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REVIEW
of PhD thesis of Lidia WANIK
on *"Geometrical and mechanical properties of jet grouting columns: experimental investigations and prediction"*

1. Base of PhD thesis's review

The review of PhD thesis of Lidia WANIK on *"Geometrical and mechanical properties of jet grouting columns: experimental investigations and prediction"* was prepared on the base of the letter of Dean of the Faculty of Civil Engineering, according to decision of the Board of the Faculty of Civil Engineering of December 14 2016.

2. General characteristic of the PhD thesis

The thesis has the ambitious goal to deal with jet grouting technology by getting an insight on the jet to soil interaction mechanism and on the reliability of empirical prediction of columns diameter, adding also new information coming from in situ and laboratory testing. The topic is of extreme interest, because jet grouting is nowadays one of the most popular ground improvement technologies, and is used for many different applications. Literature on the topic has developed relatively recently, say in the last twenty years, and there is still a strong need to have a more detailed knowledge on both the basic jet to soil interaction mechanisms and on good quality experimental data. In particular, the latter need is of extreme importance, because most times such data belong to companies that do not like to share the information. As a consequence, the topic of the thesis is of great interest to both academicians and practitioners, and was certainly worth being undertaken.

2.1. Current state of the knowledge in the range of PhD thesis

Ground improvement technologies have become a topic for detailed research only relatively recently, in comparison with more traditional technologies, like for instance piles. Since their share of the construction market is continuously increasing, there is a stronger and stronger demand to improve knowledge and design methods of the most popular ground improvement technologies like jet grouting. The problem is that often the design is based on simple rules of thumb, because many operators and engineers do not fully understand how the columns are created, and what their real features are. At the design stage, ideal perfectly vertical (or sub horizontal) cylindrical columns are usually considered, whose mechanical properties are only roughly guessed. The effect is a hidden uncertainty in calculation that corresponds to real safety margins much lower than those considered acceptable for more conventional technologies. This is not just the pessimistic point of view of an academician. It is the evidence stemming from every day experience, as well as from a number of dedicated conferences personally attended. Most times, black-box information are given, where a case

history is presented, and a final solution is shown, without any convincing and mechanically sound design approach bridging the problem to the solution. Even in books, most times jet grouting is presented in a qualitative way, implicitly assuming that these columns may be considered and designed just as piles or rigid inclusions. However, the diameter itself of the columns is unknown, not to mention the mechanical properties of the improved soil, and most times they are just guessed. Let's imagine how difficult would it be to design a piled foundation without knowing the piles diameter and the pile material properties.

Therefore, there is an urgent need to improve knowledge on the whole jet grouting process. What would be desirable is to have information (again, available to the companies, but not in a sufficient way to the academicians and practitioners) on high or very high energy treatments, because they are becoming more and more popular, while most of the empirical correlations available to forecast the columns diameter have been calibrated on databases pertaining to low values of the energy.

2.2. Structure of PhD thesis

The thesis consists of:

- Chapter 1 (Introduction): this chapter reports a short background and states the goals of the thesis, finally listing the different chapters
- Chapter 2 (Jet grotuing mechanism): the chapter begins with a brief introduction of the technology and of some of the main applications. Then, it focuses on the the description and the analysis of the evolution of the jet, considering the hydrodynamic mechanisms taking place in the peculiar case submerged jets. Finally, gives some information on the outcome of treatment in terms of jet to soil interaction.
- Chapter 3 (Modelling of submerged jet diffusion): it reports a numerical analysis of the jet propagation into a soil using ANSYS Fluent CFD software. The analysis is carried out calibrating the parameters on experimental data, and showing then the effect of different treatment variables. These results are also compared with analytical formulations of the hydrodynamic evolution of a submerged jet. The use of numerical analysis allows to introduce and analyze the effect of the air shrouding veil, which is not possible with the analytical formulation.
- Chapter 4 (Geometrical and mechanical characteristics of jet grouting columns): this chapter is devoted to the analyses of literature results on geometrical and mechanical properties of jet grouting columns. It also shows some existing methods to predict the diameter of jet grouted columns.
- Chapter 5 (Characteristics of trial field in Bojoszowy Nowe): it deals with the trial field of Bojszowy Nowe, reporting information on the geotechnical characteristics of the site and on the treatment parameters adopted for the 16 columns created (8 with single fluid jet grouting, 8 with double fluid jet grouting).
- Chapter 6 (Geometrical characteristics of jet grouting columns in Bojszowy Nowe): the chapter shows the results of all the measurements carried out at the field trial site. The values of the diameters at different depths are shown for all columns, and then compared with the predictions made using the methods previously described in Chapter 4. Based on this comparison, a new calibration of the parameters of such methods is proposed.
- Chapter 7 (Mechanical characteristics of jet grouting columns in Bojszowy Nowe): the chapter reports the results of laboratory tests (unconfined and triaxial) carried out on the spoil and on specimens prepared from samples cored from the columns. In the final

part of the chapter, an insight on the mineralogical composition of the jet grouted material is presented, and a possible explanation of the differences observed on single fluid and double fluid treated specimens is attempted.

