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Post-Grouting Behaviour of Ground Anchors in Dense Cohesionless Soils: Field Observations and Theoretical Insights

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Abstract

Post-grouting is a widely adopted technique in ground anchor systems intended to enhance grout–soil interaction through pressure-induced mechanisms. It is generally assumed to improve load transfer by inducing fissures in the initially set grout, expanding the grout body, and enlarging the fixed-length diameter. This study investigates grout behaviour under post-grouting pressure in dense cohesionless soils using data from 870 post-grouted anchors installed at nine construction sites in Budapest, Hungary, with similar ground conditions. Grouting volumes were statistically analysed, focusing on the correlation between grouting volumes and their relationship to soil properties particularly grain size distribution. Theoretical grout body diameters were estimated using expansion and infiltration models. Load–displacement test data were used to back calculate apparent free lengths and infer fixed lengths, which were compared with literature values. Two post-grouted test anchors were excavated. Both showed uniform diameters matching the original borehole, with no signs of grout body enlargement. However, large irregular grout masses were found in permeable zones, suggesting material migration toward weaker paths under pressure. These findings indicate that in medium dense to dense sands, post-grouting enhances performance primarily through local soil densification not geometric expansion, highlighting the need to revise traditional assumptions regarding grout behaviour in such conditions.

Keywords

ground anchors, post grouting, anchor performance, cohesionless soil

1 Introduction

Ground anchors are essential structural elements in geotechnical engineering, widely used to stabilize retaining structures, deep excavations, and slopes. Their use in Europe became widespread after 1958, when they were introduced as a practical solution to the spatial constraints of urban excavations [1]. Early design practices relied on classical soil mechanics, particularly Coulomb's friction model, to estimate anchor pull-out capacity. However, field observations consistently demonstrated that actual anchor performance exceeded theoretical predictions, suggesting that traditional models underestimated the behaviour of grouted anchors. This discrepancy prompted a wave of research during the 1970s and 1980s, e.g. [2–7] explored load transfer mechanisms through a series of field investigations, whereas studies such as [8–12] focused on assessing anchor bearing capacities and refining design methodologies, thereby laying the foundation for subsequent research developments.

A prestressed grouted ground anchor consists of a tensioned steel tendon embedded in soil or rock, designed to transfer structural loads to a stable ground mass [13]. The tendon is surrounded by grout, which serves two distinct functions along the anchor:

- In the free length, the grout acts as a corrosion protection barrier and prevents load transfer by separating the tendon from the surrounding soil.
- In the fixed length, the grout bonds the tendon to the soil or rock, enabling effective load transfer. [14].

Since the mid-1990s, numerous deep excavation projects have been completed across Budapest, these projects typically utilize 14–23 m long, pre-stressed, injected temporary anchors installed within a gravelly sedimentary layer [15], including those examined in this study, ground anchor grouting is performed in two stages. The first stage

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takes place immediately after drilling the borehole, during which grout is introduced into the hole under gravity. Once this initial grout has set, a second stage called pressure grouting, or post-grouting is applied to enhance the bond between the anchor and the surrounding soil [16, 17].

The effectiveness of post-grouting in dense cohesionless soils remains a subject of ongoing debate, many studies took place analysing such and explaining such behaviour like [18–25]. In such soil, high relative density can significantly restrict grout infiltration and limit body expansion. Analytical models that attempt to account for the effects of post-grouting on ground anchor performance typically assume uniform radial displacement along the grout–soil interface [26]. However, these assumptions are difficult to verify under real field conditions, where anchors are embedded several meters below ground level. Furthermore, existing theoretical models don't accurately account for key installation parameters such as grout volume, injection pressure, and soil permeability. As a result, major design standards such as Eurocode 7 emphasize the need for site-specific testing to validate anchor performance [27].

In the current study, a previously undocumented grouting phase referred to as the "Polish method" was implemented by the contractor (HBM Kft.) as indicated by Table 1 and is introduced here for the first time in the literature, and should be differentiated than what is used in bored piles where a base preloading is introduced by grouting and introduced by [28].

