TEMPERATURE MEASUREMENTS TO DETERMINE THE DIAMETER OF JET-GROUTED COLUMNS

Klaus Meinhard, Porr Technobau und Umwelt AG, Abteilung Grundbau, Vienna, Austria
Dietmar Adam, Vienna University of Technology, Institute for Soil Mechanics and Geotechnical Engineering, Vienna, Austria
Roman Lackner, University of Innsbruck, Institute for Construction and Materials Science, Material Technology Innsbruck, Austria

In this paper, a back-analysis scheme for the determination of the properties of jet-grouted structures using thermo-chemical couplings is presented. Hereby, the temperature increase in the center of the jet-grouted column is monitored and compared with the result of a thermo-chemical analysis of the hydration process in the column. As regards the latter, a multi-phase hydration model taking the chemical composition of the employed cement (or blended cement) into account is used.

INTRODUCTION

Soil improvement by means of jet grouting is performed without possible visual inspection during the entire installation process. Changes within the geological situation and of grouting parameters influence the quality of jet-grouted columns (geometrical properties and mechanical behaviour of jet-grouted soil mass). According to Eurocode EN 12716, grouting of so-called test columns (see Figure 1) and subsequent excavation are required for determination of grouting parameters. This method is time consuming and expensive. Alternatively, methods based on geophysics, mechanical sensoring, measuring the erosion of pre-installed pipes, and waste-slurry investigation have been presented to estimate/determine the diameter of jet-grouted columns.

(a) (b)

Figure 1: (a) Drilling rig used for jet grouting and (b) test columns after excavation

In this paper, a thermochemical parameter-identification scheme, considering the exothermal nature of hydrating jet-grouted soil mass, is presented. Hereby, diameter and cement content of jet-grouted columns are determined by numerical back-calculation of temperature histories measured on site at the center of jet-grouted columns.

Departing from the work presented in (Brandstätter, 2002), the thermochemical parameter-identification scheme of properties of jet-grouted columns is extended as regards the simulation of the hydration process in early-age cement-based materials and the identification of thermal properties of the in-situ soil and the jet-grouted soil mass. As regards the simulation of the hydration process, the properties (mineralogy, blaine value, ...) of the employed binder are considered within a multiphase hydration model for ordinary Portland cement (OPC), which is extended towards blended cements (OPC mixed with blast furnace slag, lime stone) and validated by means of differential calorimetry tests.
The temperature history measured on site, especially after having reached the maximum value, is strongly influenced by the thermal properties of the in-situ soil, i.e., the heat capacity and thermal conductivity. Whereas volume averaging is applied for determination of the effective heat capacity, determination of the effective thermal conductivity requires consideration of the material microstructure, represented by the number of contacts per particle, dry density, degree of saturation, mineralogy, particle size, and thermal properties of the material phases.

Finally, a user-friendly software tool for the presented thermochemical parameter-identification scheme is developed, allowing the interactive determination of the column diameter and cement content. The results obtained from application of this tool at construction sites are given at the end of this paper.

MOTIVATION

The dependence of the diameter D of jet-grouted columns on (i) the work pressure, (ii) the injection time, which is determined by the rate at which the drilling rod is rotated and withdrawn, and (iii) the properties of the in-situ soil still requires the grouting of test columns and subsequent excavation. In addition to grouting of test columns, the estimation/determination of the diameter of jetgrouted columns has been a topic of intense research, having lead to alternative techniques based on

- measuring the erosion of pre-installed pipes: Hereby, thin pipes are installed parallel to the axis of the jet-grouted column in different distance to the center of the column (approximately the predicted diameter). The erosion which occurs during the jetgrouting process provides information about the column diameter in different depths;
- mechanical sensoring devices, giving access to the location of the interface between the rather liquid jet-grouted soil mass and the surrounding soil not affected by jet grouting (Weber, 2000) (Raabe, 1994);
- geophysical methods, using (i) electrical (Frappin, 2001), (ii) electromagnetic (Tamura, 1996), and (iii) hydrophone measurements (Gross, 1997);
- waste-slurry investigation, considering the mass balance between the components of the inflow during jet grouting and the outflow (waste slurry) (Lesnik, 2003); and
- mechanical models describing the deterioration process of soil by the high-pressurejet (Martak, 1999) (Tkatschuk, 1997) (Bergschneider, 2002) (Stein, 2002).

