1. Introduction

The pressure grouting is found to be one of the most significant factors determining pullout capacity of ground anchors. Domes (2015) investigated the influence of pressure grouting in the non-cohesive soil. The impact of pressure grouting on the stress magnitudes on the anchor surface and the properties of the adjacent soil have been studied. Lee et al. (2012) analysed the influence of pressure grouting on the diameter enlargement and the pullout force of compression ground anchors. Post-grouting has been experimentally investigated by e.g. Littlejohn (1980) and Jones et al. (1980). Mišove (1984) carried out an extensive testing program on ground anchors, including excavation and detailed examination of fixed length shapes and their increased diameters. Mecsi (1997) analysed radial stress acts on the surface of the fixed length of the anchor in detail. This process is possible to modelling by numerical methods. Desai et al. (1986) analysed the interaction of a ground anchor with surrounding soil by using a 3D mathematical model and the Finite Element Method (FEM). Kim et al. (2007) investigated a load transfer mechanism from a prestressed ground anchor to sandy clay by using the ABAQUS software. Tchuchnigg (2008), Ghosh and Kumar (2015) also applied FEM techniques for ground anchor behaviour analysis. Hu and Hsu (2012) applied FLAC software to simulate the anchor-soil interaction of load tests. The anchor pullout capacity determined by the FEM needs to be validated by investigation tests. The number of investigation tests currently is very limited in the practice Duzceer et al. (2015), Ene et al. (2014), Jacquar Fondasol (2014). However, there is the relatively large amount of data available from acceptance tests (due to the requirements of standards for prestressed soil anchors, e.g. EN 1537 Execution of Special Geotechnical Work - Ground Anchors in Europe or PTI DC35.1-14: Recommendations for Prestressed Ground Anchors).
Rock and Soil Anchors in the US, an acceptance test must be carried out on every system anchor.

Statistical analyses for measured pullout resistances have been conducted previously following procedures by Hegazy (2002). The correlation the forces of applied traction versus the corresponding measured elongations of ground anchor tendon was analysed by Sciaccia et al. (2014). Shahn (2014) used the evolutionary polynomial techniques to model the pullout capacity of small ground anchors.

Hence, the authors decided to perform statistical analysis procedures with available test data and subsequently employ the obtained results as an alternative means of checking the FEM model. The combination of statistical method and FEM, including post-grouting effect, for the determining of the force-displacement curve and that of the pullout capacity of prestressed grouted ground anchors is applied in the investigation.

2. Field load test

Full-scale anchor pullout load tests (ULS) have been performed for three high-pressure grouted anchors in the experimental site in Czech Republic (Fig. 1) before the construction of a railway tunnel have been started by Velič, Mišove (2004). Tests were equipped for determining maximum pullout forces magnitudes (Fig. 1). The results from this type of test have been employed for back-analysis procedures. Sixty eight system anchors have been then used for supporting a diaphragm wall during the construction of a tunnel. The acceptance tests were set up via the same technical procedures and in the same geological conditions as those employed in the investigation tests. The characteristics of the tested anchors are summarized in Table 1.

The ground anchors have been installed in Miocene clay with very high, locally extreme, plasticity (symbol CV and CE according to the USCS). The clay was fully saturated. The index properties of Miocene clay are summarized in Table 2.

### Table 1. Tested anchor description

| Characteristic of anchor | Investigation tests | Acceptance tests |
|--------------------------|---------------------|------------------|
| Type of anchor*          | Temporary           | Temporary        |
|                          | 8xL_p,15.7–1770     | 8xL_p,15.7–1770  |
| Free anchor length L_free| 8.1 m               | 11.0 m           |
| Fixed anchor length L_fixed| 11.5 m             | 11.5 m           |
| Inclination of the borehole | 63.5°              | 22°              |

Note: * the tendon consists of eight cables with a diameter of 15.7 mm and a tensile strength of 1770 MPa.

