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Impact of sample quality on CPTU correlations in clay—example from the Rakkestad clay

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ABSTRACT: As part of the zoning plan for the new 30 km long highway, E16, from Nybakk to Slomarka, an extensive laboratory and field testing campaign was conducted by NGI. The deposit along the highway is a normally to slightly overconsolidated clay with a water content in the range of 30–45% and a plasticity index ranging between 7–25%. 72 mm diameter piston samples at 70 localities were taken and CPTUs were carried out at over 120 locations. About 180 CRS oedometer tests and 360 triaxial tests were performed. These results generally show good to excellent sample quality. However, due to the interpreted lower values of undrained shear strength from local CPTU correlations, 9 block samples were retrieved at 3 locations and additional laboratory testing was performed. The active undrained shear strength obtained from the block samples was up to 53% higher. Based on this data set, correlations were established to optimize the engineering solutions for the new road and to address the impact of sample disturbance on geotechnical engineering parameters. The results lead to important economical saving for the project and highlight the need for local and high quality samples for CPTU correlations in soft and sensitive clays.

1 INTRODUCTION

All building and construction works require reliable and proper determination of geotechnical design parameters. A careful consideration of the most appropriate investigation method is likely to result in improved understanding of soil behaviour and, therefore, in more cost-effective and sustainable solutions for the construction, transport and energy sectors. There is a need for better understanding of the behavior of soft and sensitive clays in order to improve geotechnical design, make it more innovative, and to reduce risks related to e.g. landslides and excavation failures.

NGI was recently involved in the elaboration of the detailed zoning plan for the new highway, E16, from Nybakk to Slomarka (approximately 50 km northeast of Oslo, Norway). Samples were collected using a piston sampler (Ø72 mm) at c. 70 localities and CPTU soundings were carried out at over 120 locations. About 180 CRS oedometer tests and 360 triaxial tests were carried out to assess the strength and stiffness properties of the Rakkestad clay along this E16 section. The results generally show good to excellent sample quality. However, the undrained shear strength interpreted from local CPTU correlations and based on the laboratory results was about 15% less than expected from previous experience.

To evaluate the impact of sample quality on the CPTU correlations, nine block samples (Sherbrooke type; Ø250 mm) were retrieved at three locations and additional laboratory testing was performed on the clays. This would allow for an optimization of the chosen design parameters and thereby optimize engineering solutions in connection with the construction of the new road.

The goals of the present paper are to demonstrate and document the impact of sampling methods on the stiffness and strength properties of the Rakkestad Clay, and to give recommendations on the most appropriate CPTU correlations for assessing the strength and stiffness properties of this clay. The results lead to important economical saving for the project and highlight the need for local and high quality samples for CPTU correlations in soft and sensitive clays.

2 STUDY AREA AND DATA INCLUDED IN THIS STUDY

The location of the planned highway, E16, from Nybakk to Slomarka is shown in Figure 1. The soil conditions in the study area are fairly homogenous and can be generalized with three layers. The top layer consists of a 0.4 m thick cropland overlying a layer of desiccated clay or dry crust underneath.

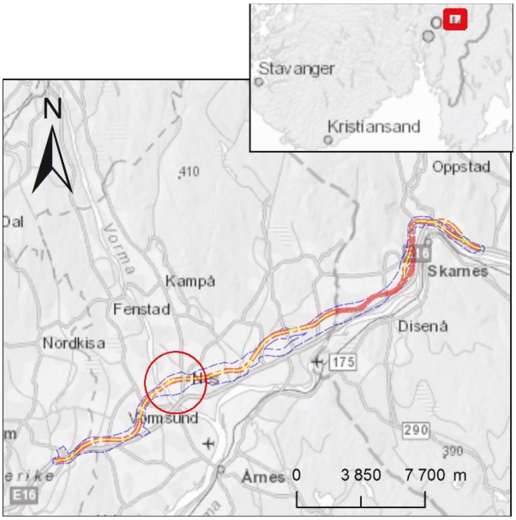

Figure 1. Location of the study area with the planned highway E16. The red circle shows the location where block samples were taken in the study area.

The dry crust generally extends 3–4 m below the ground surface. Further down, a normally consolidated and sensitive marine clay is found. The sensitivity (S_t) of the clay varies in this deeper layer (S_t up to 230) and the clay is also found to be quick (i.e. remolded undrained shear strength; $s_{ur} < 0.5$ kPa) at certain localities and depths. Aging may have led to some overconsolidation in the clay. The thickness of the marine clay deposit varies from approximately 20 to 45 m below the ground surface.