For detailed information about the mentioned techniques for estimating/determining the diameter of jet-grouted columns, the reader is referred to (Lesnik, 2003).

Among them, the thermochemical coupling in hydrating cement-based materials (the temperature influences the hydration kinetics and the hydration results in a temperature increase) was the basis for the back-calculation of properties of jet-grouted columns reported in (Brandstätter, 2002). Hereby, the temperature history in the center of the column measured on site is reproduced by numerical simulations adapting the column diameter and the cement content of the improved soil in the numerical model.

HYDRATION MODEL

Whereas an overall degree of hydration with one kinetic law was used in (Brandstätter, 2002), a multi-phase hydration model, taking the main (four) clinker phases and the chemical compounds of cement into account, was proposed in (Bernard, 2003).

Figure 2 shows the evolution of the degree of hydration ξ of the four main clinker phases C3S, C2S, C3A, and C4AF obtained from application of the multi-phase hydration model outlined in (Bernard, 2003) to each clinker phase and different evolution laws considering, e.g., a w/c-ratio of 0.3 and an average particle size of R=7µm.

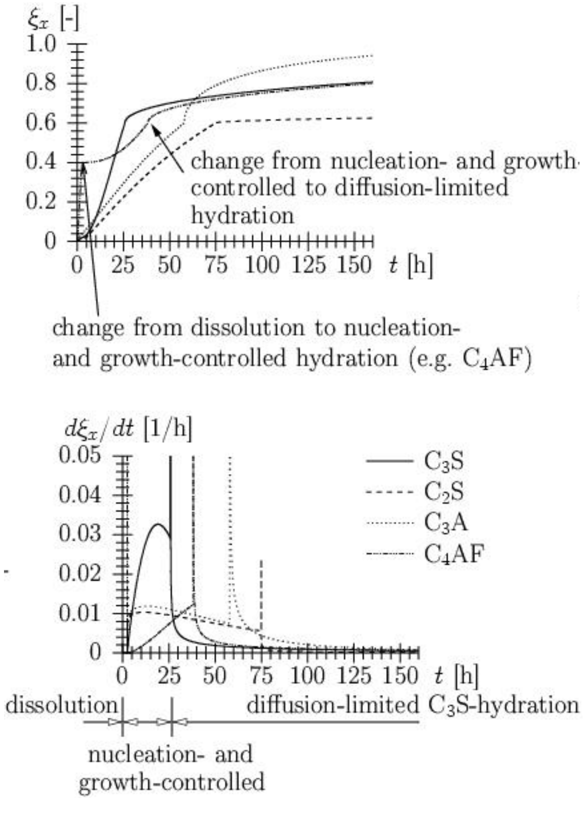


Fig. 2 ξ_x and $d\xi_x/dt$ for the four main clinker phases (water/cement-ratio=0.3; temperature=30°C; average particle size R=7µm)

In order to reduce costs of ground improvement, blended cements are commonly used during jet grouting (ordinary portland cement mixed with blast furnace slag, fly ash, silica fume, and lime stone).

For this purpose, the hydration model presented in (Bernard, 2003) was extended towards blended cements and validated by means of differential-calorimetry (DC) experiments, see (Meinhard, 2008).

DC tests were performed for blended cements composed of ordinary portland cement, with 4,895 cm2/g blaine value (Q_∞ = 475 J/g), and slag (Q_∞ = 461 J/g (Schindler (2005)), with a cement/slag-ratio ranging from 20/80 to 80/20.

Figures 3 (a) and (b) show the DC-results conducted at 30℃ and 50℃, respectively. The dashed lines represent the heat flow and heat-flow rate of the respective cement fraction in the blended cement. It was obtained from multiplying the DC-test result for pure cement with the respective amount of cement in the blended cement. Thus, the difference between the solid and dashed line can be considered as the heat release associated with slag hydration.