### Table 2. Properties of Miocene clay

| Properties          | Symbol | Unit | Value |
|---------------------|--------|------|-------|
| Water content       | w      | %    | 30.6  |
| Liquid limit        | w_L    | %    | 62.0  |
| Plasticity limit    | w_P    | %    | 24.5  |
| Particle density    | p_s    | kg·m^{-3} | 2692 |
| Void ratio          | e      | –    | 0.67  |

### Fig. 1. Schematic ground plan of the test site

### Fig. 2. Schematic of the stochastic dependence anchor head displacement versus proof load

Acceptance test reports of sixty eight above mentioned system anchors have been created during the loading according to EN 1537: 2001. The displacement $u_y$ and the force $F_y$ (proof load) at the anchor head have been measured at each loading cycle. The relationship between these two variables is described via stochastic dependence, that takes multiple $u_y$ values derived from a specific probability distribution for one particular $F_y$ value (Fig. 2). The aims of the regression analysis are:

(i) to find the parameters of the linear relation of variables $u_y$ versus $F_y$ and

(ii) to confirm the correctness and assumptions of the linear regression model.

One of the assumptions of linear regression model states that the mean values $E(u_{y,1})$, $E(u_{y,2})$, $E(u_{y,3})$ lie on the line. The mean values $E(u_{y,1})$ are the means of probability distributions of the displacement $u_y$. Samples of $u_y$ come from measurement of displacement at a specific level of the force $F_y$ for every system anchor. Assessment procedures resulted that the dependence the proof load versus displacement (measured at the anchor head) is almost linear. Assumptions of the linear regression model are:

1) it is adopted a specified model, equation is correctly selected;
2) mean error term is equal to zero;
3) an error has a constant variance component (Homo-
    scedasticity condition);
4) the components of the error vector are uncorrelated;
5) the residual component has a normal distribution.
Verification of these assumptions is carried out fur-
ther in Sections 3.1–3.8. GRETL software has performed
regression analysis. The chosen significance level of all
tests was \( \alpha = 0.05 \).

3.1. Measured data analysis
The data report results of acceptance tests have been em-
ployed as the input data for the regression analysis. The
displacements have been measured for each anchor for
three load levels. Following the Anderson−Darling Good-
ness-of-Fit test (Anderson, Darling 1952, 1954), the ap-
propriate probability distribution is allocated to the dis-
placement data set measured at each load level (Table 3).
For comparison, the stress-strain diagrams of the sys-

tem anchors have been adjusted for elastic strains (corres-
sponding to the free length difference of both anchor types
(Table 1)).

3.2. Model quality evaluation
An estimation of regression parameters \( \beta_i \) has been per-
formed applying the least squares method (LSM). Sub-
sequently, the regression diagnostic has been done. It in-
cluded checking the LSM assumptions and evaluating the
quality of the \( \beta_i \) coefficients. The following Eq summarizes
the obtained final result:

\[
    u_y = -6.28 + 0.05 F_y .
\]

A graph of the determined regression model is plotted in
Fig. 3.

One must note, that an application of the linear re-
gression model includes several additional assumptions,
which should always be verified using appropriate dia-
gnostic methods.

3.3. Variance analysis
The variance analysis (ANOVA) has been carried out for
quantifying the variability of the created regression model.
The residual sum of squares (RSS) and the determination
coefficient \( R^2 \) were calculated via this analysis.

The Pearson correlation coefficient \( R \) and the stan-
dard error of the regression \( \sigma \) were also quantified. The
data of variance analysis results of the linear regression
model are presented in Table 5.

3.4. Confidence interval for regression coefficient
The \( p \)-value of the \( t \)-statistics, calculated for the \( \beta_i \) coeffi-
cients indicates the maximal possible level of trust for which
the null hypothesis \( H_0: \beta_i = 0 \) is acceptable. Confidence in-
ternals with 95% probability have been constructed for both
parameters (Table 5). The confidence ellipse serves as point
estimate of the regression parameters (Fig. 6).

