Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-118

Diameter of jet grouting columns – analytical solution and artificial intelligence

Wolfgang Jimmy Wehr
University of applied sciences, Erfurt, Germany, wolfgang.wehr@fh-erfurt.de

ABSTRACT: The jet grouting method has been used on construction sites worldwide for decades. However, some important details are still unclear. One of these questions is the estimation of the range of the jet based on soil and nozzle parameters. Several publications can be found in the literature that deal with model tests under controlled conditions. However, it has not yet been possible to determine a generally valid design approach for estimating the range. For a new calculation approach, the tests by Bergschneider (maximum range) and Stein (development of the range over time) were combined. In addition, the new calculation approach assumes that it is not a bearing capacity failure mechanism, but an erosion process depending on pore water pressure and effective stress. Model tests were recalculated using the new formula and found to be in good agreement. In addition, a correlation matrix was created using 130 data sets of model and field test data in order to investigate the dependencies of the range of the jet on the soil and nozzle parameters. The relationships found in the correlation matrix were compared and evaluated using the analytical approach and artificial intelligence with neural networks. After training the neural networks, an excellent prediction of the jet range and diameter of the jet grouting columns was achieved for model and field test data for pressures of up to 500 bars.

KEYWORDS: Jet grouting, artificial intelligence, artificial neural networks.

1 INTRODUCTION

Many questions remain unanswered in ground improvement engineering research. This article presents a new approach of determining the radius of a jet grouting column in the ground and proposes a new design approach.

2 ANALYTICAL PREDICTION OF THE JET COLUMN RADIUS

The jet grouting method has been used worldwide for decades to create jet grouting columns in the ground. The process in the ground is highly complex and difficult to capture mathematically and physically. Significant experiments on this issue have been conducted by Bergschneider (2002) and Stein (2003, 2004), each of whom provides different calculation approaches for determining the jet range which corresponds to the column radius.

Jet grouting columns are created in all types of soil, which is why it is extremely useful that the approach can be used for any soil type.

Bergschneider (2002) only considers the maximum radius in his calculation. Thus, he provides a calculation approach based on the assumption of a bearing capacity failure in the ground at the far end of the jet. However, he does not consider the very important influence of pore water pressure and circumvents this with a simplification.

The development of the jet radius vs time in sand was described by Stein (2004) using a separation approach and various influencing parameters, such as the jet pressure and the soil density. This consideration is quite relevant for practical application, since more than just the maximum range is required for field implementation.

Both scientists thus provide part of the calculation for the complex process of the jet grouting method, but neglect important parameters. However, in order to provide a calculation approach for practical use that can be compared with empirical values, all aspects must be integrated into the calculation. An attempt is made here to integrate missing parameters and develop a calculation approach.

An initial calculation approach combined the formulas of both authors and added important parameters such as the pore water pressure, which depends on the soil permeability. However, this approach only partially achieved the desired result, as the maximum radius in various soils did not correspond to practical experience.

Many other researches have tried to predict the radius or diameter of jet grouting columns. An overview is given by Flora (2013) and Modoni et al. (2006). Most problems arise due to limited databases of model and field tests because many important parameters were not measured.

3 THE EROSION MECHANISM

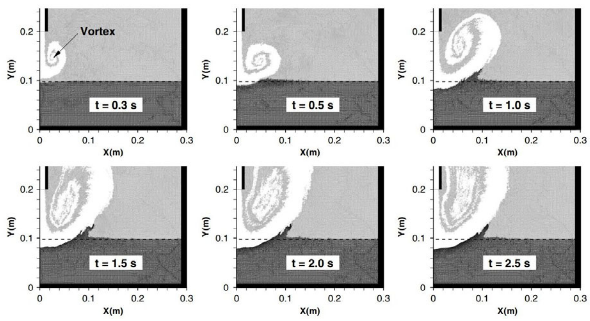

Figure 1. Erosion mechanism of a water jet in soil (Wan 2019)

A detailed examination of model tests, and in particular the hydrodynamic SPH calculations by Bui et al. (2006) and Wang et al. (2019), revealed that this is not a bearing capacity failure mechanism, but rather an erosion process with a surrounding vortex, see Fig. 1. The high-pressure water jet builds such high pore water pressure between the soil grains that the effective stresses become zero, allowing the grains to be easily transported by the water. Stein (2003) documented liquefaction with measurements in which the total stress was equal to the pore water pressure. Furthermore, earth pressure coefficients of approximately 0.9 were measured, which is only slightly lower than the earth pressure coefficient of 1.0 for liquefaction.

