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Reinforced soil technique for temporary slope stabilisation in loose saturated ground

Technique de sol renforcé pour la stabilisation temporaire des pentes dans un sol meuble et saturé

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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. The excavation was surrounded by existing sensitive infrastructure, so it was not feasible to construct shallow excavation slopes, nor feasible to use techniques such as soil nails or anchors. It was neither feasible to use a steel sheet pile wall nor a secant pile wall. To provide soil reinforcement to enhance slope stability, a system was designed that incorporated the construction of a highly permeable angular drainage stone channel along the toe of slope, combined with aggregated cemented angular stone "wedges" compacted orthogonally to the toe of the slope. This combined drainage and reinforced soil system met the economic budget for the client. To comply with Eurocode 7 design standards, including using appropriate partial safety factors on the soil parameters, a PLAXIS 3D analysis was undertaken to demonstrate stability under drained conditions. This ground stabilisation was successful, with stability maintained for the required two years until the infrastructure was ultimately constructed and backfilled.

RÉSUMÉ: Au cours de l'année 2020, une méthode permettant d'assurer la stabilité d'une excavation de sol initialement instable a été nécessaire dans un sol meuble et saturé. L'angle de pente initial était de 45° par rapport à l'horizontale, le sol saturé provoquant des ruptures de glissement locales et du sable coulant dans l'excavation. L'excavation était entourée d'infrastructures fragiles existantes, de sorte qu'il n'était pas possible de construire des pentes d'excavation peu profondes, ni d'utiliser des techniques telles que des clous à terre ou des ancrages. Il n'était pas possible d'utiliser un mur de palplanches en acier ni un mur de pieux sécants. Afin de renforcer le sol afin d'améliorer la stabilité de la pente, un système a été conçu qui incorporait la construction d'un canal de drainage angulaire en pierre très perméable le long du pied de la pente, combiné à des « coins » angulaires en pierre cimentée agrégés compactés orthogonalement au pied de la pente. Ce système combiné de drainage et de sol renforcé a permis de respecter le budget économique du client. Pour se conformer aux normes de conception de l'Eurocode 7, y compris l'utilisation de facteurs de sécurité partiels appropriés sur les paramètres du sol, une analyse 3D PLAXIS a été entreprise pour démontrer la stabilité dans des conditions drainées. Cette stabilisation du sol a été couronnée de succès, la stabilité ayant été maintenue pendant les deux années requises, jusqu'à ce que l'infrastructure soit finalement construite et remblayée.

Keywords: Soil reinforcement; drainage system; stabilising slopes.

1 INTRODUCTION

The upgrade of an energy infrastructure of national significance took place in the United Kingdom in 2020. Part of this upgrade programme required the construction of a temporary battered excavation to install buried pipework infrastructure. The excavation level varied between 76.46 m STN10 and 76.66 m STN10, where STN10 was the site-specific datum. This resulted in an excavation depth of circa 3m to 3.5 m bgl.

One side of the excavation had exposed vertical piles, with pile caps constructed above. On three sides of the excavation, the slopes were battered at slope angles varying between 30°-45° (Figure 1) and displayed soil instability. During an initial site visit, water ingress was observed seeping through the sides of the excavation, together with progressive slope failure in the form of running sand (Figure 2).

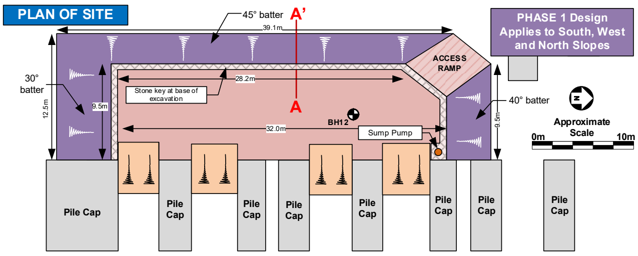


Figure 1. Site plan showing the layout of the excavation.

Figure 2. Excavation with unstable sloping sides.

As it was intended that infrastructure construction would only take 12 weeks during which undrained soil conditions were in place, the excavation had no slope reinforcement. However, due to a delay in construction programme, the excavation needed to remain open for up to two years longer than the anticipated 12 weeks, so resulting in drained (effective stress) conditions.

