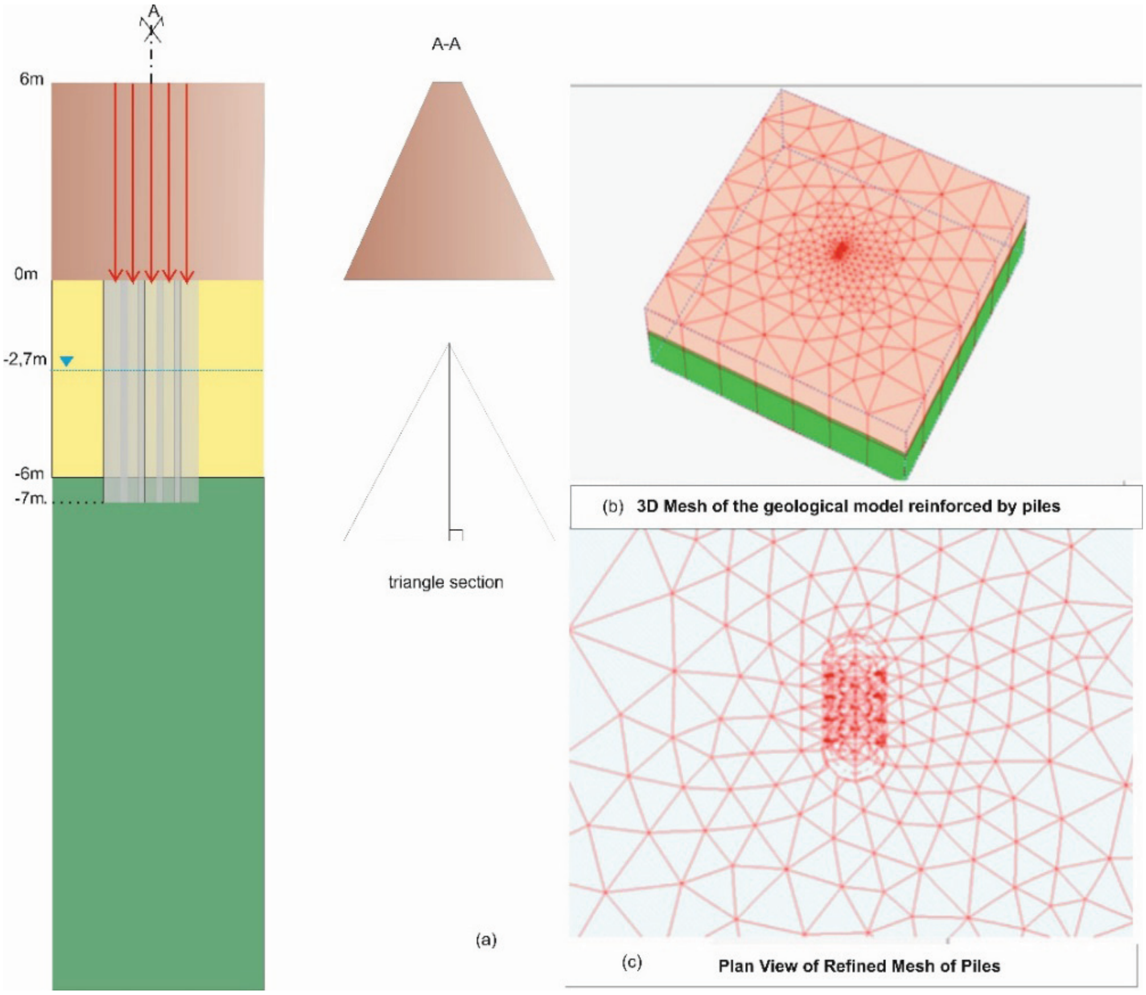
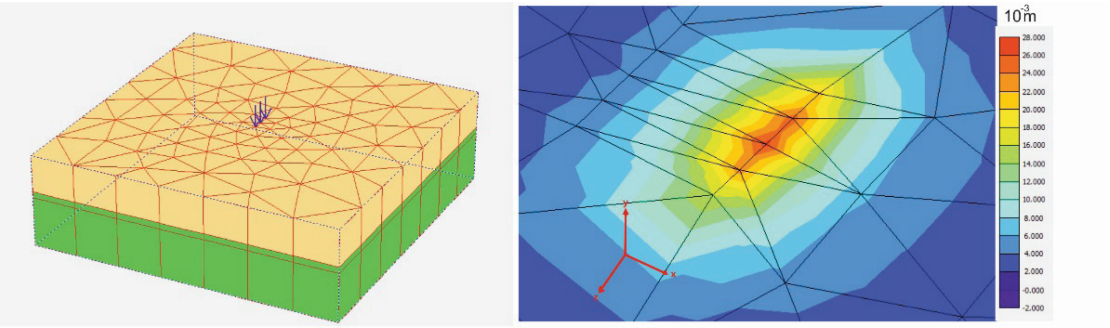