3.5. Testing of LSM assumptions
There are some assumptions behind the LSM:
- regression coefficients \( \beta_i \) can take arbitrary magni-
tudes,
- the regression coefficients are linear, the additive
    model of measuring is valid.
There is an assumption for the vector of residuals \( \varepsilon \),
stating that its elements are independent. The verification
of linear regression (1) includes verification of normality
of the value \( \varepsilon \). They correspond a normal distribution with
null mean and finite variance \( E(\varepsilon^2) = \sigma^2 \) (homo-
scedasticity) (Meloun, Militký 2011).

3.6. Heteroscedasticity testing
Heteroscedasticity term states that variance is para-
meter-dependent. The White and Breusch−Pagan (Yurekli, Ku-
runc 2005) tests of null hypothesis \( H_0: \text{checking if data are homo-
scedastic} \) were carried out. The summarized results
of those tests are presented in Table 4. In analysed case the
processed data result in heteroscedasticity. Subsequently,
the LSM analysis requires modification procedures for the
next step. It is evident also from Fig. 4 that the variance in
the analysed case is variable for all data.

3.7. Testing the normality of the error distribution
The assumption of the standard distribution of errors in-

troduces the null hypothesis \( H_0: \text{the vector of errors is usu-
ally distributed and has null mean value} \). If the distribu-
tion is normal, the points on normal quantile plots of the

---

**Table 3.** Probability distribution parameters of measured displacements for the particular stressing force level

| Stressing force level, kN | Probability distribution | Mean, mm | Standard deviation, mm | Variation coefficient | Skewness | Kurtosis |
|--------------------------|--------------------------|----------|------------------------|----------------------|----------|----------|
| 444                      | Bradford                 | 21.358   | 3.980                  | 0.186                | 0.261    | −1.023   |
| 777                      | Beta                     | 41.074   | 4.468                  | 0.114                | −0.026   | −0.406   |
| 1110                     | GumbelMin. EV I          | 64.627   | 5.648                  | 0.087                | −0.589   | 0.026    |

---

**Fig. 3.** Linear regression model built using least squares method
residuals $Q-Q$ fall close to the diagonal reference line $y = x$. The S-shaped pattern of deviations indicates excessive kurtosis of residuals (Fig. 6).

The Chi-square Goodness-of-Fit test (Pearson 1900) with the final $p$-value = 0.075 has been carried out for verification of the error distribution normality. Because of the trial, one can state that the normality of the error assumption of the considered linear analysis regression model is valid. Figure 6 presents the graphical output of the Chi-square Goodness-of-Fit test (the skewness of the distribution of residuals is 0.173, and the kurtosis is 0.311).

### 3.8. Weighted Least Squares Method

It is possible to correct the estimates of the $\beta_i$ coefficients of the model by using the weighted least squares method (WLSM). Instead of finding the minimum of the function

$$RSS = \sum_{i=1}^{n} (y_i - (\beta_1 + \beta_2 x_i))^2,$$

the minimum weighted sum of squared residuals

$$RSS_w = \sum_{i=1}^{n} w_i (y_i - (\beta_1 + \beta_2 x_i))^2$$

is determined. The latter gives more efficient estimation of $\beta_i$ coefficients. Here $w_i$ is a non-negative constant, referred to as weight. The weight was determined using the heteroscedasticity-corrected linear regression model. Equation (4) defines weight $w_i$:

$$w_i = \frac{1}{e^{(u^*)}},$$

where $u^*$ are output values, obtained from the auxiliary regression function considering the dependence of square logarithms of residuum (from the model constructed using the LSM) and interpreting the variable $x_i$ and its square magnitudes

$$\log e^2 = \beta_{1,aux} + \beta_{2,aux} x_i + \beta_{3,aux} x_i^2 + e_{aux}. \quad (5)$$