4 DEVELOPMENT OF A NEW DESIGN APPROACH

In his model experiments, Stein (2004) uses a vertical half-cylinder with a horizontal Plexiglas plate and jets vertically into the ground from above. This experimental setup is preferable to a horizontal jet because it creates a symmetrical vortex around the jet.

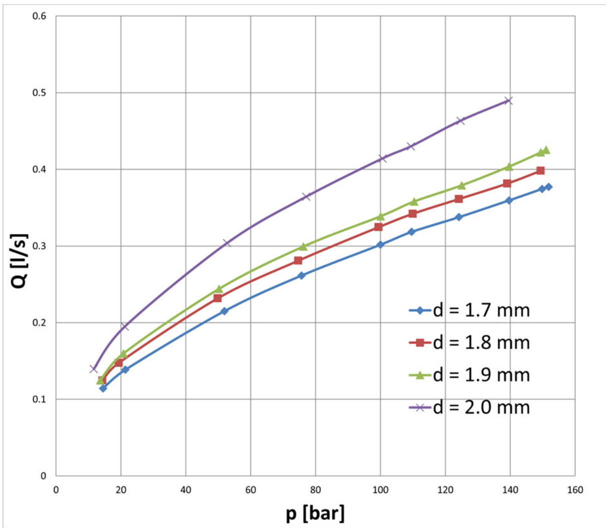

Figure 2. Nozzle characteristics of the jet (Stein 2004)

We begin by calculating the efficiency coefficients μ for the nozzles with diameters of 1.7 mm, 1.8 mm, 1.9 mm and 2.0 mm. Figure 2 shows the nozzle characteristics. The flow rate Q is therefore dependent on the nozzle pressure p, which was varied between 12.5 bar and 150 bar. For nozzle diameters 1.8 mm and 1.9 mm, mu=0.86 was obtained, and for nozzle diameters 1.7 mm and 2.0 mm, a better value of mu=0.95 was obtained.

By specifying the nozzle pressure, both the water exit velocity at the nozzle and the flow rate can be calculated.

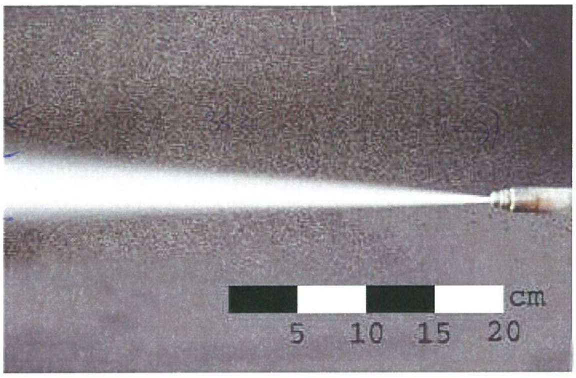

Figure 3. Water jet in air using a fluid pressure p=150bar (Stein 2004)

Using Figure 3, the expansion angle of the water jet in air can be estimated at alpha = 3.9 degrees. This is similar to the double and triple system in the soil with an air shrouded jet. The jet force is then calculated from the water density, the nozzle area and the water velocity at the nozzle. The stress resulting from the jet force at a specific distance from the nozzle can also be determined.

The core of the new calculation approach is the comparison of the depth-dependent total stress resulting from the soil's own weight and the range-dependent stress resulting from the jet force. The soil grains are only eroded as long as the stress resulting from the jet force is greater than the stress resulting from the soil's own weight. When both stresses are equal, the maximum jet range is reached.

To calculate the time-dependent jet range, two functions of Stein's separation approach are used:

$$f_1 = Rmax \left(\frac{1.31}{I_D^{0.55}}\right)^{-\frac{t}{tn}^{0.5}} \qquad (1)$$

the factor f_1 to account for the jet time t and the initial bulk density I_D,

$$f_2 = 0.385 + 0.615 \frac{p}{pref} \qquad (2)$$

and the factor f_2 to account for the jet pressure p. The reference values used are the reference time tn = 1 s and the reference pressure pref = 150 bar. Stein (2004) has already shown that the calculated and measured jet times agree well for different jet pressures and initial bulk densities, provided the maximum jet range is known. This comparison will not be repeated here.

To further quantify the influence of different sands, the influence of the grain diameter or soil permeability is included using the new factor f_3.

$$f_3 = \frac{Rmax}{Rmax,ref} = -0.6984 * \frac{d10}{d10,ref} + 1.6626 \qquad (3)$$

Stein found that the maximum range increases with decreasing mean grain diameter or decreasing permeability coefficient. For simplicity, a linear function is chosen that remains constant above a limiting grain diameter.