To provide stabilisation of the ground for a period of up to two years, the challenge to the civil engineers was to design a robust system to mitigate soil instability, including erosion protection. The constraints on any slope stabilisation were substantial, with traditional techniques such as sheet pile walls, king post walls, secant pile walls or soil anchors, excluded due to the potential impact on the surrounding sensitive infrastructure. This paper presents the design solution implemented by the civil engineers, together with the geotechnical modelling and analysis that was undertaken using PLAXIS 3D to support the design.

2 SITE CONDITIONS

The pipeline excavation had previously been constructed using battered slopes by a previous contractor. To the western, southern and northern sides of the excavation, there were slopes which were calculated to be in the range of 30° to 45°.

However, as a consequence of the high water-table, and steep slope angle, under drained soil conditions, the combination of the low drained shear strength and high groundwater seepage face resulted in local instability and running sand (Figure 2).

The geology on the site is characterised by predominantly superficial clay soils which overlay limestone and mudstone. The clay soils contain frequent lenses of sand and silt. The water level across the site is typically one metre below ground level. The geology with the construction detail overlaid is depicted in Figure 3. All elevations are presented relative to the site datum named STN10, where +7.47 m OD = 80.0 m STN10.

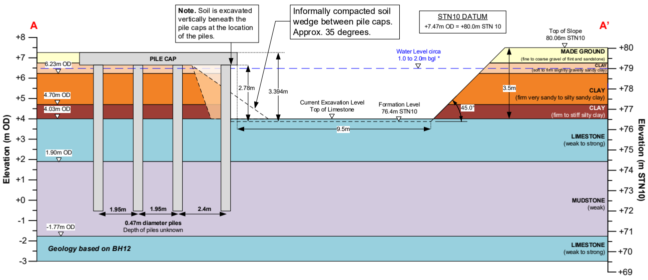


Figure 3. Conceptual model including the general excavation geometry.

3 GEOTECHNICAL SOIL PARAMETERS

The geological sequence, as depicted in Figure 3, 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.

Derivation of geotechnical parameters for each unit are presented in the following sections. This derivation has required the incorporation of limited available site investigation, historical research, industry best practice, and authors' own judgement.

3.1 Unit 0: Made ground

Made Ground was described as fine to coarse gravel of flint and sandstone, from which it was considered appropriate to adopt drained parameters for this unit; with drained strength parameters presented in Table 1 used as inputs to the finite element analysis.

A conservative value of Young's Modulus has been selected (Table 1) based on a typical well-graded loose '*Sand/Gravel silty*' from Table 2 (Obrzud and Truty, 2010). Poisson's ratio was selected from a table of typical values for soils (Bowles, 1996).

Table 1. Geotechnical Characteristic Parameters – Unit 0 – Made Ground.

Parameter	Characteristic Value
Weight density, γ	17 kN/m^3
Angle of internal friction, φ	25.0°
Effective cohesion, c'	0.0 kPa
Young's Modulus, E'	7.0 MPa
Poisson's ratio, ν'	0.2

Table 2. Typical values of Young's Modulus for granular materials (MPa) (Obrzud and Truty, 2010).

USCS	Description	Loose	Medium	Dense
GW, SW	Gravels/Sand well-graded	30-80	80-160	160-320
GM, SM	Sand, uniform	10-30	30-50	50-80
GM, SM	Sand/Gravel silty	7-12	12-20	20-30

3.2 UNITS 1, 2 and 3 – Clay soils

The clay soils were broken down into three units based on the geological descriptions:

- UNIT 1: soft to firm dark brown slightly gravelly sandy Clay.
- UNIT 2: firm mottled orange and reddish brown very sandy to sandy silty Clay.
- UNIT 3: firm to stiff dark grey silty Clay

Weight density test data were not available for the natural clay soils, however a range between 17 kN/m^3 and 21 kN/m^3 was expected based on historical site investigation. Parameters in Table 2 have been selected based on this range and experience of working with similar soils.