### 3.9. Summary of the regression analysis and discussion of results

Two model variants describing the dependence of $u_y$ versus $F_y$ have been developed, following the procedures described above:

$$\text{LSM: } u_y = -6.28292 + 0.0504999 F_y + \varepsilon, \quad (6)$$

$$\text{WLSM: } u_y = -5.58890 + 0.0496875 F_y + \varepsilon. \quad (7)$$

It was found that the WLSM yields higher accuracy dependence of $u_y$ versus $F_y$ comparing with the one obtained by LSM having performed the regression diagnostic. The $p$-values of the $\beta_i$ coefficients are lower the ones obtained by the WLSM. The confidence intervals of the $\beta_i$ coefficients are narrower for WLSM (Table 6, Figs 7 and 8). The determined residual sum of squares RSS and Akaike Information Criterion (AIC) values are less in the case of the second model. The higher $R^2$ indicates the higher explanatory power of the WLSM (Table 5).
A branch of the stress-strain diagram for the anchor is constructed as a base for the regression model (7) and is plotted in Fig. 11.

The verification analysis of the assumptions of linear regression model confirmed the linear dependence of the proof load versus displacement. The correctness of the specified model and his assumptions of mean error term equal to zero have been met. The hypothesis of the normal distribution of residual components is also valid. The assumptions of the constant error of variance component was not met, which led to an adjustment of the LSM. The obtained results are valid for the loading intervals of performed acceptance tests.

4. Finite element analysis

The Plaxis software 2D (Brinkgreve et al. 2012) have been employed for numerical (FEM) modelling of the pullout resistance for ground anchor. An axisymmetric model, a width of 12 m and a height of 24 m has been created. The anchor has been modelled vertically positioned to achieve the condition of axisymmetry. The latter is a certain simplification compared with reality (Table 1).

4.1. Description of the 2D mathematical model

The mesh of 2D 15-nodded triangular finite elements with fourth order interpolation of displacement and twelve Gauss points for the numerical integration have been employed along anchor length. An additional mesh refinement has been set close to the fixed length of the anchor (Fig. 10). Figure 10a presents meshes (optimized and initial) and Fig. 10b the transition from the free to the fixed length. Displacement controlled loading at the anchor head has been adopted. The interface anchor body and surrounding soil have been modelled by the interface of finite elements, which is implemented in software Plaxis.

The total influence of post-grouting is done by two aspects:

(i) increasing of diameter of the fixed body of the anchor,

(ii) increasing of a radial stress caused by its volumetric expansion due to the post-grouting.

Prescribed volumetric strain values of the relevant finite elements have been assigned to introduce the effect of the post-grouting (Fig. 9).

Similar procedures have been applied in, e.g. for the mathematical modelling of compensation grouting (Kummerer 2003). The volume of elements change $\Delta V_0^e$ is a function of the given volumetric strain and that of the original volume $V_0^e$:

$$\Delta V_0^e = \varepsilon_{T,vol}V_0^e. \tag{8}$$

### Table 5. Quality comparison of estimated models

| Model   | RSS  | $F$   | $p$-value $F$ | $R^2$ | $R$    | $\hat{\sigma}$ | AIC |
|---------|------|-------|---------------|-------|--------|----------------|-----|
| LSM     | 4789 | 5159  | 7.6e–175      | 0.9515| 0.975  | 4.26           | 1523|
| WLSM    | 628  | 10161 | 3.5e–212      | 0.9748| 0.9873 | 1.55           | 984 |

### Table 6. Confidence intervals of the parameters for the LSM

| Model | Coefficient | $p$-value | 95% confidence interval          |
|-------|-------------|-----------|----------------------------------|
| LSM   | $\beta_1$–const | 1.59e–028 | $-7.2709700$ $-5.2948600$       |
|       | $\beta_2$–$F_y$ | 7.56e–175 | $0.0491156$ $0.0518843$         |
| WLSM  | $\beta_1$–const | 3.30e–099 | $-5.9092800$ $-5.2685300$       |
|       | $\beta_2$–$F_y$ | 3.52e–212 | $0.0487170$ $0.0506581$         |