For comparison, the pressure-dependent jet ranges of different sands in the model are compared with the calculated values.

The maximum jet ranges Rmax specified by Stein of 0.39 m, 0.49 m, and 0.63 m at nozzle pressures p of 50 bar, 100 bar, and 150 bar are in good agreement with the results of the proposed calculation method (Rmax = 0.31 m / 0.48 m / 0.60 m) at medium and high pressures. The nozzle with a diameter of 1.8 mm was used for the tests with Karlsruhe sand.

It is noticeable that the values agree less well at p = 50 bar. It is known that the jet expansion angle increases with increasing pressure. The more turbulent the flow becomes with increasing velocity, the larger the jet expansion angle becomes. Substituting 3.5 degrees for p=50 bar instead of 3.9 degrees for p=150 bar, one obtains exactly Rmax = 0.39 m. Unfortunately, there are no experimental data available for verifying the jet expansion angle at low pressures.

Since Stein's experiments were only conducted up to a pressure of 150 bar, Bergschneider's field tests with up to 500 bar are also taken into consideration.

5 CORRELATION ANALYSIS

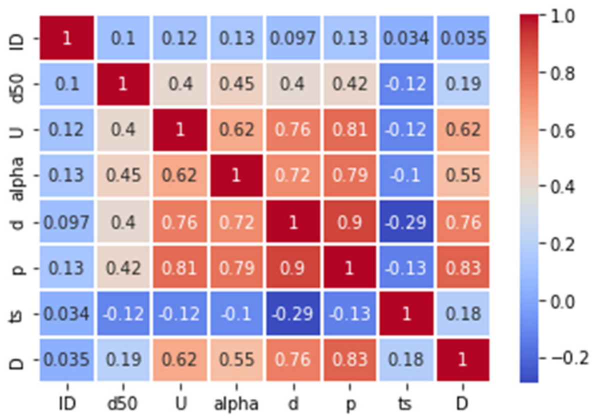

Figure 4. Heatmap between the correlation of input and output values

In Fig.4, a heatmap is used to visualize the correlation between the input and output variables. A heatmap correlation matrix uses Pearson's correlation coefficient by default (Pearson 1896). A value of 0 indicates no correlation, whereas values of +/-1 indicated perfect positive or negative correlation between variables.

To achieve the best possible correlation, 130 test values from several authors were used: Mitrenga (2003) with pressures between 10 and 40 bar, Stein (2004) with pressures between 50 and 150 bar, and Bergschneider (2002) with pressures between 400 and 500 bar. This covers the entire pressure range used in practice. To include the data of the field trials, the jetting time is calculated from the withdrawel time, the column diameter and the expansion angle of the jet (Bergschneider et al. 2003).

Important influencing variables on the jet grouting diameter are therefore: fluid pressure p, nozzle diameter d, uniformity coefficient of the soil U, and the angle of propagation of the jet alpha. The influence of other parameters like the relative density Id can neglectable as the ranges measured for the same sand with different densities were very similar.

6 MODELING WITH NEURAL NETWORKS

A general introduction to machine learning and artificial neural networks (ANN) may be found in Hocking (2022). Some researches have already tried to apply ANN's to predict the jet grouting diameter like Ochmanski et al. (2015), Wang et al. (2021) and Njock et al. (2021) with limited field data.

Modelling in this research project was carried out using the Anaconda Python distribution and the Spyder package for code editing. In total 130 data sets from tests by Mitrenga, Stein and Bergschneider were imported using the Pandas library. Typically, 70-80% of the training and test data is used for training (Hastie et al. 2009). In this case 80% of all values are used as training data and the architecture of the neural networks is as follows: 7 input neurons (fluid pressure, nozzle diameter, angle of propagation of the jet, jetting time, relative density of the soil, average diameter of the soil particles), 3 hidden neuron layers with different numbers of neurons and 1 output neuron (jet grouting column diameter). The batch size is finally taken to 1 and the number of epochs to 100.

It is very important that the hyperparameters are optimized according to a specific strategy (Soranzo 2022): it is first started with only one hidden layer and the number of neurons is increased until the coefficient of determination R^2 no longer increases. Then, the next hidden layer is added and the number of neurons is increased again until an additional layer no longer results in an improvement in the coefficient of determination. To keep the calculation time to a minimum, a batch size of 10 or more is used to start with and the value is gradually reduced to 1 at the end of the calculations. The number of epochs is increased at the end until R^2 no longer increases.

7 MODELING RESULTS

80% of the dataset described in section 6 was allocated for training. This methodology yielded an excellent training coefficient of determination with the help of artificial intelligence using neural networks R^2 of 0.94 for training and R^2 of 0.94 for testing.