Drained shear strength parameters for these units were selected on the basis that the excavation was expected to remain open for two further years. As shear strength data were not available to determine the drained strength parameters of the Clay, Plasticity Index (I_p) test data were used to determine undrained shear strength, together with equations outlined in British Standard: Code of Practice for Earth Retaining Systems (British Standard, 2015*,* Section 4.3.1.4).

Conservative values of Young's Modulus and Poisson's ratio were selected for each Clay unit using the typical values for soils (Bowles, 1996). Effective cohesion, *c'* is taken as 0.0 kPa as suggested in British Standard: Code of Practice for Earth Retaining Systems (British Standard, 2015)

A summary of the characteristic parameters used for each Clay unit for the slope stability analysis are presented within Table 3.

Table 3. Geotechnical Characteristic Parameters – Units 1, 2 and 3.

Parameter	Unit 1	Unit 2	Unit 3
Weight density, γ (kN/m³)	18	19	19
Angle of internal friction, φ'_{pk} (°)	21	21	21
Effective cohesion, c' (kPa)	0	0	0
Young's Modulus, E' (MPa)	2	5	7
Poisson's ratio, v'	0.2	0.2	0.2

3.3 Units 4 and 5 – Limestone and mudstone

Rock behaviour differs from soil as it is generally stiffer and stronger. A linear stress dependency, as obtained from the Mohr-Coulomb model is generally not sufficient. The Hoek-Brown failure criterion is a better non-linear approximation of the strength of rock, and accounts for several factors including strength, disturbance and weathered nature of the rock. Input parameters to PLAXIS 3D are as follows: Young's Modulus, *E* (kPa); Poisson's ratio, *v* (-); Uniaxial compressive strength (UCS) of intact rock, σ_{ci} (kPa); Intact rock parameter, m_i (-); Geological strength index, GSI (-) and Disturbance factor, *D* (-).

Borehole descriptions suggest the Limestone is medium strong and thinly to medium bedded. The Mudstone is described as extremely weak to weak and thickly laminated to medium bedded. The selection of Young's Modulus and Poisson's ratio (Table 4) is based on typical values of Young's Modulus available in the literature (Some Useful Numbers, 2016).

Table 4. Summary of Design Rock Parameters – Units 4, 5.

Parameters	Limestone Unit 4	Mudstone Unit 5
Young's modulus, *E* (kPa)	1.5×10^7	1.0×10^6
Poisson's ratio, *v* (-)	0.2	0.2
Uni-axial compressive strength of intact rock, σ_{ci} (kPa)	49,200	20,000
Intact rock parameter, m_i (-)	10	4
Geological strength index, GSI (-)	12	10
Disturbance factor, *D* (-)	0	0

4 GROUNDWATER

Groundwater was encountered in boreholes outside the excavation at levels of circa 1 m bgl, and observed seeping into the excavation up to circa 2 m above the toe of the slope. Approximately 30 m away from the excavation was an area of a previous excavation which had been backfilled with sand and gravel. This area became waterlogged due to the surrounding clayey soil having a much lower permeability, and acted as a hydraulic boundary which defined the position of the water table boundary condition at a distance of 30 m in the PLAXIS 3D finite element model (*PLAXIS 3D, 2019).*

5 DESIGN METHOD FOR SOIL STABILISATION USING SLOPE REINFORCEMENT

The excavation was surrounded by existing sensitive infrastructure, so it was not feasible to construct shallow excavation slopes, or feasible to use techniques such as soil nails or anchors. was neither feasible to use a steel sheet pile wall nor a secant pile wall. To provide soil reinforcement to enhance slope stability, a system was designed that incorporated the construction of a highly permeable angular drainage stone channel along the toe of slope, combined with aggregated cemented angular stone “wedges” which are compacted orthogonally to the slope toe.

The construction sequence is as follows:

- Install a stabilising angular stone key at the toe of the slope (Figure 4) so groundwater can seep out of the batter without loss of soil fines.
- Sump pump residual water away from sump in the corner of the excavation.
- Install cemented aggregate wedges in the slope at spacings of 2.5 m. These wedges increase friction between the soil particles and prevent circular slip failure from occurring along the long west side of the excavation (Figures 4 and 5).
- Place angular stone onto the remaining exposed slope face, then push into the soil and compact with the bucket of the excavator. This will mitigate the surface erosion due to rainfall. Place the stone on exposed surfaces of the aggregate wedges to give a uniform appearance across the slope.
- Visually monitor the embankments during and after stabilisation works for any ground movement.
- Regularly refer to the Inspection, Testing and Monitoring (ITM) Plan, and to the staged sequence of installation.

