Jet grouting – Chances of risk assessment based on probabilistic methods

Jet-grouting – possibilités de l'évaluation du risque basée sur les méthodes probabilistiques

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ABSTRACT: Jet grouting can be applied in either temporary or permanent works for different purposes. Worldwide jet grouted structures are employed to control groundwater flow, to strengthen the soil, e.g. reinforcement of soil mass or underpinning, or to combine both purposes. Depending on the object of the jet grouting works specific demands concerning quality and performance on capacity respectively safety and serviceability are required. Both, characteristics and quality of structures made by jet grouting scatter largely. Different purposes of the structures cause different failure modes which themselves are influenced by several factors. Thus various relevant factors have to be specified. The different factors of risk are fixed by identification of failure modes and their causes within the reliability theory. Heading for a quality management, steps and hints are given to take into consideration the expected risk even during designing process of jet grouted structures. This will lead to a reduced risk and a safer construction.

RÉSUMÉ: Le Jet-grouting peut être utilisé dans le cadre de travaux divers, permanents ou temporaires. Les structures en Jet-grouting sont utilisées pour contrôler les écoulements d'eau souterraine, pour renforcer le sol, par exemple en traitement de masse ou en reprise en sous-œuvre, ou en combinant les deux. Selon l'objectif des travaux de Jet-grouting, certaines exigences peuvent être requises concernant la qualité et les performances en matière de capacité, sécurité et fonctionnement. Les caractéristiques ainsi que la qualité des structures de Jet-grouting diffèrent beaucoup. Aux différents objectifs des structures correspondent différents modes de rupture, eux-mêmes influencés par plusieurs facteurs. C'est pourquoi de nombreux facteurs doivent être spécifiés. Les différents facteurs de risque sont déterminés en identifiant les modes de rupture et leurs causes d'après la théorie probabiliste. En vue d'un management qualité, des dispositions et des conseils sont présentés pour prendre en compte le risque attendu, y compris en phase de dimensionnement d'une structure de Jet-grouting. En découleront un risque réduit et une construction plus sûre.

1 INTRODUCTION

The jet grouting method is commonly used to control groundwater flow, to strengthen soil, e.g. soil improvement and underpinning, or to combine both aims. Depending on the purpose of the jet grouted structure different demands concerning quality and performance on capacity respectively on safety and serviceability are required. Concerning the geotechnical design of jet grouted structures especially the heterogeneity of the jet grouted body (see fig. 1), which is an assembly of jet grouted elements, has to be taken into consideration.

Although the European Standard prEN 12716 (1999) for "execution of special geotechnical work: jet grouting" has been prepared by the Technical Committee CEN/TC 288 especially for jet grouting purposes, in some cases the existing standards and regulations are not sufficient to guarantee that the jet grouting construction will

- remain fit for the use for which it is required;
- sustain all actions and influences likely to occur during execution and use

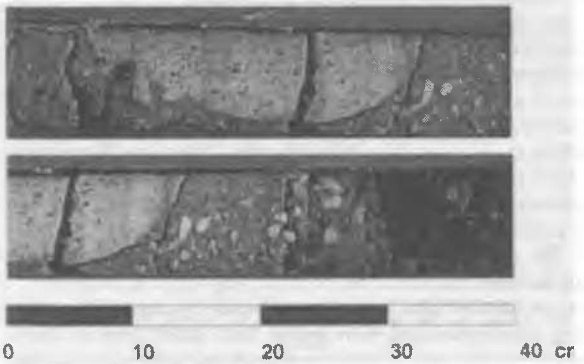

Fig. 1: Drill cores from jet grouted structure executed in Berlin Sand

as required in the EC 1 (1991), Section 2.1. Updates are necessary which focus especially on jet grouting works. Therefore scientific and experimental research work is essential to describe the interaction between soil properties, geotechnical investigations, design, installation, controlling methods, probability of event (failure) and potential of hazard.

The purpose of this article is to explain the process of risk assessment with special focus on all relevant components that can be determined as specific for structures made by jet grouting. This means to pay attention to all factors concerning the execution process and the geotechnical as well as the structural design. The different factors are examined regarding their importance for typical modes of failure and chances of probabilistic methods are presented.

2 RISK ASSESSMENT

2.1 *Introduction*

Every project contains some sort of modification of the existing situation and therefore implies a risk. The term "risk" is defined as the product of the probability of an event, in most cases a failure, multiplied by the number of losses that would result from the event (failure) (Rißler, 1998). Instead of the fact that often people´s intuitive feeling prefers to deny the existence of any risk, nevertheless it is always present. Its existence can neither be negated nor eliminated. The only possible way to handle the risk is to reduce it to a level that can be accepted by the public considering an acceptable economical expense at the same time.

