Enhancing the Pullout Capacity of Expandable Mechanical Plate Anchors in Sandy Soil Through Cement Grout Injection: Experimental Investigation

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1- **Abstract**

Expandable plate mechanical anchors are widely used in geotechnical engineering projects to provide stability and resist tensile forces. Despite their ease and rapid installation, their performance strongly depends on the proper expansion of the plates and the interaction between the anchor and the surrounding soil, and in many cases the expected load-bearing capacity is not achieved due to construction limitations or unfavorable ground conditions. In this study, the potential for improving the pullout capacity of these anchors through cement grout injection in sandy soil was investigated. To this end, a series of preliminary tests and anchor pullout tests were conducted under different conditions. The parameters examined included grout injection pressure, grout volume, injection height relative to the anchor plates, and the relative density of the sandy soil. The results showed that cement grout injection can significantly increase the tensile capacity of the anchors, provided that the injection is carried out after the plates are fully expanded. It was also observed that premature grout injection may form a grout bulb above the anchor, preventing the proper expansion of the plates and weakening the system performance. Furthermore, the findings indicate that injection pressure plays a key role in grout penetration and the formation of an effective grout bulb; low pressures result in insufficient penetration, while excessively high pressures may cause failure or instability of the grout mass. The study also revealed that in dense sandy soils, higher injection pressures are required to achieve noticeable improvement in anchor capacity.

Keywords

Mechanical plate anchor, Pullout capacity, Grout injection, Firuzkuh sandy soil.

2- Introduction

Anchors are extensively used to stabilize slopes and support retaining structures [1]. Among available systems, the expandable mechanical plate anchor system (EMPAS) is favored for its rapid installation; however, their performance depends on plate geometry and soil conditions [2]. Research into vertical plate anchors in sand [1, 4] underscores the importance of soil-anchor interaction. While pressure-grouting is a recognized technique for deep foundations [3], its combined application with expandable mechanical anchors remains a novel area of study. This research evaluates the injection parameters and defines practical installation guidelines for this hybrid system.

The performance of such anchors, however, depends strongly on the plate geometry, the degree of expansion, the soil properties, and the loading conditions. Loose or unstable ground and incomplete plate expansion can prevent the anchor from developing its expected capacity. Although pressure-grouting has been shown to improve the axial performance of related systems such as helical piles and ground anchors, the combination of post-installation grout injection with an expandable mechanical anchor had not been examined before.

This gap defines the research question of the present study: if an expandable mechanical anchor fails to achieve its target capacity after installation, can in-situ cement grout injection compensate for the deficit without re-drilling? The study pursues three objectives: (1) systematic evaluation of the injection pressure, volume, and injection height as the governing installation parameters; (2) clarification of the interaction mechanism between the grout bulb and the soil failure wedge; and (3) definition of practical installation guidelines for the hybrid system.

3- Methodology

The soil used in all tests was Firuzkuh 131 sand, a uniform, poorly graded sand (SP) with rounded to sub-rounded particles and no fines. Its minimum and maximum dry unit weights were 1.42 and 1.60 g/cm³, its specific gravity 2.56, and its friction angle 34°. The sand was placed in a rigid 1 m × 1 m × 1 m steel test box at three relative densities of 30%, 50%, and 70%.

The anchor was a prototype-scale (1:1) expandable mechanical plate anchor with a 160 cm shaft and a 30 cm × 30 cm steel plate assembly. Plate expansion angles of 15°, 30°, and 45° were examined. Four radial injection ports, each 4 mm in diameter, were provided on the shaft at levels 15, 30, 45, and 60 cm above the plates, and the shaft section below each level was sealed to prevent downward grout migration. The grout was a cement-based mix with a water-to-cement ratio of one and 0.1% superplasticizer, injected from a 35 L tank by an air compressor at up to 10 bar. Loading was applied by a 5-ton manual jack; the pullout force was measured with a 2-ton load cell and displacements were recorded electronically.

The program proceeded in four stages: (1) preliminary tests in medium sand with grout volumes of 2–6 L, from which 4 L was adopted as the fixed volume, since beyond 4 L no meaningful lateral bulb growth occurred; (2) 27 baseline pullout tests (three densities × three plate angles, three repetitions) to establish the un-grouted reference capacities; (3) 12 tests (three densities × four injection levels) at 7 bar and a 45° plate angle to find the optimal injection height; and (4) 27 tests (three densities × three plate angles × three pressures of 5, 6, and 7 bar) at the optimal volume and injection level.

Early trials showed that injecting the grout before the plates were expanded caused the hardened grout to act as an umbrella that impeded load transfer and plate expansion. In the final protocol, the anchor was first pulled to fully expand the plates, the load was released, the grout was injected, the system cured for 10 days, and the final pullout test was then performed. The ultimate pullout capacity was defined as the peak load of the load–displacement curve.