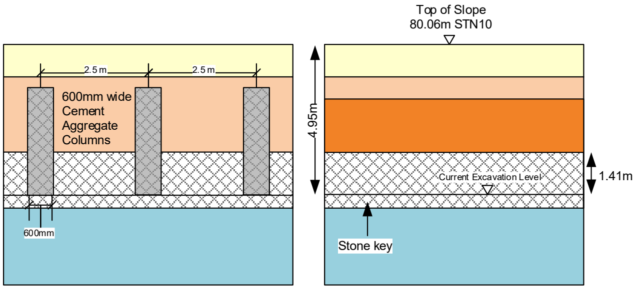
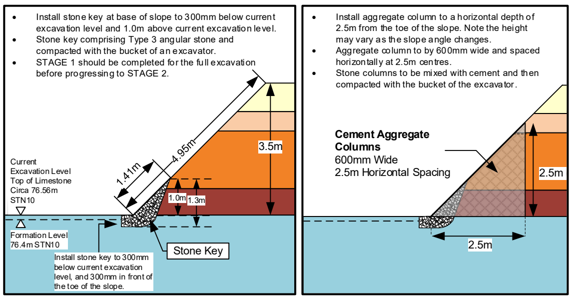


Figure 4. Inclined view of stone key aggregate wedges.



- Install stone key at base of slope to 300mm below current excavation level and 1.0m above current excavation level.
- Stone key comprising Type 3 angular stone and compacted with the bucket of an excavator.
- STAGE 1 should be completed for the full excavation before progressing to STAGE 2.

- Install aggregate column to a horizontal depth of 2.5m from the toe of the slope. Note the height may vary as the slope angle changes.
- Aggregate column to by 600mm wide and spaced horizontally at 2.5m centres.
- Stone columns to be mixed with cement and then compacted with the bucket of the excavator.

Install stone key to 300mm below current excavation level, and 300mm in front of the toe of the slope.

Figure 5. Sectional view of stone key aggregate wedges.

5.1 Unit 6: Compacted angular stone key used for drained reinforcement

The compacted angular stone key used MOT Type 3 (Figure 6) angular stone (SIMTEC Material Testing), with the weight density (Table 5), selected using a table of typical values (Some Useful Numbers, 2016).

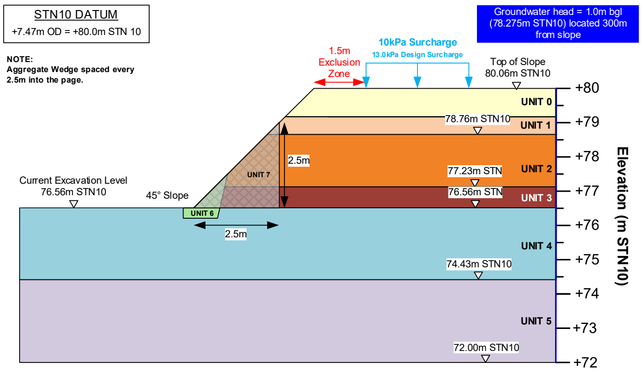


Figure 6. Conceptual model of the cemented angular stone soil reinforcement.

Table 5. Geotechnical Characteristic Parameters – Unit 6 Angular Stone Key.

Parameter	Unit 6
Weight density, γ (kN/m³)	19
Young’s Modulus, E (MPa)	100
Contribution from particle angularity φ'_{ang} (°)	4
Contribution from the PSD, φ'_{PSD} (°)	4
Effective angle of shearing resistance, $\varphi'_{cv,k}$ (°)	38
Contribution from Dilatancy, φ'_{dil} (°)	6
Peak angle of internal friction, φ'_{pk} (°)	44
Effective cohesion, c’ (kPa)	0
Poisson’s ratio, v’	0.2

Based on a gravel classification of ‘GW - Medium Dense’ Young’s Modulus of compacted angular stone, was selected using values in Table 5. Shear strength was determined using the equations and tables presented in British Standard (British Standard, 2015) Section 4.3.1.3:

5.2 Unit 7 – Cemented aggregate wedge

Each aggregate wedge was constructed using angular stone mixed with cement. When cured, this resulted in a high strength similar to concrete.