This study aims to bridge the gap between the theoretically assumed models and real field performance by analysing data from 870 post-grouted ground anchors installed across nine different construction sites in Budapest. Despite site variability, the anchors share nearly identical soil conditions of gravelly sand soils. Grouting volumes from gravity, Polish and Post-grouting phases were compiled and statistically analysed. Correlations with grain size distributions were explored to understand the influence of soil properties on grout absorption. Theoretical grout body diameters were calculated using both body expansion and infiltration models and then compared with direct measurements from excavated anchors. Additionally, load–displacement test results were analysed to assess apparent free lengths and evaluate it with the assumed ones and the corresponding design capacities.

Field observations revealed little to no visible expansion of the grout body, contradicting common design assumptions. The measured grout diameters closely matched the borehole dimensions (~14 cm). Minor grout infiltration was observed only in isolated zones, typically in the form of large, irregularly shaped masses, suggesting that the dominant mechanism is soil densification rather than radial displacement and that the material grouted is not behaving as intended. These findings support the need to refine current post-grouting design assumptions and highlight the importance of incorporating efficiency correction factors into analytical models. The study offers practical insights into the behaviour of post-grouted anchors in dense sands and contributes to a clearer understanding of grout–soil interaction mechanisms.

2 Research program

The research program originated from the observation of a discrepancy between the design grout mortar quantities and the in-situ recorded injection volumes, despite the

Table 1 Summary of the provided data about the grouted ground anchors

Site	No. of anchors studied	Polish method	Diameter of drilled borehole (m)	Free length (m)	Fixed length (m)	Top of fixed length (m)*	Bottom of fixed length (m)*
Taksony	58	N/P	0.139	9.0 - 10.0	7.0	5.0, 5.4	7.2
Szervita	80	NA	0.133	14	7.0	7.4	9.2
Pillar	118	NA	0.133	14.5	7.0	7.7	10.1
SLH	18	P	0.152	10.5, 6.0	7.0, 8.0	10.24	13.00
City Pearl	45	P	0.152	6.0	10.0	5.95	10.05
CP2	46	P	0.152	6.0–11.0	8.0, 10.0	6.0–7.5	8.60–11.0
CP3	56	P	0.152	6.0–11.0	10,9.0	6.5–8.0	8.5, 13.4
Duna Pearl	102	P	0.152	9.0	6.0	7.55	10.0
BOA	108	P	0.152	9.0,12.0	9.0–12.0	9.80–10.0	14.0, 15.30
BOH	128	P	0.152	8.0–12.0	6.0–8.0	8.75	12.50
MBH	111	P	0.133	7.0	10.0	6.5	10.75

*Relative to ground level, NA: Not Applied, P: Applied.

anchors demonstrating satisfactory performance in pullout tests. To investigate this, two anchors were excavated after installation and post-grouting one located at the Pillar project and the other at the Taksony utca project in Budapest, Hungary, each founded in soils with properties summarized in Table 1. Building on these initial field observations, the program was subsequently structured to evaluate the performance of post-grouted ground anchors in dense cohesionless soils through a combined approach of grout volume analysis and theoretical modelling. The central aim was to determine whether the widely assumed mechanisms of body expansion or grout infiltration adequately describe grout behavior under field conditions, and to explore the implications of these mechanisms for anchor design, particularly considering the observed discrepancies.

Data collection was conducted in collaboration with the local contractor HBM Kft. and encompassed real-time grouting volume records for gravity, Polish, and post-grouting phases, results of proof and performance pullout tests, detailed anchor geometry, and site-specific soil investigation reports. Tables 1 and 2 provide an overview of the anchor geometries and installation conditions at each site, along with representative ranges of grain size distributions derived from borehole samples reported in the investigation documents.