Fig. 7. Confidence ellipse of regression coefficients for the LSM

Fig. 8. Confidence ellipse of regression coefficients for the WLSM

Fig. 9. Consideration of high-pressure grouting in the Finite Element Model
The components of the volumetric strain vector $\mathbf{\varepsilon}_v$ are as follow (in the case of the isotropic volumetric strain):

$$\mathbf{\varepsilon}_v = \begin{bmatrix} \varepsilon_{T,xx} & \varepsilon_{T,yy} & \varepsilon_{T,zz} & \varepsilon_{T,xy} & \varepsilon_{T,yz} & \varepsilon_{T,zx} \end{bmatrix}^T, \quad (9)$$

$$\varepsilon_{T,xx} = \varepsilon_{T,yy} = \varepsilon_{T,zz} = \frac{\varepsilon_{T,vol}}{3}, \quad (10)$$

$$\varepsilon_{T,xy} = \varepsilon_{T,yz} = \varepsilon_{T,zx} = 0. \quad (11)$$

The Mohr-Coulomb (M-C) model was chosen for simulation of soil behaviour Brinkgreve et al. (2012). Input parameters have been determined for the available geological survey; relevant technical reports have been produced by company Amberg Engineering Brno a.s. (Table 7).

During the loading of a grouted ground anchor, the grout in the fixed length have been stressed by gradual tension up to the tensile strength limit magnitude. Tensile cracks occurred during the process. When using the linear elastic model, the tensile stress magnitude is unlimited. Due to the M-C model, tensile stress limitation has also been applied to the grout material. An additional plasticity function is available (Eq 12), where $\sigma_1$ is the maximum allowable tensile stress (tensile strength) magnitude. The grouting material has strength in tension $V_T = 2000$ kPa, so:

$$f_t = \sigma_1' - \sigma_T. \quad (12)$$

4.2. Methodology of the performed analysis

According to Mišove (1984), the grouted ground anchor final diameter of anchor root varies within the range of 20 cm to 40 cm, depending on geological conditions. By this assumption, one can determine the available values of the volumetric strains, that serve as input data for the calculation procedures. A parametric study has been performed to investigate the influence of the diameter, which varied within the interval mentioned above range (Table 8, steps 2a, 2b, and 2c). In the final step 3 (Table 8), the increase in the diameter of the fixed length of the anchor ($d_{fixed} = 40$ cm) has been considered in combination with neglecting the corresponding volumetric strain being induced actually. By combining the separate initial data, one can investigate the relative influence of both factors (of diameter and that of radial stress) for anchor behaviour. The performed modelling cases are presented in Table 8.

Table 8. Methodology of the performed analysis

| ID | $d_{fixed}$ mm | Volumetric strain | Description |
|----|----------------|-------------------|-------------|
| 1  | 156            | No                | Only gravity (tremie) grouted |
| 2a | 200            | Yes               | Calculation with anchor root diameter expansion to $d = 20$ cm with corresponding volumetric strain |
| 2b | 300            | Yes               | Calculation with anchor root diameter expansion to $d = 30$ cm with corresponding volumetric strain |
| 2c | 400            | Yes               | Calculation with anchor root diameter expansion to $d = 40$ cm with corresponding volumetric strain |
| 3  | 400            | No                | Calculation with anchor root diameter expansion to $d = 40$ cm without the inclusion of corresponding volumetric strain |
4.3. Summary of the FEM analysis and discussion of results

Force versus deformation diagrams has been plotted for each case (Figs 11 and 12). Besides the FEM calculation results, the regression dependence found using the WLSM (Chapter 3) and the measurements from three investigation load tests (anchors K1 to K3) have been added to Figs 12 and 13.

The alternative analysis case ID 1, which ignores the post-grouting influence, significantly underestimates the anchor pullout capacity. In the case ID 2a, the theoretical pullout capacity has been reached prematurely. For case ID 2b a better prediction has been obtained comparing with that of for ID 2a case, though the calculated pullout capacity was still lower than the measured capacity by experiments one. For the last considered alternative ID 2c, the satisfactory agreement of measured versus computed displacements has been reached even at the highest load increment stages. One must emphasize that final state has not been reached during the investigation test despite a substantial increase in anchor permanent displacements. The latter situation conforms to the ID 2c prediction. The linear regression provides a sufficient match with the measured and computed displacements for several first loading stages (lower than 500 kN magnitude). For larger load magnitude stages, the regression analysis underestimates the anchor head displacement. The latter finding confirms the significant contribution of permanent soil plastic deformations developed on the soil – anchor interface.