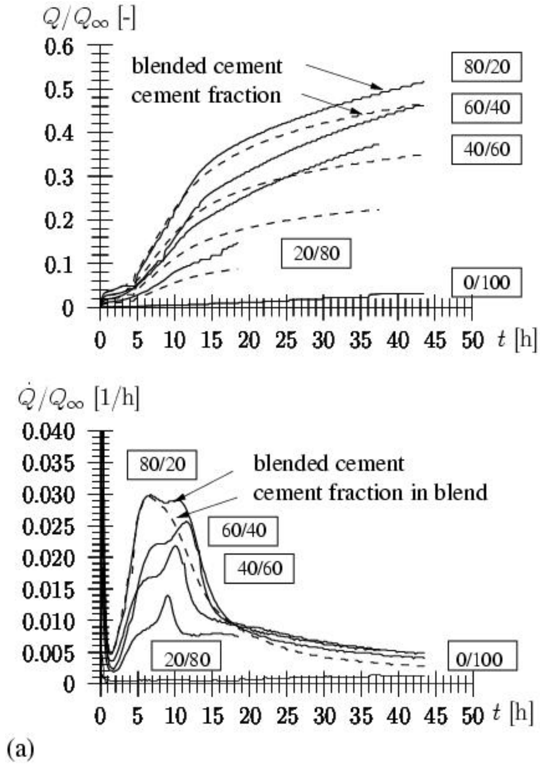


Fig. 3(a) DC-test results: heat flow Q and heat-flow rate dQ/dt for different cement/slag-ratios (OPC/slag, Q_∞ = 468 J/g for all blended cements) at 30℃

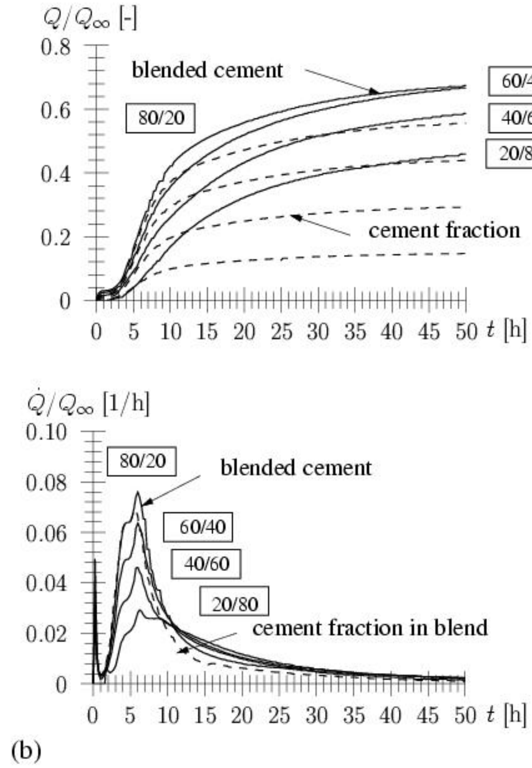


Fig. 3(b) DC-test results: heat flow Q and heat-flow rate dQ/dt for different cement/slag-ratios (OPC/slag, Q_∞ = 468 J/g for all blended cements) at 50℃

THERMAL PROPERTIES OF GRANULAR MATERIAL

For the solution of thermal problem, the volumetric heat capacity C [kJ/(m^{3}K)], and the thermal conductivity k [kJ/(mhK)] of the jet-grouted soil mass and the in-situ soil are required. In order to account for the large range of these properties in granular, dry to fully-saturated material, determination of C and k from the properties of the different material phases, such as particles, water, and air is proposed. Whereas the heat capacity depends on the volume fractions of the material phases only, both material composition and arrangement (morphology) influence the thermal conductivity.

In addition to models given in the literature for dry and saturated state (Lackner, 2005) (Misra, 1995) a FEM-based model is employed to determine the thermal conductivity in the range of low and high values for the degree of saturation. Hereby, the effect of water bridging in the contact area of two particles is considered.

DEVELOPMENT OF SOFTWARE TOOL

THEORETICAL BACKGROUND

For the description of the exothermal process of hydrating jet-grouted soil mass, the kinetics of the hydration process is assumed to depend only on the mass of hydrates formed and on the current temperature. The underlying field equation for the thermochemical problem is derived from the first law of thermodynamics. In the absence of volume heat sources, this law is given as

$$C_{eff}\dot{T} - \sum_x \ell_{\xi_x}\, \dot{\xi}_x = -\operatorname{div}\mathbf{q}\ , \tag{1}$$

with C_{eff} [kJ/(m^3 K)] as the effective volumetric heat capacity, and $l_{\xi x}$ [kJ/m^3] as the latent heat of hydration per unit volume related to the chemical reaction of the *x-th* clinker phase. The heat flow vector **q** is related to the temperature T via Fourier's linear (isotropic) heat conduction law,

