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EXPERIMENTAL CHARACTERIZATION OF JET GROUT USING DIGITAL IMAGE CORRELATION TECHNIQUE

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Abstract: Jet grouting is a well-established and versatile ground improvement technique widely used to enhance the mechanical performance of weak or heterogeneous soils. It has proven effective across diverse soil conditions, motivating further experimental and parametric characterization. While sustainability goals have encouraged the use of eco-friendly additives, cement-based mixtures remain predominant due to their adaptability and reliable performance. Despite its widespread application, the mechanical behavior and failure mechanisms of in-situ jet grout columns have received limited experimental investigation, especially under uniaxial loading. This study explores the potential of Digital Image Correlation (DIC) as an advanced, non-contact optical technique for measurement of full-field displacements and strains on the surface of an object and fracture behavior during mechanical testing. Although DIC is more or less regularly used for concrete, natural rock, and composites, its application to jet grouting materials is rarely reported. Core samples were obtained from an active construction site, specifically from a coarse-grained soil layer, and were subjected to laboratory testing to evaluate key mechanical parameters such as: compressive strength, stiffness, and stiffness-to-strength ratios. The experimental approach aims to assess material variability and evaluate the relevance of standard modulus-based design parameters. The findings contribute to a deeper understanding of jet grout behavior and demonstrate the value of DIC as a complementary method for the performance assessment and design verification of jet grouted systems in coarse-grained soils.

Keywords: jet grout, digital image correlation, uniaxial strength, modulus

1. INTRODUCTION

Soil improvement techniques have become an essential component of modern geotechnical engineering, particularly in the construction of foundations, excavation support systems, and seepage control barriers in challenging ground conditions (Croce et al., 2014; Nicholson, 2015). Among these techniques, jet grouting has emerged as one of the most versatile and widely applied methods, thanks to its capacity to improve soil properties and address a broad range of geotechnical challenges (Croce et al., 2014; Tinoco et al., 2011). Despite its extensive use, the technology's complex behavior and associated uncertainties often remain poorly understood by many practitioners, leading to both underutilization and misapplication (Toraldo et al., 2018).

Jet grouting is an in-situ mixing process in which a cement-based grout is injected into the soil at high pressure (300–600 bars) through small-diameter nozzles located at the end of a drill string (Croce et al., 2014; Nicholson, 2015; Wang et al., 2013; Tinoco et al., 2011; Akin, 2016). The high-velocity jet cuts and erodes the soil, simultaneously mixing it with grout to create soil-cement columns with improved mechanical and hydraulic

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properties (Wang et al., 2013; Nicholson, 2015; Croce et al., 2014). Depending on the system used, jet grouting is generally classified into single-fluid, double-fluid, and triple-fluid systems, each varying in terms of erosion efficiency and mixing capabilities (Croce & Flora, 2000; Croce et al., 2014; Tinoco et al., 2011).

Despite its extensive application in practice, the mechanical behavior and failure mechanisms of jet-grouted columns have been the subject of limited experimental investigation. The behavior of jet-grouted soilcrete is highly dependent on numerous variables, including soil type, operational parameters (e.g., injection pressure, nozzle diameter, grout composition), and environmental conditions (Correia et al., 2009; Toraldo et al., 2018; Akin, 2016). Previous studies have demonstrated that the physical and mechanical properties of jet-grouted columns, such as: uniaxial compressive strength, unit weight, porosity, and stiffness, are significantly affected by both the granulometric characteristics of the treated soil and the jet grouting process parameters (Croce & Flora, 2000; Akin, 2016). A particularly important aspect of jet grouting is the variability in the strength and stiffness of the produced columns, which often requires site-specific testing and empirical correlations for design purposes (Tinoco et al., 2011; Toraldo et al., 2018).