2.1 Field observations

As illustrated in Figs. 1–4, the excavated anchors exhibited a uniform diameter along the entire grouted section, with no evidence of fissuring or disruption of the initially placed gravity grout. This observation challenges the common design assumption that post-grouting enhances anchor capacity through radial enlargement of the grout body. Instead, large and irregularly shaped masses of

Fig. 1 Excavated anchor body at Taksony Street project

Fig. 2 excavated anchor body showing irregular shape masses at Pillar project

Table 2 The observed grain size distribution ranges from borehole samples taken around the anchors

Site	D1%	D2%	D3%	D4%	D5%	D6%	D7%	C_u	C_c
Taksony	3–6	7–74	20–38	0–19	0–16	0–20	0–5	3–11.5	0.3–1.2
Szervita	0–1	4–8	21–29	20–24	28–31	10–24	0	9.3–12.4	0.5–0.6
Pillar	6	9	40	10	15	20	0	8.35	0.7
SLH	18	66	15	0–1	0	0	0	3.3	1.2–1.7
City Pearl	0	1	12–62	2–39	10–42	9–34	0–14	2.4–22.7	0.3–1.9
BOH	9	9–17	37	12–18	20–25	2–5	0	7–10	1.1–1.5

Where:
D1: the percentage of particles with sizes smaller than 0.063 mm;
D2: the percentage of particles with sizes between 0.063 mm and 0.20 mm (Fine sand);
D3: the percentage of particles with sizes between 0.20 mm and 0.63 mm (Medium sand);
D4: the percentage of particles with sizes between 0.63 mm and 2.0 mm (Coarse sand);
D5: the percentage of particles with sizes between 2.0 mm and 6.30 mm (Fine gravel);
D6: the percentage of particles with sizes between 6.3 mm and 20.0 mm (Medium gravel);
D7: the percentage of particles with sizes larger than 20.0 mm (Coarse gravel).

Fig. 3 Irregularly shaped masses found near the grouted anchors body

Fig. 4 Diameter of excavated anchor at Pillar project

hardened grout were identified in isolated zones adjacent to the anchor shaft.

This suggests that the post-grouted material, rather than displacing soil or uniformly infiltrating the surrounding matrix, migrated under pressure into localized zones of lower resistance likely corresponding to more permeable or weaker soil layers. Importantly, this behaviour does not support either the body expansion theory which assumes radial displacement of the surrounding soil nor the infiltration theory, which assumes uniform penetration of grout into the pore spaces of the soil. Instead, the evidence indicates that post-grouting did not contribute to any meaningful diameter enlargement of the grout body. Under pressure, the grout simply followed stress paths toward weaker points in the soil, where it accumulated without enhancing the structural diameter of the fixed length.

Consequently, a comprehensive grout volume analysis was undertaken to evaluate the behavior and distribution of the injected material.

2.2 Volume analysis

During anchor installation, three distinct grouting phases were documented: gravity grouting, the Polish intermediate method, and post-grouting. The gravity volume refers to the amount of grout placed in the borehole immediately after drilling using the tremie method. In this phase, grout is not pressurized but instead flows under its own weight, hence the term "gravity".

An intermediate Polish method was applied at six of the nine sites, performed on the same day as gravity grouting. Using a double-casing drilling system, the outer casing was partially withdrawn while leaving a short section in place near the anchor. Grouting pipes were then inserted, and grout was injected under moderate pressure (up to 10 bar) to fill the annular void created by casing removal. The objective of this step was not soil stabilization but compensation for pressure loss and restoration of internal borehole pressure conditions. This distinguishes the Polish method from post-grouting in both its timing and its function.

In contrast, the post-grouting phase consisted of delayed, high-pressure injections performed 24–48 hours after the initial grouting. Post-grouting was carried out through sealed grout pipes installed alongside the tendon, equipped with manchette valves positioned along the fixed anchor length. These valves act as controlled openings, enabling additional grout to be injected under pressure into the already-set mortar [29]. The process is designed to fracture the initial grout body and displace it outward into the surrounding soil, thereby enlarging the effective diameter of the fixed length and enhancing load transfer [13].