Figure 7 : FEM simulation steps: (a) sketched case model, (b) 3D Mesh of the geological model reinforced by piles, (c) Plan view of Refined mesh of piles

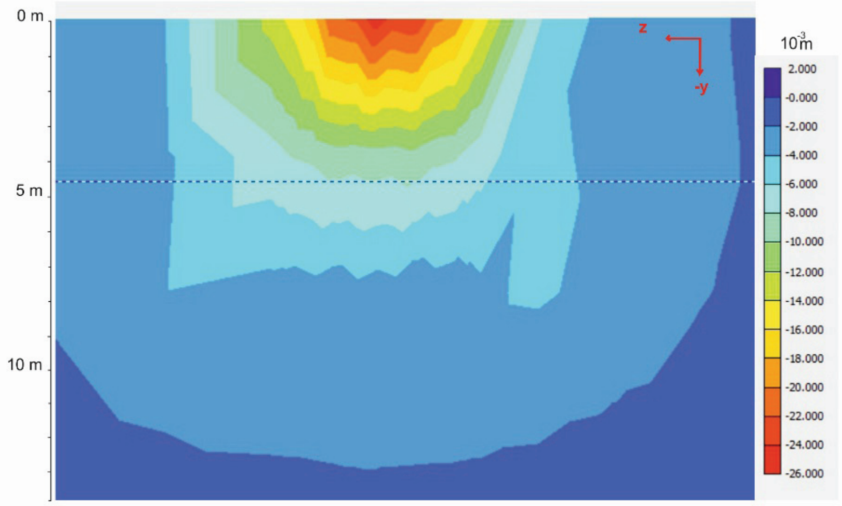
Table 2 : Material and Piles properties

Parameters	**Name**	**Unit**	**Values**		
			Colluviums	Marl	Pile
Unsaturated soil weight	γ_{unsat}	KN/m^3	19.8	17	24
Saturated soil weight	γ_{sat}	KN/m^3	19.8	18	–
Cohesion	c	KPa	10	30	–
Poisson's ratio	υ	–	0.3	0.3	0.3
Friction angle	ϕ	°	38	25	–
Young's modulus	E	KPa	40000	13000	$29.2\ 10^6$