Figure 5 shows a typical mean squared error (MSE) trend, showing a steep initial decline that subsequently tapers off.

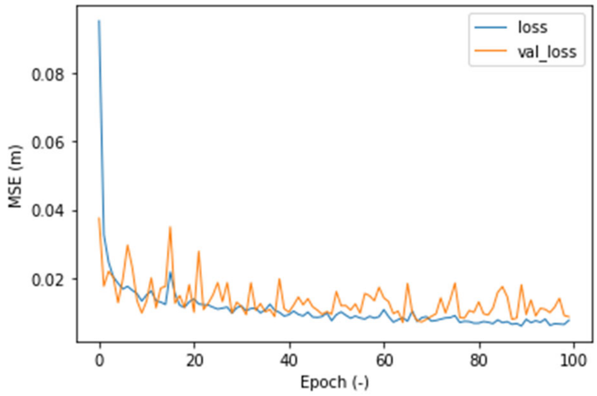

Figure 5. Mean square error (MSE) over the number of epochs for the training and test data sets.

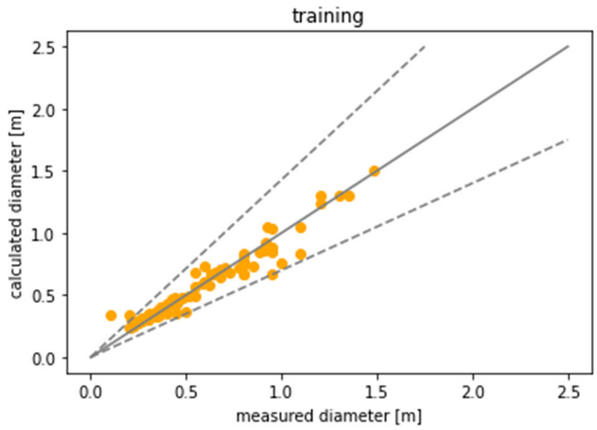

Figure 6. Comparison of the measured and predicted jet grouting diameters during training

Figures 6 and 7 compare the measured and predicted jet grouting diameters. The solid line corresponds to 0% deviation and the dashed lines to +30%/-30% deviation.

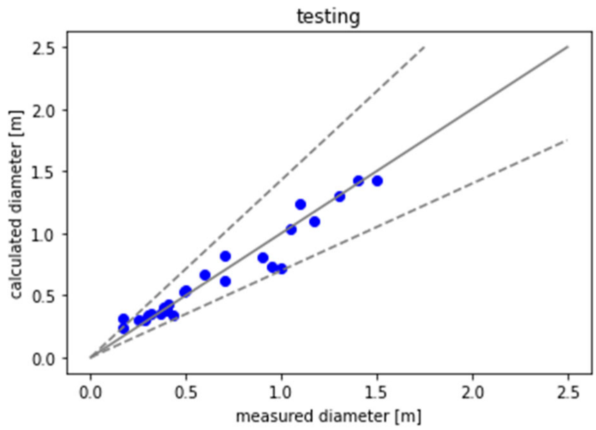

Figure 7. Comparison of the measured and predicted jet grouting diameters during testing

8 VALIDATION OF THE PREDICTIONS

Table 1: Comparison of Bergschneiders field tests and design values of the maximum range Rmax

R_{Tests} [m]	Analytical R [m]	$deviation_{Wehr}$ [%]	ANN R [m]	$deviation_{ANN}$ [%]
1.18	0.91	22.88	0.95	19.49
0.95	1.32	38.95	0.97	2.11
0.55	0.59	7.27	0.63	14.55
0.65	0.59	9.23	0.63	3.08
0.93	1.07	15.05	1.05	12.90
1.10	1.19	8.18	1.17	6.36
1.30	1.68	29.23	1.31	0.77
1.20	1.55	29.17	1.30	8.33
1.00	1.06	6.00	1.01	1.00
1.05	0.92	12.38	0.95	9.52

In order to validate the results, the measured jet ranges Rmax in the field were compared with the analytical model of Wehr and the artificial neural network. An average deviation of the analytical results from the tests were found to be 17.8%. However, the average deviation of the ANN results from the tests were only 7.8%.

Concluding the above the ANN predictions were more accurate and are recommended for practical applications in the future. It has to be kept in mind that starting such an ANN project for jet grouting requires a solid database and might be time consuming in the beginning.

9 CONCLUSIONS AND OUTLOOK

A new design method to estimate the maximum radius Rmax of the jet grouting column in the soil was achieved by comparing the total stresses resulting from the soil's own weight and the jet pressure. If both are equal, the fluid jet does not spread further in the soil. The comparison is based on an erosion mechanism in which grains are transported when the pore water pressures are at least large enough for the effective stresses to be zero.