2.2.1 Descriptive analysis

Descriptive and frequency analyses were conducted on the recorded grout volumes to identify patterns, trends, and anomalies within the dataset. Post-grouting volumes were statistically compared with gravity grouting volumes and grout volumes from the newly implemented polish method to evaluate consistency and variability across the anchors.

Fig. 5 illustrates the distribution of gravity grouting volumes, expressed as a percentage of the designed target volume, reveals a generally consistent execution of the grouting process across the analysed anchors. Most anchors approximately 70% were grouted within the range of 70% to 110% of the intended volume, with a clear concentration around the 80–100% interval. This indicates a strong alignment with design expectations, reflecting effective control over grouting quantities during field execution. Notably, the occurrence of over-grouted anchors (above 110%)

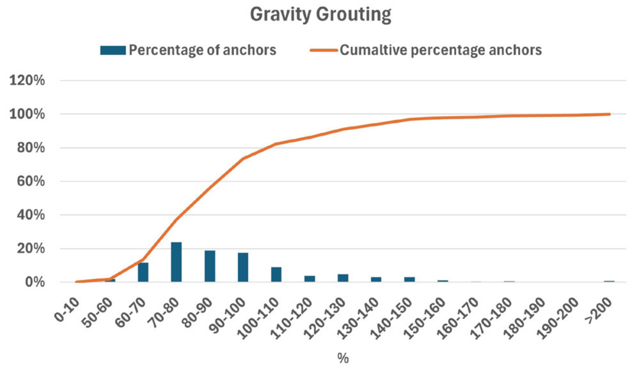

Fig. 5 Distribution of gravity grouting volumes as a percentage of the expected value

and under-grouted anchors (below 70%) was limited, and volumes exceeding 130% were rare. The cumulative curve further supports this observation, showing that over 90% of the anchors remained below 120–130% of the target volume. These results suggest minimal material waste and affirm that the gravity grouting process being driven by the natural flow of grout into drilled boreholes produced consistent outcomes. Variations observed can be reasonably attributed to typical construction uncertainties, such as slight differences in borehole dimensions, material behaviour, or site-specific conditions.

Fig. 6 illustrates the distribution of grouting volumes associated with the Polish method (Lengyel grouting), which shows a more scattered pattern compared with gravity grouting. Approximately 60% of the anchors received between 100% and 150% of the design volume, while a considerable number exceeded this range, with some reaching up to 200%. This variability reflects the nature of the method, in which grout is injected under moderate pressure after partial casing withdrawal to fill the annular void left behind. The process inherently introduces variability depending on soil conditions and execution precision.

An estimated 65% of the grout injected during this phase may be considered non-contributory to load transfer, as it primarily occupies the void created by casing removal. This explains the considerable excess of material observed in the field compared with calculated design volumes, which stems from differences between theoretical grout demand and the actual application procedure. The boreholes were drilled using a double-casing system to accommodate sandy gravel soils, with casing sections typically 2 m in length. Following gravity grouting, the outer casing was withdrawn, leaving a 0.5 m segment in place near the anchor body and exposing 1.5 m. At this point, grouting pipes were introduced to prevent injection points from being positioned too close to the retaining wall surface. Pressurized grout, applied at pressures of up to 10 bar, then filled the annular void while simultaneously exerting pressure on the gravity-placed grout. This procedure compensated for localized loosening caused by casing withdrawal and effectively re-established pressure equilibrium in the borehole. The resulting volume difference defined by the gap between the casing and the borehole wall was thus filled under pressure, distinguishing this method from both conventional gravity grouting and delayed post-grouting.

Despite the high variability, the results remain consistent with the operational objective of the Polish method: to restore pressure conditions during casing removal. The anomalies observed can be attributed to typical field uncertainties, including variations in casing withdrawal depth and irregularities in borehole geometry.