A high number of undisturbed samples were retrieved from 102 boreholes with an Ø72 mm GEONOR piston sampler. The compiled database with results from tests on 72 mm samples is further referred to as the *Reference database.*

To evaluate the effect of sample quality on the strength and stiffness characteristics of the clay, Ø250 mm Sherbrooke block samples were retrieved at three locations along the planned E16. These locations are referred to by their borehole identification numbers which are 2371, 2411 and 2284. All block samples were carved at similar depths as the previously retrieved 72 mm samples and are representative of the general soil conditions in the study area.

3 GEOTECHNICAL PROPERTIES OF THE CLAY

3.1 *Index properties*

The water content of the clay samples in the study area ranges from 30–45% while the total unit weight varies between 17.5 and 19.5 kN/m^3 (Fig. 2). The plasticity index (Ip) is generally in the range of 7–25%. An example of a geotechnical profile with index properties for borehole 2371 is shown on Figure 2.

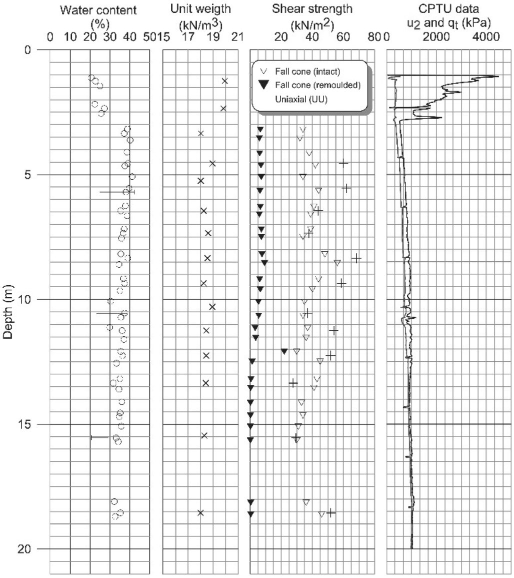

Figure 2. Typical borehole log (2371) in the study area showing results from index tests, strength tests and CPTU.

3.2 *Effective stresses and stress history*

From the geological history of the area, no exceptional loading events are known; only normal sedimentation processes. Some overconsolidation is however observed at some locations in the study area due to unloading caused by erosion from creeks and rivers over the past. Groundwater level is 1–2 m below the ground surface. The pore water pressures were measured at several depth intervals and locations throughout the study area. The data generally show pore water pressures equal to 60–85% of hydrostatic conditions.

The preconsolidation pressure (or yield stress), p'_c, has been measured from CRS oedometer tests on the 72 mm and 250 mm samples. In general the overconsolidation ratio (OCR) in the clay ranges from 1.3 to around 6 at some locations. Figure 3 shows typical CRS results for tests carried out on block and 72 mm piston samples in the study area. CRS results on the block samples clearly show a better distinction between the over consolidated stress range and the normally consolidated stress range. Hence the reliability in the selection of p'_c and OCR is better from the CRS test results on block samples.

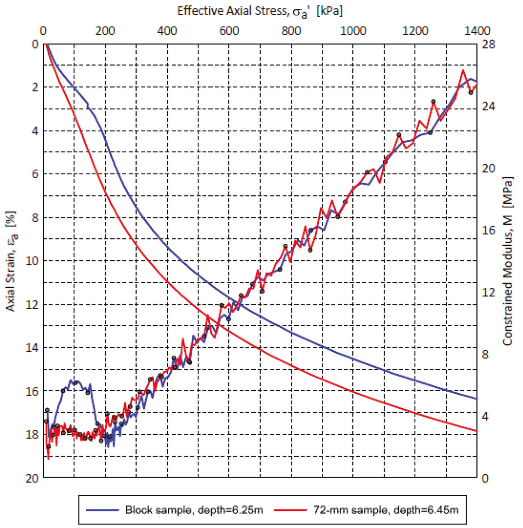

Figure 3. Example of oedometer test results from samples collected with a 72 mm sampler and a 250 mm block sampler in the study area. Test results are from borehole location 2371.