To also calculate the time dependent range of the jet, the separation approach according to Stein was used and supplemented with a function to account for different sands with different grain diameters. A comparison of the results with the tests demonstrates the applicability of the approach.

Using a heatmap with Pearson coefficients a strong correlation of fluid pressure and nozzle diameter with column diameter was found for 130 data sets using field and laboratory tests. Additionally it was confirmed that the relative density of the soil has only a very small influence.

Artificial neural networks have been used to recalculate and predict the radius of model and field jet grouting columns successfully with a high coefficient of determination of 0.94. The key to achieve excellent results is the optimization of hyperparameters. Using a solid database of model test results including relevant fluid pressures it has been possible to predict the jet range with an average deviation of only 8%.

Additional field test results by Keller Grundbau GmbH have been analysed as well and will be reported elsewhere.

10 REFERENCES

Bergschneider, B., 2002. *Zur Reichweite beim Düsenstrahlverfahren im Sand.* Ph.D. thesis. Universität Wuppertal

Bergschneider, B., Walz, B., 2003. *Fuzzy-Logik-gestützte Abschätzung der Reichweite eines Düsenstrahls*. Bautechnik 80, Heft 7.

Bui, H.H., Fukawaga R., Sako K., 2006. Smoothed particle hydrodynamics for soil mechanics, *Numerical methods in geotechnical engineering* – Schweiger (ed.), Taylor and Francis

Flora, A., Modoni G., Lirer, S. und Croce, P., 2013. The Diameter of Single, Double and Triple Fluid Jet Grouting Columns: Prediction Method and Field Trial Results. *Géotechnique* 63, Nr. 11 (September): 934–45. https://doi.org/10.1680/geot.12.P.062

Hastie, T., Tibshirani, R., & Friedman, J. (2009). *The Elements of Statistical Learning: Data Mining, Inference, and Prediction* (2nd ed.). Springer.

Mitrenga, J., 2003. *Entwicklung eines Planungsinstruments zur Vorausberechnung von Säulendurchmessern beim Düsenstrahlverfahren.* Ph.D. thesis, RWTH Aachen, ISBN 3-86130-330-2

Modoni, G., P. Croce, und L. Mongiovì. 2006. Theoretical Modelling of Jet Grouting. *Géotechnique* 56, Nr. 5 (June): 335–347. https://doi.org/10.1680/geot.2006.56.5.335.

Njock A., G.-P., Shen S.-L., Zhou A., und Modoni G., 2021. Artificial Neural Network Optimized by Differential Evolution for Predicting Diameters of Jet Grouted Columns. *Journal of Rock Mechanics and Geotechnical Engineering* 13, Nr. 6 (Dezember): 1500–1512. https://doi.org/10.1016/j.jrmge.2021.05.009.

Ochmański, M., G. Modoni, und J. Bzówka., 2015. Prediction of the Diameter of Jet Grouting Columns with Artificial Neural Networks. *Soils and Foundations* 55, Nr. 2 (April): 425–436. https://doi.org/10.1016/j.sandf.2015.02.016.

Pearson, K. (1896). *Mathematical Contributions to the Theory of Evolution. III. Regression, Heredity, and Panmixia.* Philosophical Transactions of the Royal Society of London. Series A, 187, 253–318.

Soranzo, E., 2023. Lecture notes, artificial intelligence in geotechnics. Universität für Bodenkultur, Vienna

Stein, J. & Grabe, J., 2003. Jet grouting tests and simulation. Proc. 13th *Eur. Conf. Soil Mech. Geotech. Engng, Prague* (eds I. Vanicek, R. Barvinek, J. Bohac, J. Jettmar, D. Jirasko and J. Salak) 2, 899–902.

Stein, J., 2004. *Experimentelle und numerische Untersuchungen zum Düsenstrahlverfahren.* Ph.D. thesis (J. Grabe, Hrsg.) Hamburg: Technische Universiät Hamburg-Harburg

Wang, Y., Peng, C., Meng X., 2019. Investigation of submerged soil excavation by high-velocity water jet using two-fluid smoothed particle hydrodynamics method, *Journal of hydraulic engineering,* June

Wang, Z.-F., und Cheng, W.-C., 2021. Predicting Jet-Grout Column Diameter to Mitigate the Environmental Impact Using an Artificial Intelligence Algorithm. *Underground Space* 6, Nr. 3 (Juni): 267–80. https://doi.org/10.1016/j.undsp.2020.02.004.