In recent years, increasing attention has been given to the use of non-destructive techniques as reliable indicators for assessing the quality and mechanical properties of soilcrete. Among these, Digital Image Correlation (DIC) has emerged as a valuable tool, offering full-field strain measurements with high spatial resolution and providing detailed insight into localized deformation and fracture behavior that are difficult to capture with conventional instrumentation such as LVDTs (Linear Variable Differential Transformer) or strain gauges.

With the aid of DIC static modulus of elasticity of compressed concrete can be accurately obtained, in reasonable comparison to the LVDT method (Loh et al. 2022). This method enables additional observations, such as characterization of the cracking patterns, impossible to be performed using only LVDT method. The stress field obtained by the DIC test showed that the cracking modes of the mortar and concrete specimens were different (Zhang et al. 2022): concrete specimens cracked from the center, and mortar specimens cracked from the edge, which could affect the reliability of the tensile strength calculation of mortar specimens. There have been also reported data acquisition based on the StereoDIC in uniaxial compression testing of rock cores. The authors point out the positive effects of such approach, including: full field shape, deformation and strain fields on the surface of the specimen, almost no need for specimen preparation (other than applying the group of dots on the surface), possibility to avoid areas of local disturbances and failures, acquisition of a larger amount of data compared to conventional methods, enabling proper statistical analysis in estimating the desired properties (Abdulqader et al., 2020). Another study (Lingga et all, 2019) has shown relatively small mean differences of 5.1% and 14.5% in lateral and axial strain measurements of concrete samples, in comparison to conventional LVDT and string potentiometer methods. The authors reported that the placement of point of interest is greatly influencing the 3D-DIC's generated elastic properties, and strongly recommended a comprehensive analysis what to examine on the specimen, prior to the experiment. Although widely applied in materials science, the application of DIC to jet grouting materials remains limited.

The objective of this study is to investigate the mechanical behavior of jet-grouted material formed in a gravelly sand stratum through uniaxial compression testing combined with DIC strain monitoring. Core samples were extracted from an active construction site. The experimental program focuses on evaluating key mechanical parameters such as uniaxial compressive strength (UCS), Young's modulus, and stiffness-to-strength ratios (β). Special attention is given to capturing the stress-strain response and characterizing potential variability in stiffness and strength. The outcomes are discussed in the context of existing literature to assess the applicability of standard modulus-based design approaches and to explore the advantages of using DIC in the evaluation of jet grout performance under field conditions.

2. MATERIALS AND METHODS

The samples analyzed in this study were collected from the construction site of the National Football Stadium located in Surčin, Serbia. During the installation of bored piles, localized soil collapse of the surrounding ground was observed, which indicated inadequate stability of the soil mass. As a remedial measure, jet grouting was applied as a ground improvement technique to enhance both the strength and stiffness of the weak and heterogeneous subsurface layers and to ensure the safe continuation of piling works.

According to the geotechnical report prepared by Geomehanika DOO (2023), the geological profile at the site consists of the following layers:

- Humus (h) - humus and humified dust, with plant root remnants and organic matter. The layer thickness is approximately 0.70m locally and up to 1.10m. This layer was removed during the construction of the facilities.
- Silty - sandy clay (pr) - yellow-brown silty (loess-like) material with the presence of sandyclayey material.

- Silty Sand (p-pr) - sandy material, yellow-brown in color, limonitic, fine-grained, watersaturated. With increasing depth, a change to gray-brown color, well-cemented, well-granulated.
- Silty Clay (pr-gl) - silty clayey material, yellow to brown in color, moderately plastic, moderately compressible. With increasing depth, the percentage of sandy fraction in the mass increases.
- Gravelly Sand (p*) - sandy-silty material with the presence of fine-grained gravel in the matrix. Gravel clasts up to 5 cm, well-compacted layer, gray to brown in color, fine to medium-grained sand.
- Silty Clay (gl-pr) - brown to brownish material, hard consistency, slightly compressible. The material exhibits moderate to high plasticity.