$$\mathbf{q} = -k_{eff}\operatorname{grad} T \tag{2}$$

with k_{eff} [kJ/(mhK)] as the effective thermal conductivity. The kinetics laws controlling the heat release were provided within the multiphase hydration model. Alternatively, a single-phase hydration model may be used in case no information about the chemical composition of the used cement is available. Hereby, an Arrhenius-type kinetics law for the evolution of the overall degree of hydration ξ is employed, reading

$$\dot{\xi} = \tilde{A}(\xi)\ \exp\left(-\frac{E_a}{R(273+T)}\right), \tag{3}$$

where $A(\xi)$ [s^{-1}] is the chemical affinity, E_a=33.5 kJ/mol is the activation energy for T>293 K and 33.5+1.47(293-T) for T<293 (Freiesleben, 1977), R=8.315 J/(mol K) is the gas constant, and T [°C] is the temperature. The chemical affinity $A(\xi)$ is obtained from the heat-flow rate *dQ(t)* and the heat flow *Q(t)* determined by DC experiments by combining

$$\dot{Q}(t_i) = Q_\infty m_z \dot{\xi} \quad \rightarrow \quad \tilde{A}(t_i) = \frac{\dot{Q}(t_i)}{Q_\infty m_z}\exp\left(\frac{E_a}{R(273+T)}\right) \tag{4.1}$$

and

$$\xi(t_i) = Q(t_i)/Q_\infty, \tag{4.2}$$

where m_z is the mass of cement considered in the DC experiment and Q_∞ is the latent heat of cement, which is set equal to 600 J/(g cement) (Carlslaw, 1959). For the numerical simulation, $A(\xi)$ obtained from Equation (4.1) and (4.2), which is given for discrete values of ξ corresponding to the time instants t_i of the DC-test data, is approximated by an analytical function, reading

$$\tilde{A}(\xi) = a\frac{1-\exp(-b\xi)}{1+c\xi^d}, \tag{5}$$

where the constants *a*, *b*, *c*, and *d* are obtained from regression analysis. For the singlephase hydration model, the overall latent heat of hydration (Equation (1)) is given by the latent heat of cement multiplied by the cement content *s* [(kg cement)/(m^3 jet-grouted soil mass)], reading

$$\ell_\xi = 600\ s\ [\text{kJ/(m}^3\text{ jet-grouted soil mass)} \tag{6}$$

SENSITIVITY STUDY

In order to illustrate the influence of properties of jet-grouted columns (column diameter D and cement content s) on the temperature history at the center of a jet-grouted column, a numerical study is performed first. The geometric dimensions of jet-grouted columns in most applications (except e.g. sealing slabs) are characterized by *L*/D > 1, where *L* and *D* denote the length and the diameter of the column, respectively. Hence, the three-dimensional thermochemical problem can be reduced to a plane model considering only the cross section of the column. Hereby, the temperature flow in the longitudinal direction of the column is set equal to zero. Moreover, the axisymmetry of the cross-section of the jet-grouted column allows to further reduce the numerical model to a one-dimensional axisymmetric model (see Figure 4). At all boundaries of this model, adiabatic conditions, with $q_n = q \cdot n = 0$, are assumed.

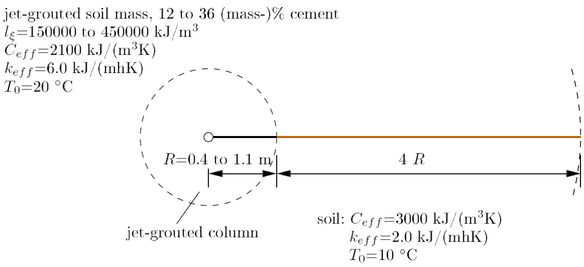


Fig. 4 Sensitivity study: geometric dimensions, material properties, and initial temperatures T_0

The axisymmetric problem shown in Figure 4 is solved by means of the finite element method (FEM).

The obtained results show that an increase of the amount of cement *s* effects the heating period of the jet-grouted column at the beginning of the hydration process, whereas a change of the column diameter mainly influences the decrease of the temperature in the cooling period (see Figures 5 and 6). This clear distinction of the influence of the unknown parameters *D* and *s* on the temperature history is illustrated in Figure 7, showing the time instant corresponding to the maximum temperature and the maximum temperature in the jet-grouted column as a function of the column radius *R* and *s*.