- Chapter 8 (Conclusions and future perspectives): this short final chapter summarizes the main results obtained in the thesis, and highlights future perspectives for the research on jet grouting

3. Evaluation of PhD research

Some of the results arising from the thesis are of publishable quality, as demonstrated by the fact that both journal and conference papers have already arisen from the work.

The physical format of the dissertation and the quality of figures is excellent; the quality of the English language is good.

4. Detailed and discussion remarks

The goals declared in the Introduction seems a bit wider than the results accomplished in the research, and so it seems that they have not been fully accomplished.

Chapter 2, on jet grouting mechanism, reports literature information on the technologies and on the jet to soil interaction mechanisms. Even though the arguments are well introduced, the large amount of technological innovations reportated in literature, now available on the market and often used in practice, are completely ignored. The insight on the jet to soil mechanism is not very deep, being limited to report only basic correlations among the involved variables. Information on what is known in literature on the possible effect of the air shrouding veil is disregarded, which is not fully consistent with the fact that some of the numerical analyses are carried out in Chapter 3 to show its beneficial effect.

The numerical analyses reported in Chapter 3 are very interesting, as they do give some insight on the jet diffusion mechanisms, clearly showing the effects of density and viscousity in a wide range of Reynold's number values. Interestingly, by comparing numerical and analytical results, a novel and interesting relationship between the hydrodynamic parameter Λ of Hinze's theory and the Reynold's number is proposed, thus allowing to adapt Hinze's model to the analysis of jet grouting. The effect of air coating is finally analyzed in this chapter carrying out some numerical analyses. This is interesting, and would have been nice to have a wider parametric analysis with some more insight on the results, since it is a really important technological aspect. Looking at the results, the beneficial effect of air seems a little overestimated for high air velocities. The very little available informations (see for instance Sondermann 2011, workshop on jet grouting in Paris) indicate that at low air velocities, increasing the velocity increases jet effectiveness. Once you get to velocities higher than 150-200 m/s, however, further incremenents seem basically to be ineffective. The value of 150 m/s may be considered an optimum value that combines economy and effectiveness, at least for the typical initial velocities of the grout.

The literature review reported in Chapter 4 on the geometrical and mechanical properties of jet grouting columns, as well as on the existing methods to predict columns diameter, is comprehensive and clear, and nicely summarizes the most relevant literature outcomes.

Chapters 5, 6 and 7 are the core part of the thesis, showing all the experimental activities carried out at the fild trial test site and in the laboratory.

All the relevant information on the test site are clearly reported in Chapter 5, as well as the jet grouting parameters adopted. It would have been desirable to use nozzles with larger diameters and higher energies, to have fresh data in a range of flow rates and energy now becoming popular but less explored by the available literature. In any case, a sufficiently wide range of treatment energies has been explored.

The measurements and predictions reported in Chapter 6 show that all the considered methods have sound basis. The discussion and the recalibration carried out in this chapter are interesting and useful, and confirm that the existing methods tend to underestimate columns diameter. Since this is expecially true for higher energies and this thesis has not widened such a range, the question if such methods can be used out of their calibration range still remains open.

Chapter 7 summarizes all the experimental results obtained in laboratory. The testing activity carried out is conventional, and the results obtained confirm what is known in literature, without adding new evidences from a mechanical point of view. What is very interesting is the mineralogical evidence of the lower existance of cement in the specimens cored in double fluid jet grouted columns. This technology is more effective in terms of diameter, but introduces a number of differences in terms of jet to soil at the microscale that are clearly demonstrated by these mineralogical analyses.

Chapter 8 nicely summariezes the outcomes of the research, and outlines future perspectives in a convincing way.

5. Summary and conclusions

The work deals with the challanging topic of getting an insight on jet grouting and on showing and interpreting new experimental data. No novel results arise from the numerical analyisis of the submerged jet, but an interesting calibration of a hydrodynamic parameter to be used in empirical prediction methods is proposed. The main value of the thesis consists in the production of good quality experimental data, both in situ and in the laboratory, which are an extremely valuable contribution to the evolution of the technology of jet grouting and, as a consequence, of the design methods.

Based on these conclusions, I confirm that the PhD thesis of Lidia WANIK on *"Geometrical and mechanical properties of jet grouting columns: experimental investigations and prediction"* satisfies the requirements of the Act about scientific degrees and scientific titles and degrees in the field of art (Dz. U. Nr 65, poz. 595, ze zm. w Dz. U. z 2005 r. Nr 164, poz. 1365 oraz w Dz. U. z 2011 r. Nr 84, poz. 455) of 14th March 2003 and its subsequent amendments.

Therefore, I support the acceptance of the Candidate's dissertation and grant permission to Lidia WANIK to conduct public discussion over her dissertation.

In faith,

(Alessandro Flora)