Although jet grouting was carried out in both silty sand and gravelly sand, this paper focuses only on the investigation of columns formed in the gravelly sand layer. The same report indicates that the gravelly sand layer is found at depths between 20 and 26 meters. This layer is characterized by an internal friction angle of 35–40°, cohesion of 0–2 kPa, bulk density of 18.8–19.0 kN/m³, and natural moisture content ranging from 6.6% to 30.8%.

To assess the uniaxial compression performance of jet-grouted material, the Digital Image Correlation technique was performed. Digital Image Correlation (DIC) is a non-contact optical measurement technique used for measuring full-field displacements and strains on the surface of an object. The DIC method is based on analysing the changes in the pattern of a specimen's surface between sequential images by using correlation algorithms. By comparing subsets of pixels from the undeformed and deformed images, DIC can determine how points on the surface have moved, enabling precise calculations of displacement and strain.

Digital Image Correlation is the leading optical measurement method. This method is widely used in various materials and structural testing within most industry segments, in research and development at universities and research facilities, due to its accuracy, versatility, and ability to capture complex deformation behaviour in real-time. The DIC has several advantages over traditional measurement techniques such as strain gauges, extensometers and displacement transducers. It provides a full-field strain map, enabling detection of strain heterogeneity and localised effects. As a non-contact measurement technique, it eliminates a mechanical interaction with the specimen under testing, reducing the potential measurement errors or damage to the specimen surface. Modern DIC systems are robust and handle rough or uneven concrete surfaces more effectively than traditional sensors. A significant advantage of DIC is post-processing capability. It allows reprocessing the same data and refining the analysis without repeating the physical test, flexible and advanced data extraction, enhanced visualisation of deformation of the specimen under test and integration with other data sources data such as force data, thermography or acoustic emissions, as shown in Figure 1.

Figure 1. *Testing experimental setup and one of the cracking patterns of the specimen*

3. LABORATORY TESTING AND RESULTS

Eight core Ø70/H70 samples of the jet grouting columns were taken by core drilling of the jet columns at the depth of 20 m to 26 m, and prepared in the laboratory for uniaxial compressive strength testing. The columns were formed using the double-fluid system, with a diameter of 1500 mm and a water–cement ratio of 1.0. The specimens had an age ranging from 28 to 84 days at the time of testing.

The Amsler and Sohn compressive testing device was used for loading the specimens. The acquisition of load values was conducted by the load cell placed under the tested specimen. Between the load cell and the specimen was thick steel plate, intended to eliminate deformations of the lower surface of the specimen. For strain measurement of cores subjected to uniaxial compression testing, the X-Sight M16 DIC system was used. Two 2D DIC sets were installed, allowing the recording of specimen surfaces and measurements from two sides. The DIC setup consists of 16 megapixel cameras and LED lights. The appropriate speckle pattern was applied to the specimen surface by spray paint.

Figure 2 shows the testing experimental setup for uniaxial compression testing combined with DIC strain monitoring.