In practice, technical standards intend to regulate this objectively.

The calculated risk can be determined with the terms „risk assessment" and "risk management" (see fig. 2).

Risk analysis implies the collection of all available information to determine the risk for people, environment and goods. Therefore the reliability theory can be used to identify all relevant fac-

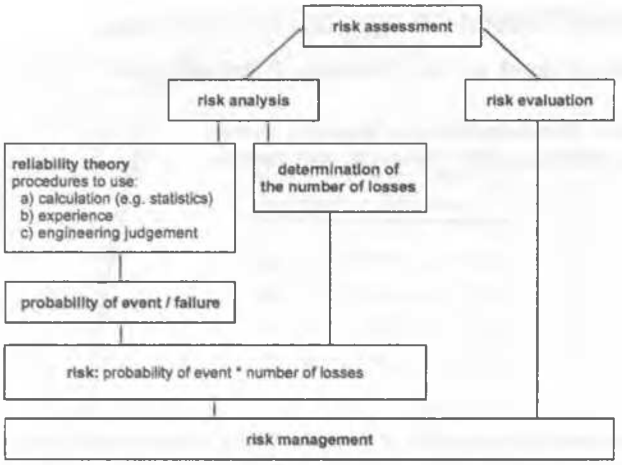

Fig. 2: Systematic explanation of terms to determine the risk

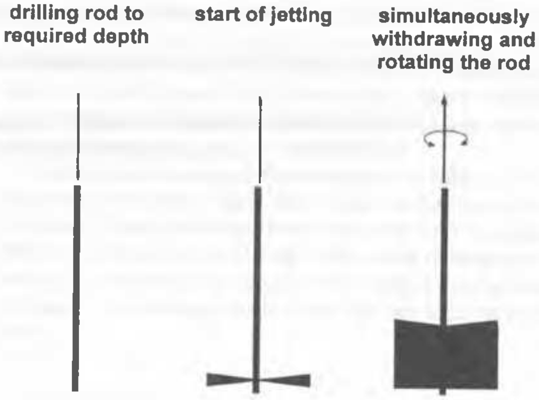

Fig. 3: Execution steps for jet grouting work

tors of risk. In practice this means to identify and collect modes of failure, hazards and weak points. To determine the probability of the different factors of risk for the reliability theory several methods are available: calculation e.g. by statistic analysis, experiences and estimation or engineering judgement. The last mentioned method will be necessary in those cases when no experiences or results from similar projects are available. In many situations probabilistic theories or calculation methods might be available. The quality of the determined probabilities normally vary a lot concerning their quality. So the main task of risk analysis is to gain quantitative results that can be explained and controlled under rational and impartial aspects.
In combination with the number of losses finally the risk can be stated. This implies the definition of risk assessment. Risk management means dealing with the risk by taking into account the evaluation of risk (Rißler (1998) and Whitman (1984)).
In many cases it is possible to take steps for reduction of risk, e.g. by using quality control and quality assurance methods.

2.2 *Risk assessment for jet grouting method*

Using the jet grouting method single elements can be executed. The process of execution can be divided into several steps as shown in figure 3. First step is drilling the rod to the final depth that is identically with the bottom of the jet grouted element. Second step is starting the jetting. The drilling rod is simultaneously rotated and withdrawn and the disaggregating and cementing fluids (air, water, cement) are jetted. A continuous flow of cuttings from the jet points to the ground surface is required to prevent ground pressures from building up to the jet pressure, leading to ground deformation. Depending on rotation angle, speed of withdrawal and number of rotation per minute as well as from jet pressure and injection rate the shape (column or panel) and dimension of the element can be influenced.
According to the assembly of jet grouted elements (partially or fully interlocked), nearly every type of jet grouted structure can be formed: blocks, walls, bottom slabs or canopies. Possible purposes of these structures are: static, water control or a combination of both. Corresponding to the purpose of the structure the demands on the jet grouted structure might vary a lot caused by different types of action as well as because of required quality of execution. The risk accords to the purposes and has to be valuated depending on different situations.
The characteristics of the quality of the jet grouted structure are influenced by a lot of factors which themselves are depending on each other. Some factors, such as soil properties and ground profile are fixed and can hardly be influenced or changed. The ground investigation shall be accurate and is essential for a successful execution. Nevertheless one has to keep in mind that the investigation of the ground cannot be entire, inter- and extrapolation always will be necessary. This means that the soil properties during designing process are not fixed, they might vary. On the other side factors like performance parameters are variable and have to be specified in in-situ trials, always with respect to the design parameters which take into account the difficulties and purpose of construction. All variable performance parameters have to be fixed in a so called method statement before starting the execution and have to be supervised and monitored during the process. Depending on number and types of quality control during execution the quality and reliability of the construction can be improved.