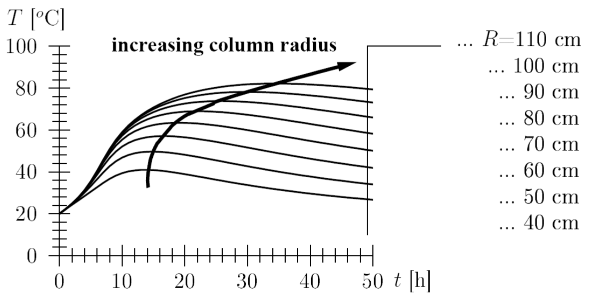


Fig. 5 Sensitivity study: Influence of column radius *R* on temperature histories obtained at the center of jet-grouted column (cement content *s*= 500 kg/m3; jet-grouted soil mass: C_{eff}=2,100 kJ/(m^{3}K), k_{eff}=6.0 kJ/(mhK); soil: C_{eff}=3,000 kJ/(m^{3}K), k_{eff}=2.0 kJ/(mhK); single-phase hydration model: *a*=3.15, *b*=50.7, *c*=2300, and *d*=5.00)

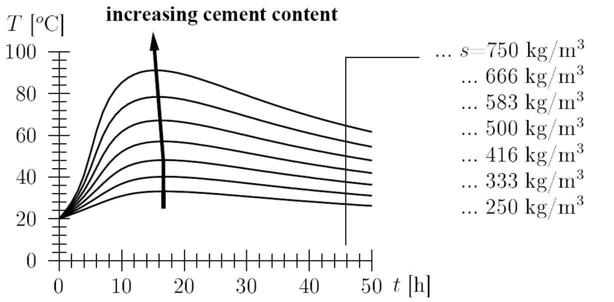


Fig. 6 Sensitivity study: Influence of cement content s on temperature histories obtained at the center of jet-grouted column (column radius *R*= 60 cm; jet-grouted soil mass: C_{eff}=2,100 kJ/(m^{3}K), k_{eff}=6.0 kJ/(mhK); soil: C_{eff}=3,000 kJ/(m^{3}K), k_{eff}=2.0 kJ/(mhK); single-phase hydration model: *a*=3.15, *b*=50.7, *c*=2300, and *d*=5.00)

PARAMETER IDENTIFICATION

For identification of the values of *R* and *s*, the temperature history at the center of the jet-grouted column is computed for 5×5 (*R, s*)-pairs. The so-obtained temperature histories are compared with the temperature history measured on site. The (*R, s*)-pair giving the lowest deviation between the numerically-obtained and measured temperature history is used as the center of the new, reduced search interval (see Figure 8). The parameter identification is stopped, when the size of the search interval becomes lower than 5 cm for the radius R of the jet-grouted column and 10 kg/m3 for the cement content s.

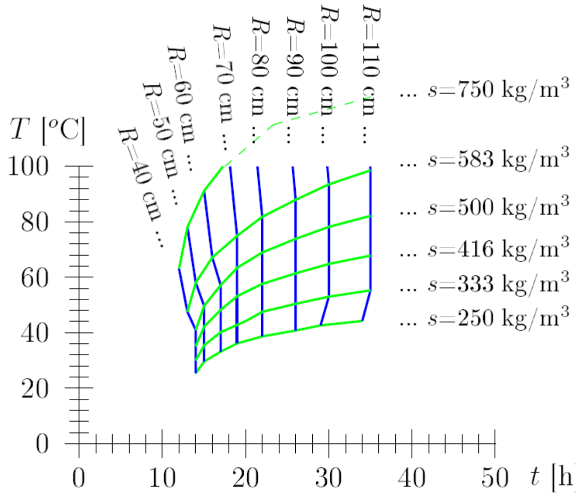


Fig. 7 Sensitivity study: Maximum temperature in jet-grouted column and respective time instant as a function of column radius *R* and cement content *s* (jet-grouted soil mass: C_{eff}=2,100 kJ/(m^{3}K), k_{eff}=6.0 kJ/(mhK); soil: C_{eff}=3,000 kJ/(m^{3}K), k_{eff}=2.0 kJ/(mhK); single-phase hydration model: *a*=3.15, *b*=50.7, *c*=2300, and *d*=5.00)

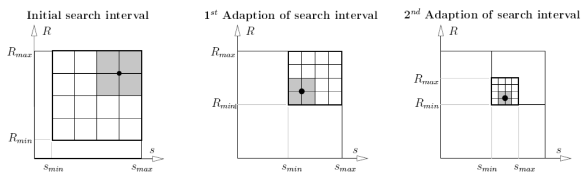


Fig. 8 Parameter identification: Illustration of adaption of search interval containing (*R, s*)-pair characterized by lowest deviation between numerically-obtained and measured temperature history (•: (*R, s*)-pair giving lowest deviation between numerically-obtained and measured temperature history within corresponding search interval)

USER INTERFACE

For the application of the developed parameter-identification scheme in engineering practice, a user interface was programmed. Figure 9 shows a screen shot of the user interface containing the result of the parameter-identification scheme.