Fig. 7 illustrates the distribution of post-grouting volumes for the analysed anchors, expressed as a percentage of the expected design volume. The results indicate that most anchors received less than 100% of the intended post-grout quantity, with the highest concentration falling within the 90–100% range. Interestingly, the distribution

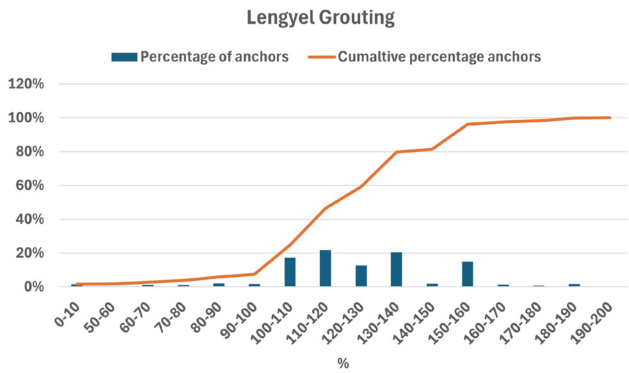

Fig. 6 Distribution of Polish method grouting volumes as a percentage of the expected value

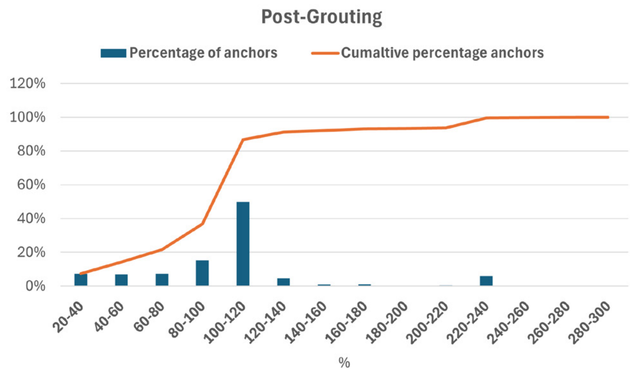

Fig. 7 Distribution of Post grouted volumes as a percentage of the expected value

shows a relatively uniform spread across lower percentage intervals approximately 5% of anchors were post-grouted within each 10% range (e.g., 0–10%, 10–20%, 20–30%, and so on), up to the 80–90% range. This steady distribution across the lower end of the spectrum suggests that limited grout intake was not isolated but rather consistently observed across the dataset. The cumulative curve further confirms that over 90% of the anchors were grouted with volumes at or below the design target. These findings imply limited grout penetration or body expansion during the post-grouting phase, likely due to the dense and low-permeability nature of the surrounding soil.

2.2.2 Regression analysis

To investigate potential soil–grout interactions, regression analyses were carried out between grout volumes and key grain size distribution parameters.

The aim of this phase was to assess whether a relationship could be established between the different grouted volumes and to examine whether grout uptake could be influenced or predicted by in-situ soil properties. Pearson's correlation test was employed to evaluate linear relationships, respectively, providing a comprehensive understanding of the extent to which soil characteristics may affect grout behaviour.

Correlation quantifies the degree and direction of association between two variables. It reflects the strength and nature of their linear relationship but does not imply causation. It is important to note that correlation coefficients are sensitive to outliers, which can significantly influence the results. Pearson's product-moment according to [30] is expressed as:

$$r = \frac{\Sigma XY}{\sqrt{\left(\Sigma X^2\right)\left(\Sigma Y^2\right)}} \quad (1)$$

r = Pearson's coefficient of correlation

X = Value of the deviations of coordinate x from $\bar{x}$ (their mean value). That is, $X = x - \bar{x}$

Y = Value of the deviations of co-ordinate y from $\bar{y}$ (their mean value). That is, $Y = y - \bar{y}$

The values of Pearson's correlation coefficient r range between +1 and −1 and indicate both the nature and strength of the linear relationship between two variables. A positive value of r signifies a direct correlation, while a negative value indicates an inverse correlation. In terms of strength, values between ±0.90 and ±1.00 represent a very strong correlation; ±0.70 to ±0.89 indicate a strong correlation; ±0.40 to ±0.69 indicate a moderate correlation; ±0.10 to ±0.39 indicate a weak correlation; and values near 0 suggest no linear correlation.