3 RELIABILITY THEORY

3.1 *Soil*

Jet grouting is a method for ground treatment using the soil both as foundation ground and as building material. Methods and number of geotechnical investigations for using the soil as foundation ground are adjusted to several national and international standards (e.g. DIN 4020 (1990), BS 1377 (1990)). In comparison: standards for using the soil as in-situ building material do not exist. On the one hand demands on soil as building material have to be much higher than demands on soil as foundation ground.
On the other hand the investigation of ground is only partially possible. This fact should normally entail very careful controlling of the executed elements. Unfortunately inspections of the geometry of the elements are actually not practicable on a statistically significant number of jet grouted elements. But it is proven that the diameter of jet grouted columns varies (Maybaum & Kayser, 2000). From this follows that it is absolutely necessary to find out much more carefully than required for soil as foundation ground the soil properties and the ground profile. Only by extensive investigations and knowledge of the soil it is possible to base the direct transfer of performance parameters on the properties and characteristics of the executed jet grouted element in similar geotechnical conditions. prEN 12716 (1999) gives all relevant hints for geotechnical investigation for jet grouting works in chapter No. 5. Very important seem to be the aspects of "high organic content" and "cobbles and/or boulders" which caused several hazards of jet grouting structures in the past few years. Defects in element geometry, in strength of grouting material, irregularities caused by jet shadowing and others appeared and at least led to a reduction in serviceability.
To sum it up, for obtaining reliable design values for geotechnical parameters very careful investigations and recommendations according to EC 7 (1997) must be taken. Field and laboratory tests have to be done to obtain measured values. A very careful interpretation of all test results is required. The suitability of derived values to determine design values is absolutely not advisable. The distinctions between different values are not clear enough in most cases.

All obtained results should be evaluated by comparison with existing experiences and with results from other types of tests. Statistical evaluations are most recommended with respect to the distribution of test results.

3.2 *Design*

For design the jet grouting structure has to satisfy all fundamental requirements of the relevant technical standards (e.g. on European level according to EC 2 and EC 7) which demand that the structure shall be designed and executed in such a way that structural safety and serviceability including durability is guaranteed. The designing process implies also that due regard is given to the purpose of the jet grouted structure and all possible actions (loads and imposed displacements). At the end of the designing process the geometry of the structure, including all relevant data about position, number and dimension of jet grouted elements, is fixed. All jet grouting parameters have to be evaluated during preliminary in-situ trials, where at least one jet grouted element should be constructed with the given working procedure. Additionally a method statement should be submitted where all quality control procedures, measurements, testing methods and required working documents are included.

In Germany, for the design process of jet grouted structures for ultimate and serviceability limit state, design values are used identically to those for non-reinforced concrete structures (in some cases also reinforced concrete if needed) with the lowest concrete strength class. The compressive strength as well as the elasticity modulus are set up as fixed values with homogeneous material properties. The design of the jet grouted structure as part of the soil-structure system is done according to technical standards such as EC 7. The simplifying step of fixing the material properties for the jet grouted structure as homogeneous has to be done because actually there are no calculation methods available that can take into account the real material properties which vary in a more or less wide field within the same structure. For example the construction of bottom seals with anchors against uplift, the above mentioned design process can lead to an overestimation of safety that does not really exist. In these cases the design with varying values seems to be useful and should be recommended. To estimate the material properties and values statistical approaches can be helpful.

Figure 4 shows the distribution of the varying material properties of a jet grouted block executed in Berlin Sand in Germany. The single-axial compressive strength and the E-modulus of 45 drill core samples have been tested. The measured values for the elasticity modulus range within far limits. The same effect has been found out for the compressive strength that varies between 2,5 MN/m² and 27,5 MN/m². The mean value is found at 9,67 MN/m² which is almost a third of the maximum value. Nevertheless the investigated distributions are not exactly representative for the real material properties of the jet grouted structure because some parts of the drill core samples have not been tested, since the cementation in these parts of the sample (especially in samples taken from parts where jet shadows appeared) was not sufficient for testing. Therefore the material properties depend extremely on the position of areas with low compressive strength and low elasticity modulus and the area of maximum loading because the unfavourable positioning of maximum action at the same position where the strength properties are worst might lead to the reduction of load capacity and in worst case lead to the failure of the structure. A FE-simulation of an anchored 40 m * 40 m bottom slab loaded by 180 kN/m² hydrostatic water pressure has been done, only distributing the elasticity modulus. Figure 5 shows the results of the difference between the distribution of moments Δ M1 with constant E-Modulus and with random selected material parameters according to the results from the tests in Berlin Sand. The maximum moments and stresses raise by up to 60 %.