Moreover, "result sheets" are provided, containing all relevant information, input data, and the result from parameter identification, see Figure 12.

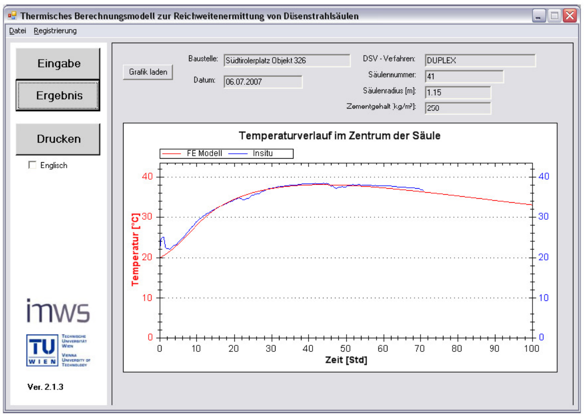


Fig. 9 User interface: Screen shot showing result from parameter identification

APPLICATION

The developed tool for identification of the diameter *D* [m] of jet-grouted columns and the cement content *s* [kg/m3] of jet-grouted soil mass was applied to more than 100 jet-grouted columns at construction sites in Europe. The grouting method used at the these construction sites were different. For every cement employed DC experiments were conducted.

INSTALLATION OF TEMPERATURE SENSORS ON SITE

Figures 10 and 11 illustrate the installation of a temperature sensor in jet-grouted columns. Figure 10 shows the temperature sensor which, after installation, will be connected to a monitoring device. Right after termination of the jet-grouting works, the drilling rod is moved into the jet-grouted column until the future position of the temperature sensor is reached. Thereafter, the sensor is installed through the high-pressure channel of the drilling rod (see Figure 11). Finally, the drilling rod is withdrawn, while the temperature sensor remains at its position.

CONSTRUCTION SITE, VIENNA, AUSTRIA

On this site, jet grouting was performed in June 2005 in areas of future shafts and as underpinning for a collector and a telephone pole. Four test columns were produced in order to determine the effect of different jet-grouting parameters. The water/cement-ratio of the used cement grout was 1.0.

Since information about the mineralogical composition of the employed cement is available, the multiphase hydration model for blended cements was employed in numerical simulations.

Fig. 10 Temperature sensor ready for installation

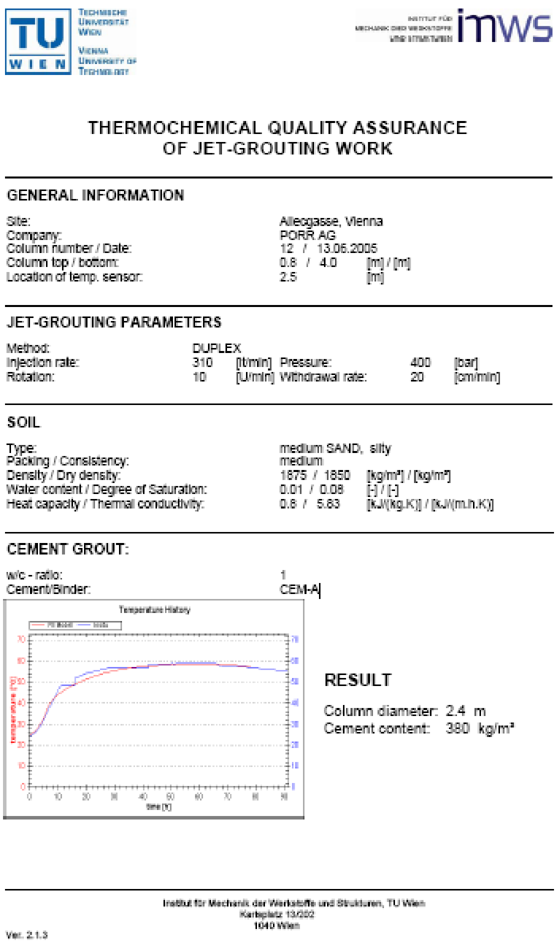
Fig. 11 Installation of temperature sensor through high-pressure channel of drilling rod

The thermal properties of the in-situ soil and the jet-grouted soil mass were determined.