To assess the statistical significance of these correlations, p-value testing was conducted alongside the calculation of Pearson's coefficient. The p-value represents the probability that the observed correlation occurred by chance under the null hypothesis of no association. A commonly accepted threshold for statistical significance is $p < 0.05$, meaning there is less than a 5% chance that the result is due to random variation. If the p-value falls below this threshold, the correlation is considered statistically significant, indicating a meaningful linear relationship [31].

Correlation between grout volumes

While statistically significant, the observed correlations between the grouting phase gravity, Polish, and post-grouting remain weak and must be interpreted with caution. In cases where no Polish method was used, a weak negative correlation ($r = -0.25$, $p = 6.7 \times 10^{-5}$) was found between gravity and post-grouting volumes, suggesting that anchors receiving higher gravity grout tended to exhibit reduced ability to intake post grout. This trend may reflect physical limitations in the borehole's capacity to accept additional grout once initially filled, or early grout setting reducing permeability assuming it takes place. Conversely, where the Polish method was introduced as an intermediate pressure compensation phase, a weak-to-moderate positive correlation was observed between gravity and post grout volumes ($r = 0.31$, $p = 4.61 \times 10^{-15}$), with further correlations indicating that anchors receiving higher gravity grout also accepted more Polish grout ($r = 0.114$, $p = 0.004$), and Polish volumes correlated with post-grouting volumes ($r = 0.249$, $p = 9.6 \times 10^{-9}$). While one should expect that with the Polish method in between the two phases (gravity and post grout are expected to have a different relation. These findings can be explained with those certain anchors due to favorable local soil conditions, borehole stability, or construction execution were generally more receptive to all grouting phases. Therefore, correlation patterns are likely driven more by constructability factors than by a functional dependency between grouting phases. As such, while trends exist, they do not offer strong predictive power and should not be interpreted as evidence of procedural causality.

Correlation between volumes and grain size distribution of soil

Tables 3 and 4 present the relationship between the grouted volumes recorded on site both for gravity grouting and post-grouting and the grain size distribution parameters obtained from the soil investigation reports. These parameters are based on laboratory test results conducted on soil specimens collected from boreholes located near the anchors, specifically at depths corresponding to the grout body zones. The aim is to evaluate whether soil gradation characteristics have any measurable influence on grout uptake during either grouting phase.

The results presented in Table 3 and Table 4 demonstrate that soil gradation characteristics have a measurable influence on grout intake during both gravity and post-grouting phases. In the gravity grouting phase shown in Table 3, coarse sand (D4) and fine gravel (D5) exhibited moderate poitive correlations with grout volumes (r = 0.39 and r = 0.34, respectively), both highly significant ($p < 10^{-16}$). This suggests that in soils with dominant coarse fractions, gravity grout flows more readily into the borehole, likely due to larger and more interconnected pore spaces. On the other hand, fine sand (D2) and medium sand (D3) displayed weak to negligible correlations, and coarse gravel (D7) also had a low negative correlation (r = −0.13), indicating a less consistent effect on grout intake. In contrast, post-grouting volumes as shown in Table 4 showed stronger and more consistent trends. Negative correlations were observed with medium sand (D3, r = −0.37) and coarse sand (D4, r = −0.45), both highly significant ($p < 10^{-19}$), suggesting that denser sand matrices may reduce the effectiveness of pressurized grout injection, possibly due to lower permeability and reduced potential for grout expansion. Meanwhile, medium gravel (D6) and coarse gravel (D7) showed positive but weak correlations (r = 0.23 and r = 0.14), suggesting that coarser fractions support higher grout uptake under pressure. Additionally, the uniformity coefficient (C_u) and curvature coefficient (C_c) support this interpretation. C_u values correlate positively with post-grouting volumes (r = 0.43, p = 1.2E-26), indicating that a wider range of particle sizes especially with a significant coarse component may provide better pathways for grout migration. However, C_c shows a weaker correlation (r = 0.38), suggesting that while grain shape and gradation curve curvature contribute, the overall range and presence of fines play a larger role. These patterns support the interpretation that soils with higher fines content (e.g., higher D2, lower C_u) are more likely to have voids filled with fine particles, reducing available space for grout migration and thereby limiting intake. Conversely, when coarse grains dominate and fines are limited, grout volumes tend to increase due to greater void connectivity and injection potential.