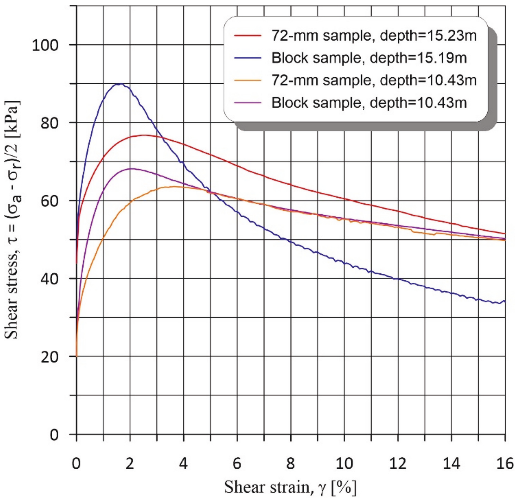

Figure 4. Example of CAUC triaxial test results from samples collected with a 72 mm piston sampler and a 250 mm block sampler in the study area. Test results are from borehole location 2371.

3.3 *Strength properties*

Typical results from anisotropically consolidated triaxial tests sheared in compression (CAUC) are shown in Figure 4 for both 72 mm samples and block samples from the same location and depth. According to the sample quality criteria proposed by Lunne et al. (1997) all samples were categorized as being of good to excellent quality. All stress-strain curves on Figure 4 show a strain softening behavior for the Rakkestad clay. However, results from CAUC tests on block samples show a higher peak shear strength and a more brittle behavior than those on the 72 mm samples (Fig. 4). The difference in peak strength can be important and was observed to be up to 53.8% at some locations (Table 1).

Table 1. Relative increase in undrained shear strength from block samples with respect to 72 mm samples.

Borehole no.	Depth m	s_u^C 72 mm kPa	s_u^C Block kPa	% increase %
2371	5.43	57.3	61.9	8.0
2371	10.43	63.6	68.2	7.2
2371	15.23	76.8	89.9	17.2
2411	6.21	45.1	56.6	25.5
2411	10.45	–	61.1	–
2411	12.06	48.0	73.8	53.8
2284	6.25	28.7	44.0	53.3
2284	11.36	–	51.1	–
2284	12.4	34.9	48.7	39.5

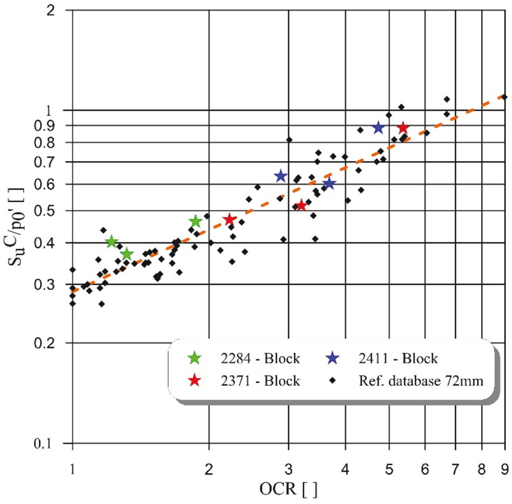

Figure 5. Normalized undrained shear strength ratio (s_u^c/p_0') from triaxial tests (CAUC) as a function of OCR.

Figure 5 illustrates the undrained shear strength normalized by the in situ effective stresses (p'_0) against OCR for CAUC laboratory tests. The normalized strength results from block samples show less variation than the 72 mm reference database. Also, the block samples generally give higher undrained shear strength ratio than that obtained from tests on 72 mm samples from same locations and depth.

4 CPTU CORRELATIONS

4.1 *Correlations for OCR*

CPTU correlations for assessing OCR in Norwegian clays have previously been established by Karlsrud et al. (2005). These correlations were established based on CPTU cone factors such as $N_{\Delta u}$, N_{kt} and N_{ke}, and a large database of block samples with overall similar soil conditions as those found herein. However, in this study, all form of correlations between OCR and the CPTU cone factors were found to be poor (i.e. very low regression coefficient; r^2). The best fit regression result was obtained between the normalized cone parameter Q_t and OCR (Fig. 6) through the following equation:

$$OCR = 0.35 + 0.645Q_t \qquad r^2 = 0.95 \qquad (1)$$

where $Q_t = (q_t - \sigma_{vo})/\sigma'_{vo}$, q_t with being the corrected cone resistance, σ_{vo} the total vertical stress and σ_{vo}'the vertical effective stress.

As shown on Figure 6, the trendline of Equation 1 is very similar to the Q_t-OCR trendline defined by Karlsrud et al. (2005) for clays with sensitivity higher than 15. One can also note little variation in the block sample data compared to the 72 mm data points. For a given a value of Q_t, the best regression line for the 72 mm reference database provides a much lower OCR value (i.e. black line in Fig. 6).

