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UTILISING UNSATURATED SOIL MECHANICS FOR THE DESIGN OF TEMPORARY EXCAVATION SLOPES

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ABSTRACT

During 2020, a method to provide stability to an initially unstable soil excavation was required in loose saturated soil. The initial slope angle was up to 45° to the horizontal, with saturated ground causing local slip failures and running sand into the excavation.

Due to space constraints, it was not feasible to construct shallow excavation slopes. The excavation was also surrounded by existing sensitive infrastructure including gas mains; therefore, it was not feasible to use reinforcement techniques such as soil nails, anchors, steel sheet pile walls, or a secant pile wall. To provide soil reinforcement to enhance slope stability, a system was designed that incorporated the construction of a permeable drainage stone key along the toe of slope, combined with aggregated cemented angular stone "columns" compacted orthogonally to the toe of the slope. This combined drainage and reinforced soil system met the economic budget for the client. To meet Eurocode 7 design standards, including appropriate partial safety factors, a PLAXIS 3D analysis was conducted. Furthermore, to reach a fully utilized safety case where the design stabilisation resistance exceeded the design destabilisation actions, the PLAXIS 3D unsaturated soil model that calculates effective stress in terms of Bishop's definition ($\sigma' = \sigma - ua + \chi(ua - uw)$), was utilised.

As input to this model, a soil water retention curve for the clay soils was derived from the particle size distribution using data available from the site investigation. This ground stabilisation was successful, with stability maintained for the required two years until the infrastructure was ultimately constructed and backfilled.

Keywords: unsaturated soil mechanics, slope stabilisation, groundwater modelling, slope failure, temporary works, groundwater control.

INTRODUCTION

In 2020, an upgrade of critical gas infrastructure required a temporary excavation with slopes ranging from 30° to 45°. The excavation, ranging from 3.0m to 3.5m in depth, was situated adjacent to sensitive gas infrastructure and existing vertical piles. A high groundwater table and weak

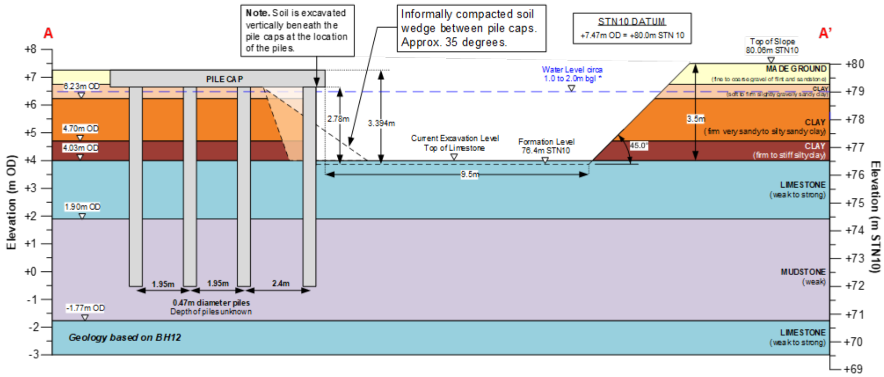

Figure 1 *Conceptual model including the general excavation geometry*

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soil conditions caused local slope failures within the excavation. Traditional stabilization methods such as soil nails, anchors, or sheet piles were not viable. Due to construction delays, the excavation remained open for two years instead of the planned 12 weeks, necessitating a robust stabilization solution. This paper presents the design, analysis, and performance evaluation of the implemented solution.

GROUND CONDITIONS

The geological sequence, as depicted in Figure 1, is summarised as follows:

- Unit 0: MADE GROUND comprising gravel-sized fragments of flint and sandstone.
- Unit 1: Soft to firm, slightly gravelly, sandy CLAY.
- Unit 2: Firm mottled, very sandy to sandy, silty CLAY.
- Unit 3: Firm to Stiff dark grey silty CLAY.
- Unit 4: Weak to strong dark grey LIMESTONE.
- Unit 5: Extremely weak to weak, thickly laminated grey MUDSTONE.