2.2.3 Theoretical modelling of grout body expansion

In this section, the data provided for the in situ concreting volumes of the ground anchors were employed to calculate the expected in situ diameter of the grouted bodies based on two theoretical approaches. The first approach is the body expansion theory, which assumes that the post-grouting process leads to mechanical expansion of the grout body by displacing the surrounding soil, thereby increasing the anchor's diameter after fracturing the initial grout body formed by gravity grouting. The second approach is the infiltration theory, which assumes that the post-grouted material cracks the original grout body but does not displace the soil; instead, the grout infiltrates into the surrounding pore spaces without causing bulk soil movement. Using these two methods, theoretical diameters were calculated for each anchor and compared with their corresponding in situ measured values. Under the body Expansion model, predicted diameters ranged from 0.11 m to 0.45 m, with an average of 0.27 m and a standard deviation of 0.075 m. This suggests moderate variation within a relatively narrow band of expansion, consistent with the assumption that grout primarily displaces the surrounding soil through radial pressure. In contrast, the Infiltration model yielded larger predicted diameters, ranging from 0.17 m to 0.71 m, with a higher average value of 0.4 m and a greater standard deviation of 0.12 m. These results reflect the assumption that grout spreads into the available pore

Table 3 Pearson correlation coefficient for gravity grout

Volume Type/Grain size	D1	D2	D3	D4	D5	D6	D7	C_u	C_c
Pearson correlation (r)	−0.22	−0.25	−0.01	0.39	0.34	0.10	−0.13	−0.05	−0.11
P-value	1.2E-07	2.1E-09	7.9E-01	2.1E-22	6.4E-17	2.3E-02	1.6E-03	2.5E-01	8.5E-03

Table 4 Pearson correlation coefficient for post grout

Volume Type/Grain size	D1	D2	D3	D4	D5	D6	D7	C_u	C_c
Pearson correlation (r)	0.65	−0.01	−0.37	−0.45	−0.04	0.23	0.14	0.43	0.38
P-value	4.3E-68	8.9E-01	2.3E-19	2.2E-28	2.9E-01	2.5E-08	9.3E-04	1.2E-26	5.2E-20

space, leading to a wider range of potential outcomes, particularly in soils with varying porosity or permeability.

These results highlight the contrast in grout behaviour predicted by each model. While the body expansion theory reflects a more confined mechanical response, the infiltration theory captures the broader spread of grout under conditions where pore-scale infiltration dominates. Comparing both sets of predictions with the actual field measurements enables a more informed interpretation of grout performance and anchor behaviour under post-grouting conditions. It is important to note that the design of the studied anchors assumed that post-grouting would enlarge the grout body diameter to approximately 0.60 m. However, even when back-calculating from the provided grouting data, the predicted diameters fell well short of this value. This discrepancy justified the decision to excavate selected anchors to directly observe their post-grouting geometry particularly since all anchors had passed their respective acceptance tests.

2.3 Estimating fixed length from proof and performance loading tests

Using the load–displacement curves obtained from the proof and performance tests which is generally follow the French recommendations for ground anchors [17] for each anchor, the displacement corresponding to the design load was recorded. Based on this displacement, the apparent free length of each anchor was back calculated using the elastic elongation equation:

$$L_a = \frac{A_t E_s \delta_e}{P} \times \frac{1}{10^9} \quad (2)$$

A_t (mm^2) is the cross-sectional area of the prestressing steel, E_s (kPa) is the Young's modulus of the prestressing steel, δ_e (mm)is the elastic movement at the test load, and P (kN) is equal to the test load minus the alignment load.