(a) 3D Mesh properties

(b) 3D Plan View of relative shear stresses after dam loading



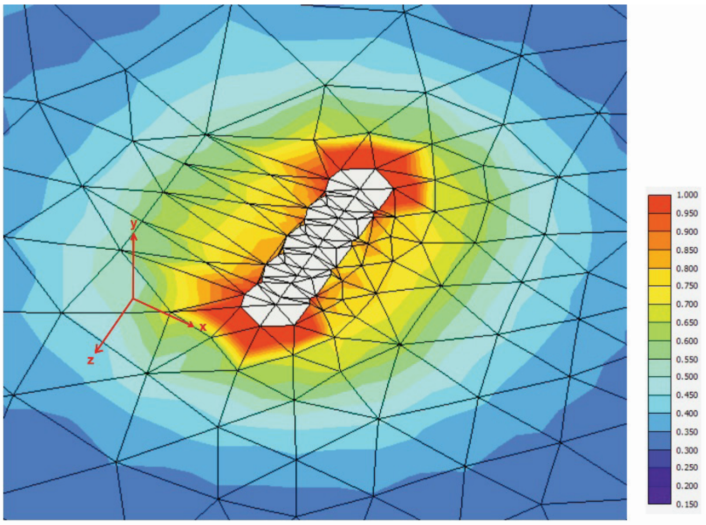
(c) Cross section of deformed soil under dam loading - Total vertical displacements Uy

Figure 8 : Deformed Mesh and vertical displacements Uy at the end of embankment dam construction

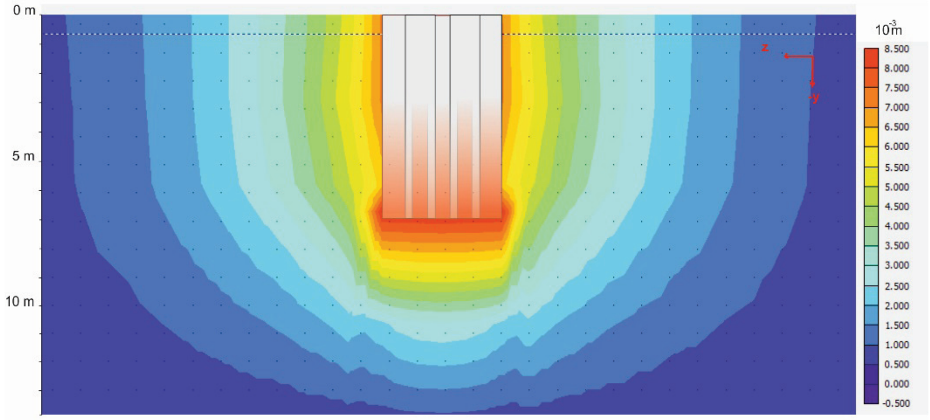
4.2 Phase 2: With jet grouting columns:

jet grouting reinforcement with columns is now simulated and analyzed by applying FEM calculations to a relatively simple and idealized case of uniformly loaded array of circular massive piles. The typical 3D finite element mesh used to analyse the piles subjected to vertical loads is shown in Figure 7(b,c). Column properties are detailed in Table 2. In order to reduce time iterations, a total of 5 piles only with 1.2 m diameter and an average length of 7 m were loaded in compression as well as tension. Thus, two main phases of piling and loading were considered across two main layers of colluviums and Marl, as sketched in Figure 7(a). To show the load-settlement behavior of the foundation with jet grouting columns, geometry and finite element mesh were performed according to the sketched simplified model. To eliminate the influence of boundary effects on the piles performance, the overall dimensions of the model boundaries comprise a width 11 times the array of columns considered (4,4m) and a height 2 times the pile length (7m). At all times, the piles are considered as linear-elastic material, while for the surrounding soil layer, the Mohr-Coulomb rule is adopted. Figure 9 (a) shows stresses around the piles in a 3D plan view, due to deformation of surrounding subsoil after loading. It seems that extreme relative shear stresses are located in both sides of the columns array, probably caused by the load transfer between secant columns to the surrounding soil. This insight into the column response through the 3D simulated model, confirms jet grouting characteristics on the load-transfer mechanisms. Extreme total displacements that corresponds to vertical displacement Uy resulting from the loading of the grouted piles have a value of - 8,18 .10^{-3} m (Figure 9(b)), that represent more than 98% of the total displacements occurred.

Compared with the total displacements induced after embankment dam construction and without ground reinforcement, jet grouted foundation deformations decrease by 70%.