4- Results and Discussion

4-1- Baseline behavior without grouting

The 27 baseline tests established the reference capacities of the un-grouted anchor. The ultimate pullout load ranged from 196 kg (loose sand, 15° plates) to 305 kg (dense sand, 45° plates), and within each density larger plate angles produced higher capacities, because more steeply inclined plates mobilize a larger soil failure wedge. The displacement at peak load decreased systematically with increasing density, from 80–109 mm at D_r = 30% to 46–56 mm at D_r = 70%. The baseline pullout tests established the reference capacities without grouting (Table 1).

Table 1. Summary of pullout tests without grout injection

Test No.	Test Name	Avg. Displacement at peak (mm)	Avg. Max Force (kg)
1	D30-A45	80	225
2	D30-A30	100	214
3	D30-A15	109	196
4	D50-A45	51	247
5	D50-A30	64	235
6	D50-A15	70	212
7	D70-A45	46	305
8	D70-A30	50	287
9	D70-A15	56	258

4-2- Effect of injection level

With the grout volume fixed at 4 L and the pressure at 7 bar, the injection level above the plates proved decisive. Capacity increased progressively with height: in loose sand, from 222–229 kg (baseline) to 250, 286, and 315 kg at 15, 30, and 45 cm, respectively, and in dense sand from about 303–309 kg to a maximum of 453 kg at 45 cm. The 45 cm level—1.5 times the plate width—was therefore identified as optimal, placing the grout bulb squarely within the zone mobilized by the plate failure wedge. At 60 cm, the grout escaped to the surface in the loose and medium sands and no effective bulb was formed.



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Figure 1: Surface leakage of grout at 60 cm distance in 50% relative density under 7-bar injection pressure

4-3- Effect of injection pressure and relative density

Increasing the injection pressure from 5 to 7 bar consistently increased the pullout capacity for every density and plate angle, with representative gains over the corresponding baseline of roughly 20–27% in loose sand, 13–31% in medium sand, and 9–33% in dense sand at 45° plates; at only 5 bar, the improvement in dense sand was limited to about 10–14%. Higher pressure drives the grout deeper into the pore space and creates a stronger mechanical interlock with the soil skeleton, so 7 bar was adopted as the optimal pressure.

Relative density exerted a complementary influence. In looser sand the grout traveled farther, producing larger but more elongated bulbs; in dense sand the bulbs were smaller (approximately 19–22 cm at 5 bar versus 26–35 cm in loose sand) but more spherical and coherent, which the authors attribute to the stronger engagement between the compact grout mass and the tightly packed soil skeleton. Measured bulb diameters at 7 bar were about 44–46, 41–42, and 38–40 cm in the loose, medium, and dense sands, respectively.

4-4- Mechanism and practical implications

The results support a consistent failure mechanism: the hardened 4 L grout bulb, located about 1.5 plate widths above the expanded plates and formed under sufficient pressure, behaves as a" virtual second anchor plate. "It intercepts and stiffens the same soil wedge that the physical plates mobilize, forcing the failure surface to break through a cemented body and thereby raising the ultimate load while reducing the displacement at peak load. Three preconditions govern success: full plate expansion before injection, a 10-day curing period before loading, and an injection level within the mobilized wedge zone.

5- Conclusion

Post-installation cement grout injection is an effective in-situ remediation technique for expandable mechanical plate anchors: in all successfully grouted configurations the ultimate pullout capacity exceeded the un-grouted baseline (196–309 kg), with improvements of approximately 11.2% to 50%; the largest gain—453 kg versus about 303 kg—was obtained in dense sand (D_r = 70%) at 7 bar and a 45 cm injection level.

The injection pressure is a governing parameter: increasing it from 5 to 7 bar increased the capacity in every density–angle combination, while low-pressure injections in dense sand yielded only about 10–14% improvement.

The optimal injection level is 45 cm (1.5 times the 30 cm plate width): injections at 15 cm produced only 11–13% gains, and injections at 60 cm escaped to the ground surface in the 30% and 50% density sands.

The optimal grout volume is 4 L, producing an effective bulb 30–45 cm in diameter; beyond this volume no significant lateral growth occurred and grout wastage increased.

The hardened grout bulb acts as a virtual second anchor plate, engaging the overlying failure wedge and simultaneously increasing the ultimate load and reducing the displacement at peak load.

Injection must be performed only after the plates are fully expanded, and the anchor must not be loaded before the grout has cured (10 days), since early loading induces micro-cracking and separation of the grout mass from the shaft.

These findings provide a practical window of grouting parameters (4 L, 5–7 bar, 1.5H above the plates, after full plate expansion and before loading) for deploying expandable mechanical plate anchors in loose to dense sandy deposits, and a basis for future numerical and field-scale verification.

6- References

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