After excavation of the jet-grouted columns, diameters in the range of 110 to 240 cm were measured.

Figure 12 for example contains the result sheet obtained from the application of the developed parameter-identification tool, providing the general information of the construction site, the geometrical properties of the column, the employed thermal properties of the in-situ soil, the grout, and the jet-grouted soil mass. At the bottom of each sheet, the measured temperature history and the numerically-determined temperature history corresponding to the identified values for the column diameter and the cement content are given.

For each column, the deviation between the predicted and the measured diameter was less than 10%.



THERMOCHEMICAL QUALITY ASSURANCE
OF JET-GROUTING WORK

GENERAL INFORMATION

Site:	Allegasse, Vienna	
Company:	PORR AG	
Column number / Date:	12 / 13.06.2005	
Column top / bottom:	0.8 / 4.0	[m] / [m]
Location of temp. sensor:	2.5	[m]

JET-GROUTING PARAMETERS

Method:	DUPLEX				
Injection rate:	310	[lt/min]	Pressure:	400	[bar]
Rotation:	10	[U/min]	Withdrawal rate:	20	[cm/min]

SOIL

Type:	medium SAND, silty	
Packing / Consistency:	medium	
Density / Dry density:	1875 / 1850	[kg/m³] / [kg/m³]
Water content / Degree of Saturation:	0.01 / 0.08	[-] / [-]
Heat capacity / Thermal conductivity:	0.8 / 5.83	[kJ/(kg.K)] / [kJ/(m.h.K)]

CEMENT GROUT:

w/c - ratio:	1
Cement/Binder:	CEM-A

RESULT

Column diameter: 2.4 m
Cement content: 380 kg/m³

Institut für Mechanik der Werkstoffe und Strukturen, TU Wien
Karlsplatz 13/202
1040 Wien

Ver. 2.1.3

Fig. 12 Construction site, Vienna: Result sheet for jet-grouted column

CONCLUSIONS

In this paper, the thermochemical identification of properties of jet-grouted columns presented in (Brandstätter, 2002) was extended as regards the proper description of the hydration process of the employed (blended) cement by means of a multiphase hydration model and the microstructure-related identification of the thermal properties of in-situ soil and jet-grouted soil mass. The so-obtained parameter-identification tool was employed on several jet-grouting sites within the last five years, characterized by different in-situ soil conditions and grouting parameters. Hereby, the predicted column diameters agreed very well with the column diameters measured after excavation of the test columns. In addition to the column diameter, the developed parameter identification provided access to the cement content, determining the mechanical properties of the jet-grouted soil mass.

Based on the experience gained during the on-site application of the developed parameter identification tool, the following remarks for future practical applications are given:

- In case the mineralogy of the employed cement is not available, the developed multiphase hydration model for (blended) cement may be replaced by the single-phase hydration model. Hereby, however, the chemical affinity of the cement needs to be determined by respective calorimeter experiments.
- The deviation between the measured and numerically-obtained temperature history – especially after the maximum temperature has been reached – is an indicator for the proper determination of the thermal conductivity of the in-situ soil, thus, serving as validation for the developed microstructure-related model.

The presented mode of parameter identification can be further improved by considering the effect of moving groundwater and hydrating neighbour columns on the temperature history of the installed column. These are topics of ongoing and future research.

ACKNOWLEDGEMENTS

The authors thank Lafarge CTEC (Mannersdorf, Austria) for supplying the cement and blast-furnace slag used in the experimental program.
Financial support by PORR (Vienna, Austria) and the Austrian Research Promotion Agency Ltd. (FFG) is gratefully acknowledged.

REFERENCES

BERNARD, O., ULM, F.-J., LEMARCHAND, E. (2003), „A multiscale micromechanics-hydration model for the early-age elastic properties of cement-based materials.", Cement and Concrete research, 33, pp. 1293-1309.