The limit state in case ID 3 has been achieved foremost comparing with remaining simulation cases (Fig. 12); the calculated ultimate (pullout) force magnitude was even lowered the one determined by ID 2b one. The larger computed ultimate force magnitude has been obtained for the case ID 2c. In this case, the factor of effective radial stress increment, and consequently, the shear strength increment has been taken into account. The distributions of the mobilized shear stress and the radial stress in the horizontal cut at the middle of the fixed length for the final stage are presented in Fig. 13.

Mobilised relative shear stress distribution around the fixed anchor length that of for vertical displacement are plotted for case ID 2c (Fig. 14).

5. Conclusions

The paper summarized a set of pullout testing data for ground anchors in concern with performed numerical simulations of appropriate behaviour. Comparative analysis of testing and simulation results yield proper linear response for anchor soil base versus applied load. The paper focused on the prediction of force-displacement curves, rather than on the determination of the pullout capacity of ground anchors. Depending on the results of this study, the following conclusions are drawn:

1. Statistical analysis – the process of constructing the force-displacement curves of anchors from a set of acceptance tests via the use of the Weighted Least Square Method.
with an appropriately chosen weighted coefficient is described. The Weighted Least Square Method has been selected as the optimal method for this investigation via the regression diagnostic (of the qualitative evaluating criteria for two alternative models). When compared to the curve from the investigation test, the statistically determined force-displacement curve diverges from the certain prestressing force value. This result has been obtained despite the fact that determination coefficient magnitudes are large. The following result is conditioned by an application of the linear trend in the Weighted Least Square Method, regression model. This model is unconcerned with the nonlinear strain increase at the anchor bond (the permanent/plastic part of the displacement). The use of the linear trend is nevertheless justified because the force-displacement curve is almost linear in the range of considered load variation bounds, which are usually applied for acceptance tests. The importance of the constructed linear regression dependence lies in the determination of the lower control limit of the displacement values at the anchor head for the evaluation of the developed numerical model.

2. Numerical analysis – the Finite Element Method techniques have been employed to predict the force-displacement behaviour of the grouted ground anchor. The Finite Element Method analysis focused on considering the impact of high-pressure grouting. Soil-structure interaction has been simulated by using zero thickness interface elements. The Mohr-Coulomb constitutive model has been employed both for the surrounding soil and of the grout material with the aim to limit grout tensile strength.

The final analysis using the Finite Element Method proved that high-pressure grouting is the significant influence predetermining behaviour of the anchor (both on the shape of the force-displacement curve and the ultimate carrying capacity). Five different analysis cases have been performed. The high-pressure grouting has been simulated via an increasing the diameter of the ground anchor body and by the additional application of volumetric strain to the relevant finite elements. The best fit has been reached for the simulation with a diameter expansion to 40 cm and with the corresponding volumetric strain development. The reasonable match has been achieved when comparing the force-displacement curves of the ground anchor, constructed by using the mathematical model described above and the load-displacement curve obtained from the investigation tests.

The presented study confirmed that considering the influence of high-pressure grouting via the Finite Element Method techniques and the combination of the diameter increment for the fixed length of the anchor and that of the corresponding volumetric strain introduction ensures the important increase of accuracy for prediction of the load-displacement curve and subsequently for determining the proper ultimate pullout capacity magnitude.

One must emphasize that these proposed models have been used for the particular type of anchors, similar to analysed in paper ones, namely: prestressed grouted ground anchors with steel strand tendon placed in clays of very high plasticity. The latter limitation is conditioned by the fact that relative anchor-soil stiffness significantly influences the behaviour of structures like ground anchors. For different as to analysed conditions, namely for various type of pressure grouting, confining stress, soil type, and anchor type, the developed analysis models, have to be appropriately adjusted.

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