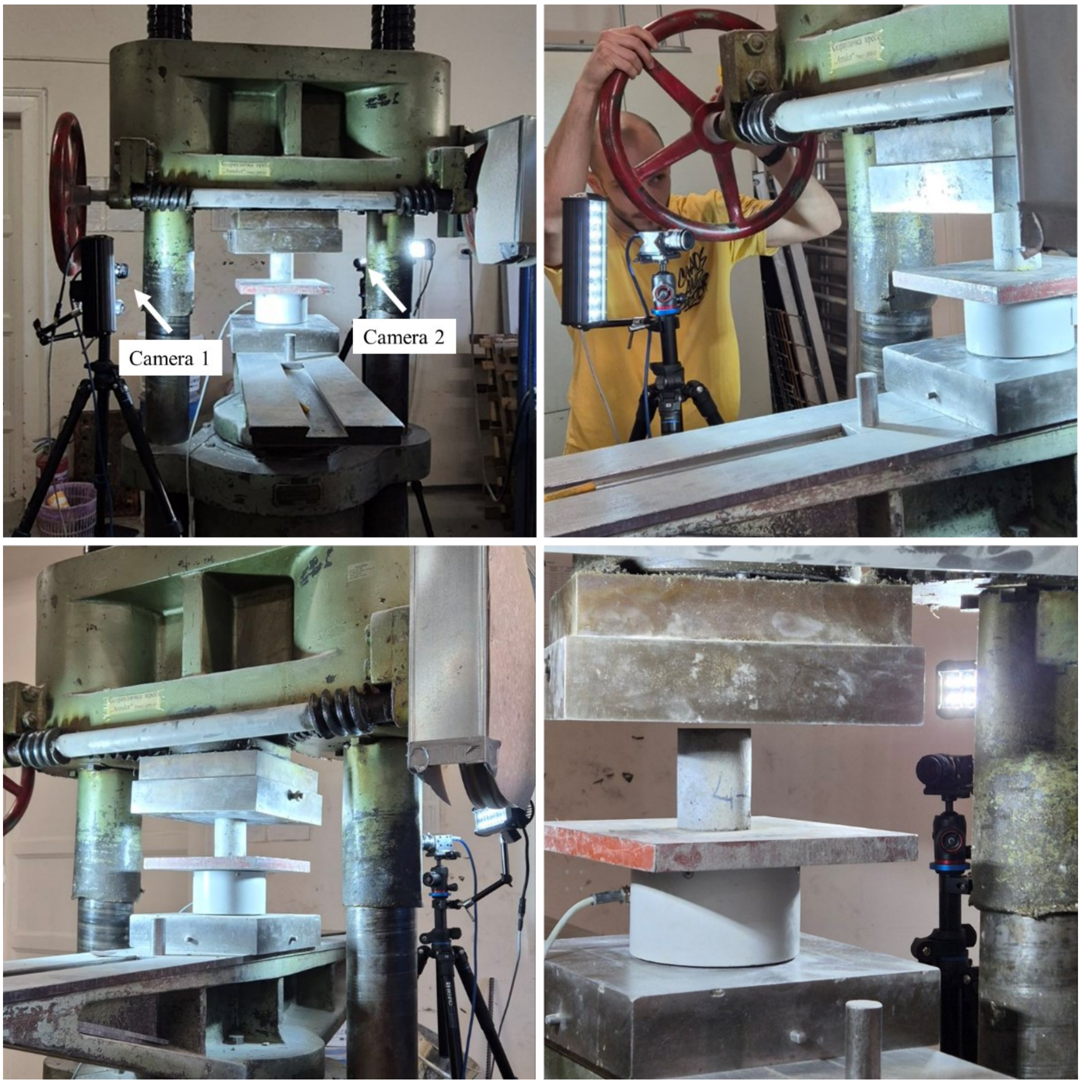

Figure 2. *Experimental setup for uniaxial compression testing combined with DIC strain monitoring*

The results of uniaxial compression testing with strain monitoring by DIC are presented in Figures 3 and 4. A total of eight samples were analyzed, all extracted from a jet-grouted layer composed predominantly of gravelly sand. The detailed results, including uniaxial compressive strength (UCS), calculated Young's moduli, and stiffness-to-strength ratios:

$$\beta = \frac{E}{q_u} \tag{1}$$

are summarized in Table 1.

Figure 3 shows the initial portion of the stress–strain curves, up to 0.2% axial strain, which was used for the determination of the Young's modulus (E) as the tangent modulus. This part of the curve reflects the elastic response of the material and is critical for assessing deformation behavior under service loads. Figure 4 shows the full stress-strain curve for one representative sample, illustrating the characteristic mechanical behavior of jet grout under uniaxial loading. A nearly linear pre-peak segment is followed by brittle failure. The curves exhibit an almost linear trend up to peak stress, indicating that the modulus remains practically constant throughout the loading phase until failure. This confirms the quasi-elastic behavior of the jet-grouted material under uniaxial compression.

The complete dataset in Table 1 includes not only the mechanical parameters but also the corresponding depth intervals from which the core samples were obtained.