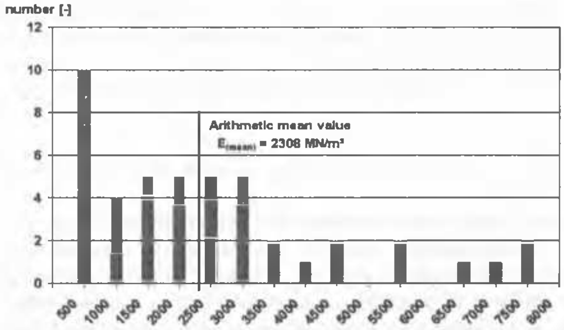

Fig. 4: Distribution of elasticity modulus in a jet grouted structure

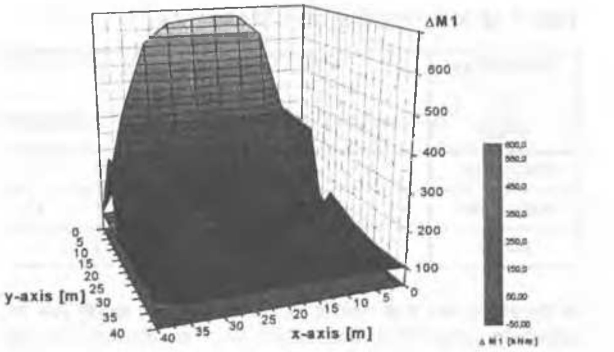

Fig. 5: Results of the FE-Simulation of an anchored bottom slab made by jet grouting in Berlin Sand and loaded by 180 kN/m² hydrostatic water pressure

3.3 *Execution and Supervision*

During execution jet grouting parameters which had been fixed in design process have to be monitored. This requires to control the geometry of the jet grouted elements but also the strength, deformability, permeability and/or density of the jet grouted material where appropriate. The minimum requirement is to record continuously the jet grouting parameters such as pressure, flow of fluids, and the translation and rotation speed of the monitor. The testing to assess the geometry of the jet grouted elements must be done by visual inspections, or randomly in defined intervals by direct measurements and test samples. In the case of exceeding the specified tolerances qualified steps must be taken to ensure the required quality of jet grouted elements and structures and with it the guarantee of serviceability. One additional step is to repeat jetting in case of unexpected high organic content (e.g. wood coal), if necessary supported by diminishing distance between element axis, or by changing jet grouting parameters. Other steps are e.g. to extend geometry of the elements or structure or to intensify and increase monitoring and supervision of execution.

4 RISK ANALYSIS AND RISK EVALUATION

The risk for jet grouted structures can be categorized into three levels A to C (see table 1). It depends on probability of event (failure) and on the number of losses. The classification of risk is actually only possible by quality and not by quantity. Quantitative prediction can be done only in some cases. As shown in chapter 3.2 some parameters are suitable for statistical analysis and then the effects of distributing values are considered for calculation and design. Level A in the categorized risk scheme means very high risk, level C stands for low risk. The economical aspect of losses and the resulting evaluation of risk is already implemented within the different levels. So risk management will deal with handling the risk, e.g. by accepting the higher level of risk, by repeating design process with a lower risk level, or by increasing supervision and monitoring in combination with selected additional measures to decrease the risk level and therefore reduce possibility of failure.

Continuous supervision and monitoring, combined with current tests in situ and in laboratory the risk can be reduced by taking countermeasures in case of exceeding fixed limits. As example can be mentioned the positioning of additional jet grouted elements in areas where measurements of inclination of the elements proved that the deviation from design position is too high.

Table 1. Qualitative categories of risk

Probability of event	Number of losses			
	disastrous	high	low	negligible
frequently	A	A	B	C
sometimes	A	B	B	C
rarely	B	B	C	C

In the same way risk reduction and increase of safety can be obtained by controlling and monitoring the diameter of the jet grouted element. The number of quality control has to be adjusted to the level of risk which seems to be practicable by taking into account economic aspects. By taking these measures all kinds of jet grouting structures can be realized implementing an acceptable level of safety. Structures that are rated to level C (e.g. constructions for groundwater control only or for strength in combination with little water loading) require only very little, standardized monitoring and supervision. Constructions rated as level A and B require additional measures for quality control, depending on number and amount of loading and purpose including the aspect of number of losses.