Table 6 depicts the PLAXIS 3D Input parameters used based on typical properties of concrete available in the literature (Some Useful Numbers, 2016).

Table 6. Geotechnical Characteristic Parameters - Unit 7 Cemented Aggregate Wedge.

Parameter	Unit 7
Weight density, γ (kN/m³)	21.0
Young’s Modulus, E (kPa)	1.0×10^6
Poisson’s ratio, v’	0.2

Slope stability validation was conducted in accordance with Eurocode 7 (Eurocode, 2004 & 2009), utilising the ‘Geotechnical Design by Calculation’ method, undertaken using PLAXIS 3D Version 2019. PLAXIS 3D (*PLAXIS 3D,2019)* is a finite element software designed for three-dimensional analysis of deformation and stability in geotechnical engineering.

6 PLAXIS 3D SIMULATION OF DESIGN SOLUTION

PLAXIS 3D was used as the design tool to develop the proposed design solution. The software was used to check that the design provided sufficient ground resistance to prevent failure of the slopes under drained conditions. Partial factors of safety were utilised and the design adjusted (primarily the spacing of the cemented aggregate wedges) until the design complied with Eurocode requirements.

6.1 Partial factors of safety

The following partial factors of safety were selected in accordance with relevant design standards (British Standards, 2015).

- Partial factor, $\gamma_m = 1.25$ to reduce tan φ'_and c' for drained shear strength
- Partial factor, $\gamma_m = 1.40$ to reduce σ_{ci} for rock
- Load factor, $\gamma_L = 1.30$ to increase destabilizing actions of surcharge loading

As defined in Eurocode 7, non-factored parameters, are referred to as 'characteristic', with factored parameters used in calculations, referred to as 'design'.

6.2 Model geometry

The following geometry in Table 7 was adopted for input into the PLAXIS 3D Mathematical Model.

Table 7: Input Values to the Plaxis-3D model.

Input	Value
Existing excavation level	76.56m STN10
Top of existing batter	80.06m STN10
Slope angle	45°
Cemented aggregate wedge – width	0.6m
Cemented aggregate wedge – height	2.5m
Cemented aggregate wedge – horizontal length	2.5m
Model width (i.e. wedge horizontal spacing)	2.5m

6.3 Surcharge loading and exclusion zone

A characteristic surcharge of 10 kPa is applied to the top of the batter as required by Eurocode 7 (Eurocode, 2004). The surcharge load has been specified 1.5m from the crest of the batter, meaning that there must be a 1.5m exclusion zone to plant and machinery.

7 RESULTS OF SLOPE STABILITY FINITE ELEMENT ANALYSIS VALIDATION

Numerical modelling of the slope stabilisation using the cemented aggregate wedge approach was carried out using PLAXIS 3D, using input values of Table 7.

Due to the symmetry between each of the aggregate wedges, the domain of the PLAXIS model needed to be only 2.5 m wide. In the vertical dimension, the various geological units (Unit 0 to Unit 3) were input as horizontal layers. The slope angle was defined as 45°, with the 13 kPa design loading applied downwards outside the 1.5 m exclusion zone.

The compacted angular stone key (Unit 6) was simulated as an irregular shaped horizontal strip as outlined in Figure 4. The cemented aggregate stone wedge (Unit 7) was simulated as a 600mm wide triangular structure, 2.5 m deep in the centre of the model (Figure 4 and Figure 6).

Figure 7 and Figure 8 depict the contours of simulated soil displacement (i) based on the working design loads, and (ii) when loads increased until simulated failure is reached.