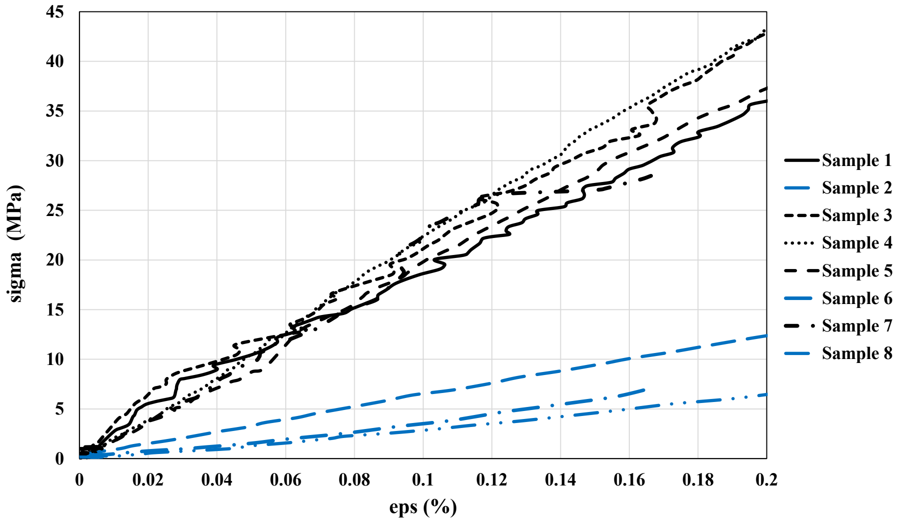

Figure 3. *Initial portions of stress–strain curves used to determine Young's moduli*

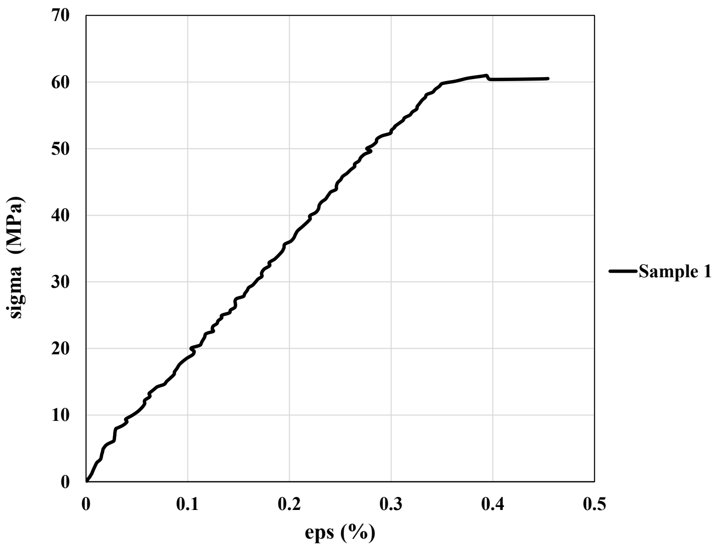

Figure 4. *Representative stress–strain curve from uniaxial compression test*

Table 1. *Full dataset from laboratory testing of jet grout specimens*

Sample No.	Depth (m)	UCS q_u (MPa)	Young moduli E (GPa)	β
1	20.0-21.0	61.0	16.8	275
2	21.0-23.0	25.0	6.2	248
3	22.0-23.0	69.7	17.6	252
4	23.3-23.8	67.4	20.0	296
5	23.3-23.8	41.1	17.7	430
6	24.0-25.0	17.9	4.4	245
7	25.0-26.0	30.0	17.5	583
8	25.0-26.0	23.0	3.9	169