In case that a structure is classified to level A, for example anchored bottom slabs with high water loading in sand, tests and monitoring of each single element of the structure is necessary, because in case of low or no cementation anywhere in the construction, this will lead to high water flow into the building pit followed by erosion underneath the slab. Therefore the development of efficient, economical methods of testing as well as testing apparatus to control and monitor the integrity of the jet grouted structure is just as important as the updating of existing technical standards for structural design.

5 CONCLUSION

Both, quality and serviceability of jet grouted structures are influenced by a various number of parameters and conditions. In this paper some of the most relevant aspects are described taking into consideration some actual developments in research work as well as in practice. The different aspects are mentioned and marked all with respect to the possibility of using the existing data for statistical investigations, for example the reliability method. This paper describes the different aspects, explains some specifications and offers hints for the relevance with respect to the properties and purposes of the jet grouted structure. By means of reliability theory the importance of the parameters can be evaluated. Taking into consideration the purpose of the jet grouted structure the evaluation is done and examples are presented for increasing safety of production and serviceability and for decreasing risk level. In general the tendency to increase measures for monitoring and supervision offers great chances for acknowledge the failure of a structure much earlier than possible today. This offers the possibility to take countermeasures just in time and by this to decrease the level of risk.

In addition the upgrading of existing technical standard offers also the chance to increase safety of structures executed by jet grouting method quite on the level of design, which means that the varying values of design parameters and specific aspects of jet grouting parameters are integrated in calculation methods.

6 PREFERENCES

EN 1991 Eurocode 1 (EC 1). *Basis of design and actions on structures.* CEN: Brussels

EN 1992 Eurocode 2 (EC 2). *Design of concrete structures.* CEN: Brussels

EN 1997 Eurocode 7 (EC 7). *Geotechnical design.* CEN: Brussels

prEN 12716 1998. *Execution of special geotechnical work: Jet Grouting.* CEN/TC 288: Brussels

DIN 4020 1990. *Geotechnische Untersuchungen für bautechnische Zwecke.* Deutsches Institut für Normung e.V.: Berlin

Bieberstein, A., Herbst, J. & Brauns, J. 1999. Hochliegende Dichtsohlen bei Baugrubenumschließungen – Bemessungsregel zur Vermeidung von Sohlaufbrüchen. *Geotechnik 22*: 114 - 122

Borchert, K.-M. 1999. Dichtigkeit von Baugruben bei unterschiedlichen Sohlen-Konstruktionen – Lehren aus Schadensfällen. *VDI-Tagung Tiefe Baugruben, VDI Berichte Nr. 1436*: 21-43

BS 1377 1990. *Methods of test for soils for civil engineering purposes.* British Standards Institution: London

Burke, G. K., Weber, A. & Tóth, P. 2000. Soilcrete-DS: Enhanced Technology for Surgical Soil Improvement. *Proceedings of the 4th International Conference on Ground Improvement Geosystems, Helsinki:* 137-144

Casagrande, A. 1965. Role of the calculated risk in earthwork and foundation engineering. *Journal of the Soil Mechanics Division; ASCE; Vol. 91, No.SM4*: 1-40

Gudehus, G. & Schwarz, W. 1998. Düsenstrahlverfahren in holzhaltigem, nichtbindigem Baugrund. Deutsche Gesellschaft für Geotechnik e.V. (ed.), *Baugrundtagung, Stuttgart*: 643-655

Hoffmann, H., Katzenbach, R., Quick, H. & Weidle, A. 2000. Überlegungen zum Risk Assessment beim Düsenstrahlverfahren auf der Basis aktueller Entwicklungen. *15. Christian Veder Kolloquium, Graz, Heft 7:* 31-46

Lesnik, M. & Semprich, S. 2000. Düsenstrahlverfahren für tiefliegende Dichtsohlen - Ursachen und Vermeidung von Leckagen. *15. Christian Veder Kolloquium, Graz, Heft 7:* 115-130

Maybaum, G. & Kayser, J. 2000. Jet-grouting for a large and watertight building pit. Hans Rathmayer (ed.), *Grouting • Soil Improvement • Geosystems including Reinforcement; Proc. of the 4th Int. Conf on Ground Improvement Geosystems; Helsinki, 7-9 June 2000*: 173-180

Rißler, P. 1998. *Talsperrenpraxis.* R. Oldenbourg Verlag München/Wien

Stein, J. 2000. Bohrabweichungsmessungen bei der Herstellung einer Düsenstrahlsohle. *Messen in der Geotechnik 2000. Mitteilung des Instituts für Grundbau und Bodenmechanik, Technische Universität* Braunschweig, Heft Nr. 62: 209-222