BRANDSTAETTER, Ch., LACKNER, R., MANG, H.A. (2002), „Bestimmung von Materialeigenschaften zementgebundener Werkstoffe mittels Temperaturmessungen: Anwendung im Rahmen des Düsenstrahlverfahrens [Evaluation of properties of cementitious materials by means of temperature measurements: Application to jet grouting]." Bauingenieur, 77(2), pp. 51-57, in German.

WEBER, K., KOGLER, K., (2000), „Neuentwicklungen zur Qualitätskontrolle von tiefen Hochdruckinjektionssohlen”. Gruppe Geotechnik Graz, Beiträge zum 15. Christian Veder Kolloquium, volume 7, pages 131–142, Graz University of Technology, Graz, Austria, in German.

RAABE, E. W., KALTHOFF, D., STEWERING, T. (1994), „Herstellung von Dichtwänden und -sohlen mit dem Soilcreteverfahren“. Mitteilung des Instituts für Grundbau und Bodenmechanik, Braunschweig Technical University, Braunschweig, Germany, 23:89–109, in German.

P. FRAPPIN, P., MOREY, J. (2001), “Jet grouting column diameter measurement using the electric cylinder method”. Travaux: Sols et fondations, (775):55–60.

TAMURA, M., FUTAKI, M., ABE, A. (1996), “Use of non-destructive method for the evaluation of reclaimed soil column”. In Proceedings 2nd International Conference of Ground Improvement Geosystems, volume 1, pages 659–664, Tokio, Japan.

GROSS, H.-W. (1997), “Jet grouting “in situ diameter control” with hydrophone measurements”. In Proceedings British Institute of Non-destructive Testing, pages 449–456, Liverpool, U.K.

LESNIK, M. (2003), “Ermittlung der Reichweite beim Düsenstrahlverfahren unter Berücksichtigung der Herstellparameter und der Bodeneigenschaften mittels Rücklaufanalyse“, volume 17, Gruppe Geotechnik Graz, Institute for Geotechnical Engineering and Soil Mechanics, Graz University of Technology, Graz, Austria, in German.

MATRAK, L. (1999), „Jet-Grouting, die Problemlösung im Tiefbau? Entwurfsgrenzen und Verfahrensrisiken“. In Vorträge der 2. Österreichischen Geotechniktagung, pages 283–305, Vienna, Austria, ÖIAV, in German.

TKATSCHUK, S., (1997), „Theoretische Untersuchung des Eindringprozesses des Hochdruckstrahls in Lockergesteine beim Düsenstrahlinjektions-Verfahren“. In Aachener Beiträge zur Rohstofftechnik und -wirtschaft, volume 12, RWTH Aachen, Aachen, Germany, in German.

BERGSCHNEIDER, B. (2002), „Zur Reichweiten-ermittlung beim Düsenstrahlverfahren im Sand.“ In Berichte aus Bodenmechanik und Grundbau der Bergischen Universität Wuppertal, volume 24. Bergische Universität Wuppertal, Wuppertal, Germany, in German.

STEIN, J. (2002), „Untersuchungen zum Düsenstrahlverfahren in einem Halbzylinder“. In Vorträge der Baugrundtagung 2002, Spezialsitzung ”Forum junger Geotechnik-Ingenieure”, Deutsche Gesellschaft für Geotechnik, volume 23, Essen, Germany, in German.

MEINHARD, K., LACKNER, R. (2008), „ Multi-phase hydration model for prediction of hydration-heat release of blended cements”, Cement and Concrete research, 38, pp. 794-802.

SCHINDLER, A.K., FOLLIARD, K.J. (2005), „Heat of hydration models for cementitious materials”, ACI Materials Journal, 102(1):24–33.

LACKNER, R., AMON, A., LAGGER, H. (2005) “Artificial ground freezing of fully-saturated soil: Thermal problem.” Journal of Engineering Mechanics (ASCE), 131(2):211–220.

MISRA, A., BECKER, B.R., FRICKE, B.A. (1995), “A theoretical model of the thermal conductivity of idealized soil”, Journal of Heating, Ventilation, Air-Conditioning and Refrigerating Research, 1(1):1–21.

FREIESLEBEN HANSEN, P., PEDERSEN, E.J. (1977), „Måleinstrument til kontrol af betons hardening“ [Measurement device for controlling hardening of concrete]. Nordisk Betong, 1:21–25, in Norwegian.

CARLSLAW, H.S., JAEGER, J.C. (1959), “Conduction of Heat in Solids. Clarendon Press, Oxford, 2nd edition.