4. DISCUSSION

The uniaxial compression tests conducted on eight core samples of jet grout extracted from a gravelly sand layer indicated two clearly performance groups, as evident from the stress-strain diagrams. The first group of high-performance samples (1, 3, 4, 5, 7) exhibit UCS values between 30 and 69.7 MPa and Young's moduli ranging from 16.8 to 20.0 GPa. The calculated β ratios vary from 252 to 583. This group reflects behavior typical for well-executed jet grouting in coarse soils, where cement infiltration is efficient and uniform. The results are closely aligned with the values reported by Croce et al. (1994) and Mongiovì et al. (1991), where jet grout formed in gravelly sand exhibits UCS in the range of 10-70 MPa and β values between 210 and 670. In particular, the high modulus of Sample 7 (17.5 GPa) despite moderate UCS (30 MPa) suggests a dense internal structure with potentially high cement content in a localized region, possibly caused by non-uniform jet dispersion or grout migration.

The second group of the low-performance samples (2, 6, 8) are characterized by significantly lower UCS values (17.9-25 MPa) and elastic moduli between 3.9 and 6.2 GPa. The β values range from 169 to 248. These values fall below the expected mechanical thresholds for gravelly sand and instead resemble jet grout performance in finer soils such as silty sands (Croce et al., 2014). This can likely be attributed to local soil heterogeneity, inefficient mixing, or grout dilution by groundwater.

Although the number of tests performed in the gravelly sand layer was relatively limited, the computed coefficient of variation (CV) of 49.3% indicates a high degree of variability in stiffness. This value is consistent with findings reported by Croce et al. (2014), where CV values for sandy and gravelly soils typically range between 15% and 47%, and are generally lower than those found in finer soils (CV = 48–75%).

The β ratio is commonly used to estimate stiffness from strength in cases where direct modulus measurements are unavailable. In the literature, this parameter is typically defined using the secant modulus at 50% of peak stress (E_{50}), due to slight nonlinearities observed before failure. However, in this study, the stress-strain response was approximately linear up to peak stress, as confirmed by DIC strain analysis. As a result, the measured modulus effectively corresponds to E_{50}, eliminating the need for further distinction between tangent and secant stiffness. β values range from 169 to 583, with most falling between 250 and 450, which matches the lower-to-mid spectrum reported for gravelly sand soils (typically 210-1200, Croce et al., 2014). The relatively low β values may be attributed to a combination of factors, such as material inhomogeneity, extraction from field conditions rather than controlled laboratory settings, and minor degradation associated with coring operations.

The disparity between these two groups highlights the critical importance of quality control, particularly in field conditions where local changes in soil texture or grouting parameters can cause substantial differences in mechanical properties. Literature confirms that core samples from field-executed jet grout columns show greater scatter compared to laboratory-prepared samples, due to extraction-induced damage and spatial inhomogeneity (Correia et al, 2009). Overall, the consistency between the experimental data and published literature supports the validity of the applied methodology and highlights the potential of DIC as a reliable tool for assessing the mechanical behavior of jet-grouted materials.

5. CONCLUSIONS

The conducted investigation highlights both the potential and the challenges of applying jet grouting in coarse-grained soils under real field conditions. The results reveal considerable variability in the mechanical performance of the tested samples, with two clearly defined performance groups identified. While the majority of samples exhibit strength and stiffness consistent with expected values for gravelly sand, lower-performing samples confirm the strong influence of local soil heterogeneity and grout distribution on the final properties. The good agreement between experimental results and published data supports the reliability of the applied methodology, while the use of Digital Image Correlation (DIC) proved to be a valuable tool for precise stiffness evaluation.

Based on the analysis of the cracking pattern of the specimens, jet grouts were found to be closer to the mortar behavior under load, showing cracking from the edge. It should be noted that the specimens reached the compressive strength values correspondent to the higher concrete strength classes, with large ultimate strains reaching more than 0.4%, which is much higher ductility than for concrete.

Overall, the findings emphasize the need for strict quality control and continuous monitoring during construction to ensure consistent performance of jet-grouted elements. Further research based on a larger dataset is recommended to better understand the influence of soil composition and grouting parameters on the mechanical behavior of treated soils.

6. ACKNOWLEDGEMENTS

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