The assumption of a linear elastic behaviour of the steel tendon underload was used to estimate the effective fixed length of each anchor by subtracting the calculated free length from the total borehole depth. These values were then plotted against the corresponding design loads and compared with the original design chart proposed by [4], which defines upper and lower boundary curves for dense and medium-dense non-cohesive soils. As shown in Fig. 8, most of the field data points fall within these boundaries, indicating strong agreement between measured performance and the expected design behaviour. Although some scatter is observed – likely due to local soil variability or construction tolerances – the results confirm the reliability of using elastic elongation-based back-calculation for estimating fixed lengths and support the continued use of the original empirical design method for preliminary evaluations in similar ground conditions.

Table 5 Calculated diameters based on both theories using grouting volume data

Theory	Minimum	Maximum	Average	Standard deviation
Body expansion	0.11 m	0.45 m	0.265 m	0.075 m
Infiltration	0.17 m	0.71 m	0.4 m	0.12 m

3 Conclusions

This study investigated the behavior of post-grouted ground anchors in dense cohesionless soils through statistical evaluation, theoretical modelling, load-displacement testing, and direct excavation. Key findings are:

- Anchor performance was not directly
- related to the injected grout volumes.
- Correlations between gravity, Polish, and post-grouting phases were consistently weak, even when statistically significant, demonstrating that grout volume alone cannot reliably predict anchor capacity.
- The incorporation of the Polish method as an intermediate pressure compensation step highlighted procedural effects on grout intake. Although it altered the relationships between grouting phases, the observed correlations remained weak, suggesting that its role is primarily to stabilize the borehole after casing withdrawal and maintain internal pressure, rather than to improve load transfer capacity.

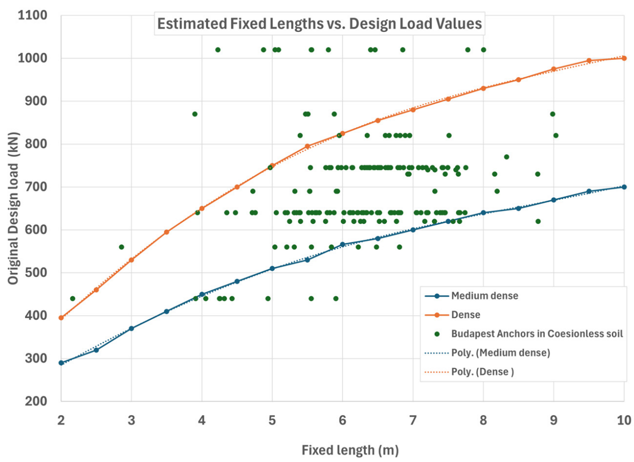

Fig. 8 Comparison between estimated fixed lengths from proof and performance tests and the original design load chart proposed by [4]

- Grain size analysis further indicated that coarse fractions were generally associated with higher grout volumes, while finer particles restricted intake, though soil gradation effects remained secondary to variability in field execution.
- Theoretical predictions based on body expansion and infiltration models estimated grout body diameters far larger than those observed in practice.
- Excavated anchors showed diameters nearly identical to the original borehole, with no evidence of systematic radial expansion or fracturing of the initial gravity grout. Instead, localized accumulations of grout were identified in more permeable soil layers, reflecting migration along preferential flow paths.

Overall, the results suggest that in Budapest Gravely sand, post-grouting improves anchor performance mainly through localized soil densification and pressure effects rather than by enlarging the grout body. These conclusions emphasize the need to revisit current design assumptions, which are often based on idealized models of body expansion or grout propagation, and to incorporate empirical efficiency factors and field-based validation through site specific testing.

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