The groundwater table was circa 1.0m below the existing ground level and circa 2.5m above the excavation level.

DESIGN SOLUTION

A reinforced soil system was designed, integrating:

A permeable drainage stone key at the slope toe to manage groundwater ingress and prevent loss of soil fines.

Cemented aggregate stone columns installed at 2.5m centres to increase friction and mitigate circular slip failure.

Surface stabilization using angular stone compacted into the slope face to mitigate erosion from rainfall.

The construction sequence included installing a stabilising angular stone key at the slope toe, installing a sump in the corner of the excavation, and using this to pump groundwater out of the stone key using a sump pump, placing cemented aggregate columns inside the slope, compacting angular stone onto the slope face, and monitoring ground movement. The construction followed a defined Inspection, Testing & Monitoring (ITM) Plan to ensure compliance with safety and stability requirements. The design was executed in accordance with Eurocode 7 standards, ensuring stability under drained conditions.

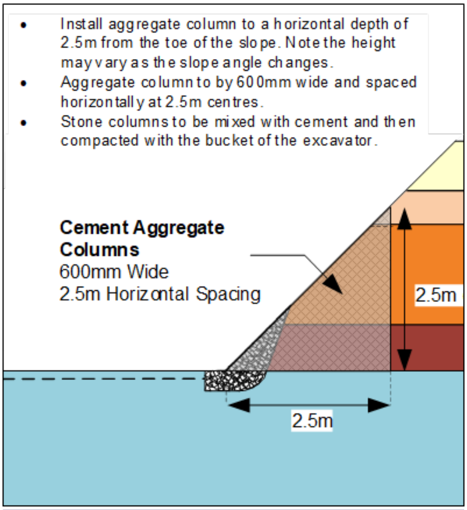

Figure 2 *Schematic of aggregate column design solution in cross-section through the slope*

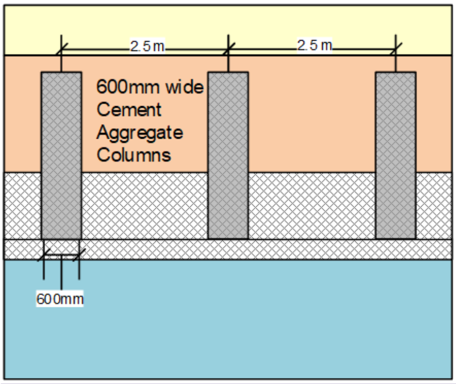

Figure 3 *Schematic of Aggregate Column Design Solution looking at the Slope Face*

DESIGN ANALYSIS USING PLAXIS 3D

PLAXIS 3D (Bentley Systems, 2025) was used as the modelling tool to develop the proposed design solution. The software was used to verify that the design provided sufficient ground resistance to prevent slope failure under drained conditions. Partial factors of safety were utilised, and the design was adjusted (primarily the spacing of the cemented aggregate columns) until the design satisfied Eurocode requirements.

The following partial factors of safety were selected in accordance with relevant design standards (British Standards, 2004):

- Partial factor, γ_m = 1.25 to reduce tanφ' and c' for drained shear strength

- Partial factor, γ_m = 1.40 to reduce σ_{ci} for rock
- Load factor, γ_L = 1.30 to increase destabilizing actions of surcharge loading.

As defined in Eurocode 7, non-factored parameters are referred to as 'characteristic', while factored parameters used in calculations are referred to as 'design' (British Standards, 2004).

Characteristic drained soil parameters were derived from site investigations, historical data, and industry-standard estimation methods (British Standards, 2015) (Bowles, 1996). For soils, the Mohr-Coulomb Model was utilised (see Table 1). For the bedrock, the Hoek-Brown Model was utilised (see Table 2). A steady state seepage analysis was undertaken first to determine the groundwater level.