(a) 3D Plan View of relative shear stresses around piles after loading



(b) Cross section of grouted piles - Total vertical displacements Uy

Figure 9 : Stresses around the columns of jet grouting and vertical displacements Uy on Plaxis 3D Foundation

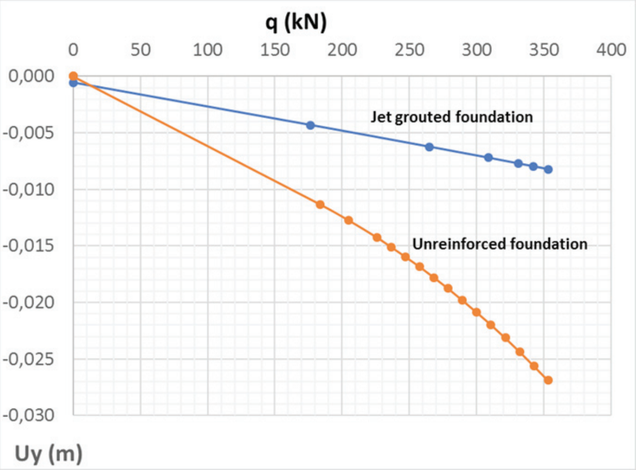


Figure 10 : Load-Settlement curve of axial loaded foundation with and without reinforcement

The load-settlement responses q-U_y of two different soils (with and without reinforcement) are reported in Figure 10. The comparison between the two modeled curves confirms that the cemented soil representing the grouted columns, is comparatively much stiffer than the original soil. In addition, vertical displacements represent more than 98% of the total displacements occurred. It shows how load fractions transferred from the bases to the surrounding soil are far more important than those from the shafts of columns.

FEM calculations are still considered as a reliable method to assess foundation stability and the response of columns during dam loading is well captured by this simplified 3D FE model. Observed degradations that occurred in the dam crest wall, at the beginning of jet grouting works, mainly due to grouting pressure and disturbances in dam-foundation interface may have induced dam material removal or degradation. It affirms how critically important is to define a procedure for assessing, monitoring and mitigating the effects of jet grouting works. The comparison between predicted deformations and real ones could help engineers gain considerable experience and practical knowledge in order to find appropriate design approach and to minimize harmful impacts.

Thus, adequate instrumentation for monitoring regularly total displacements are needed to assess safety values during and after construction. The Japanese Jet grouting Association provides design values of the column diameter and cemented soil strength as functions of the jet grouting system (double or triple fluid) and undisturbed soil properties (NSPT values) and manages uncertainty with global safety factors fixed for various types of structures. While the European standards and US guidelines stress the role of preliminary field trials and quality-control quality-assurance tests for their quantification, insisting on variability of jet grouting properties and on its influence on the performance of structures.

As a conclusion, until jet grouting structure properties are affected by random variability, in addition to column diameter reduction, cemented soil strength variability and foundation heterogeneity, appropriate instrumentation should be installed from the beginning of the jet grouting program, around the test area, to determine the soil and groundwater conditions, including soil borings, cone penetration tests during and after construction of columns, observation wells, removable extensometers, surface deformation measuring points and piezometers in addition to existing ones.

5. CONCLUSION

As an alternative to bored piles, the aim of jet grouting technology is to transfer loads to deeper and more competent strata. However, considering column diameter reduction by depth, non-negligible intact soil inclusions, in addition to voids, there is still a relevant degree of uncertainty about the use of high-pressure jet grouting technique, that might compromise the stability of infrastructures above.

Because of the lack of commonly acknowledged rules, the design of jet grout system is often based on empirical, subjective, and oversimplified methods. The results and effectiveness can be difficult to achieve and assess. Benefits and limitations are still discussed and field trials to establish jet grout parameters, column diameter measurements, strength and permeability, in addition to monitored appropriate instrumentation should be determinant for jet grouting efficiency and durability.

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