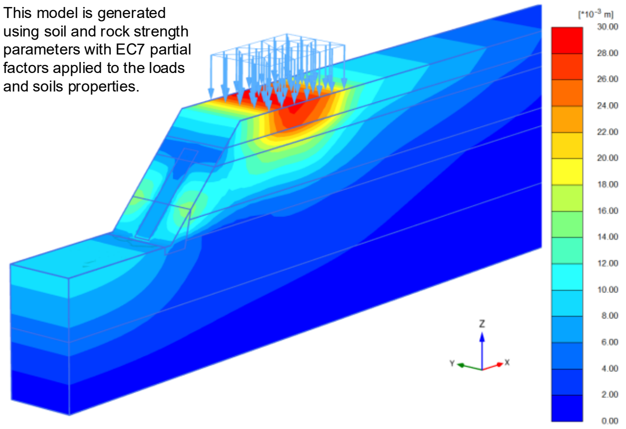
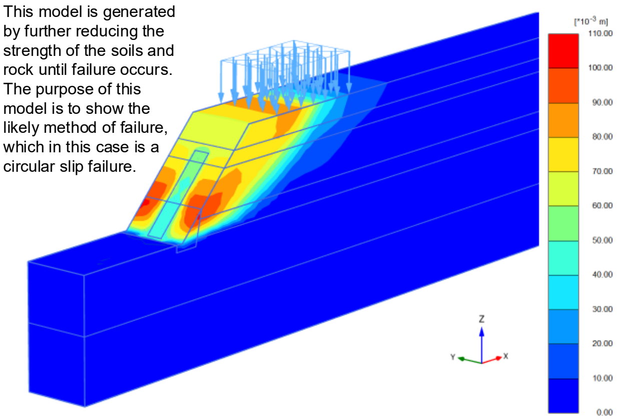

This model is generated using soil and rock strength parameters with EC7 partial factors applied to the loads and soils properties.

Figure 7. Displacement at working design load.


This model is generated by further reducing the strength of the soils and rock until failure occurs. The purpose of this model is to show the likely method of failure, which in this case is a circular slip failure.

Result:
Utilisation* = 0.94 PASS (after application of surcharge)
* < 1.0 satisfies EC7 criteria.

Figure 8. Displacement at model failure.

The PLAXIS 3D model evaluates the stabilizing design parameters required to produce sufficient forces to resist the destabilizing design actions just prior to model failure. The model then calculates the utilisation factor U, from the equation E_d / R_d where:

E_d is the design value of the effect of destabilising actions, i.e. loads and stresses

R_d is the design value of the stabilising resistance to actions, i.e. the maximum load/stress that the structure can support before failure.

To demonstrate stability, Eurocode 7 requires the Utilisation, U, to be less than 1.0. For the parameters and partial factors described in Table 7, PLAXIS calculates $U = 0.94$

8 CONSTRUCTION METHODOLOGY

The design process resulted in the completion of a series of critical documents required to ensure (i) the construction fulfils the design objectives to stabilise the excavation slopes for a period of at least two years, (ii) there is no collateral damage to surrounding infrastructure, and (iii) the construction is conducted to defined safety standards.

These critical documents included:

(a) Design Strategy document, including all relevant calculations
(b) Clear construction sequence drawings
(c) Design Risk Assessment (DRA)
(d) Inspection, Testing & Monitoring (ITM) Plan
(e) Signed design certificates
(f) Insurance certificates

All site personnel were required to be suitably trained, qualified and certificated to work on this sensitive site.

In summary, the construction proceeded safely with the excavation producing safe and stable exposed slopes for more than the two-year duration required.

9 CONCLUSIONS

An open cut temporary excavation was left open for longer than anticipated. This required the slopes to be stabilized due to the drained soils conditions that had developed, so causing the slopes to become unstable.

A unique slope stabilization solution was developed which comprised the installation of an angular stone key at the base of the slope (Figure 9), which helped to intercept groundwater and stabilize the top of the slope, together with cemented aggregate wedges installed within the slope to provide resistance to the overall soil mass (Figure 10).

The design solution was simulated in PLAXIS 3D with the utilization value, U, calculated as 0.94, demonstrating slope stability under Eurocode 7. Construction proceeded safely, with the excavation producing stable exposed slopes for longer than the two-year duration required.

Figure 9. Construction of angular stone key.

Figure. 10. Construction of aggregate wedge.

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