Table 1 *Mohr-Coulomb Soil Parameters*

Unit	γ [kN/m³]	E [Mpa]	c' [kPa]	φ' [°]
0	17	7	0	25
1	18	2	0	21
2	19	5	0	21
3	19	7	0	21

Table 2 *Hoek-Brown Rock Parameters*

Unit	E [Mpa]	σ_{ci} [kpa]	mi [kPa]	GSI [-]
4	15,000	49.2	10	12
5	1,000	20	4	10

A characteristic surcharge of 10 kPa was applied 1.5 m from the crest of the top of the batter, as required by Eurocode 7 (British Standards, 2004).

UNSATURATED SOIL MECHANICS

To reach a fully utilized safety case where the design stabilization resistance exceeded the design destabilization actions, the PLAXIS 3D unsaturated soil model was utilized for the clay soils. This model calculates effective stress using Bishop's definition (Bishop, 1959):

$$\sigma' = \sigma - u_a + \chi(u_a - u_w) \tag{1}$$

Where σ' is the effective stress, σ is the total stress, u_a is the pore air pressure, u_w is the pore water pressure, and χ is Bishop's parameter. In PLAXIS 3D, χ is equivalent to Saturation, S (Bentley Systems, 2025).

As input to this model, a soil water retention curve (SWRC) for the unsaturated clay soils UNIT 1, 2 & 3, was derived using the method of Perera et al. (2005). To derive the SWRC, a particle size distribution curve for the sandy clay soil (UNIT 2) was utilised. Below the water table, suction is not present, therefore, no SWRC was required for the bedrock material.

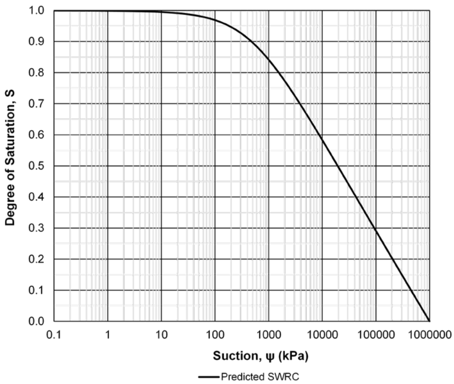

Figure 4 *Soil water retention curve estimated from the clay soil particle size distribution curve*

RESULTS

PLAXIS 3D finite element analysis was used to validate the design, simulating slope stability under working (Figure 5) and failure conditions (Figure 6). Partial safety factors were applied in accordance with Eurocode 7, resulting in a final utilization factor of 0.94 (factor of safety = 1.06), which confirmed adequate stability.

The implemented stabilization system successfully maintained excavation stability for over two years. The drainage key controlled groundwater seepage, while the cemented aggregate columns provided reinforcement against failure. Regular inspections confirmed the performance of the slope stabilisation method under drained conditions.

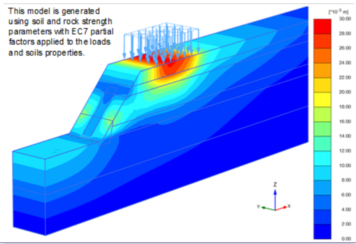

Figure 5 *Displacement at design working load*

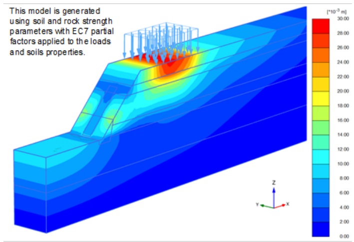

Figure 6 *Design at modelled failure*

CONCLUSIONS

A novel stabilization solution was developed for a temporary excavation in challenging geotechnical conditions. The combination of a drainage stone key (see Figure 7 for an image of this under construction) and cemented aggregate columns (see Figure 8 for an image of this under construction) provided a cost-effective and practical alternative to traditional methods. The design was validated through numerical modelling, and field performance confirmed long-term stability. This approach offers insights for similar future geotechnical challenges, particularly where site constraints limit conventional stabilisation methods.

Figure 7 *Construction of Angular Drainage Stone Key*

Figure 8 *Construction of Cemented Aggregate Columns*

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