Figure 7 presents a regression of data based on the pore pressure parameter B_q, Ip, and the OCR. The regression analysis shows a fairly high regression coefficient, only slightly lower than r^2 for Equation 1. The best fit is given as:

$$OCR = 16.5 \cdot Bq^{-2.85} \cdot Ip^{-0.75} \qquad r^2 = 0.84 \qquad (2)$$

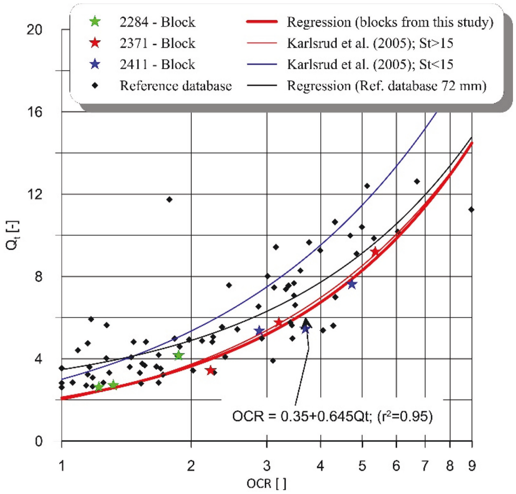

Figure 6. Normalized cone parameter Q_t against OCR.

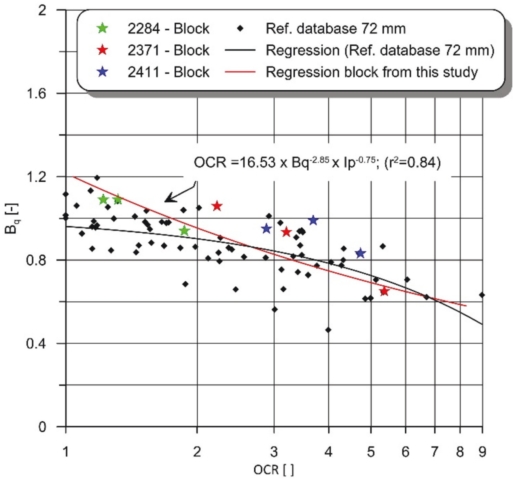

Figure 7. Pore pressure parameter B_q against OCR.

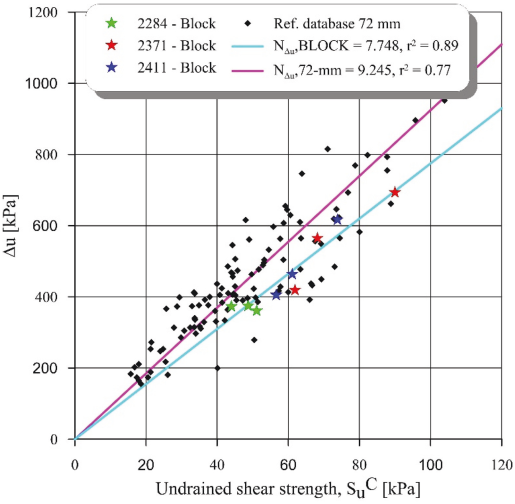

Figure 8. Excess pore pressure Δu measured at location u_2 against undrained shear strength from CAUC triaxial tests.

Once again, the results from block samples show more consistent results than those from the 72 mm reference database.

4.2 *Correlations for undrained shear strength in compression (s_u^c)*

Figures 8 and 9 illustrate the excess pore pressure and the net cone resistance against the measured undrained shear strength in compression (s_u^C) from the study area. From these figures, one can see that the undrained shear strength data correlates better (higher coefficient of determination; r^2) with the Δu parameter. On these figures, a larger scatter

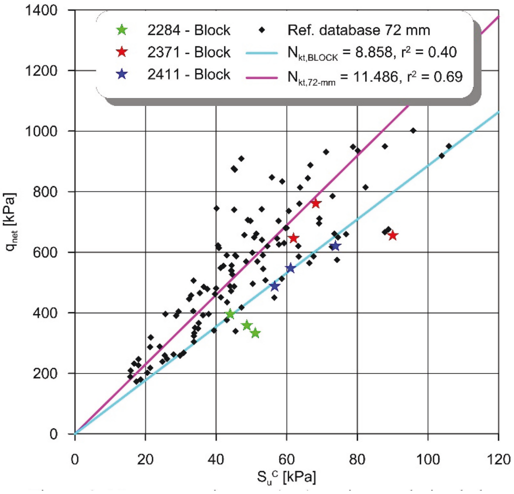

Figure 9. Net cone resistance (q_{net}) against undrained shear strength from CAUC triaxial tests.

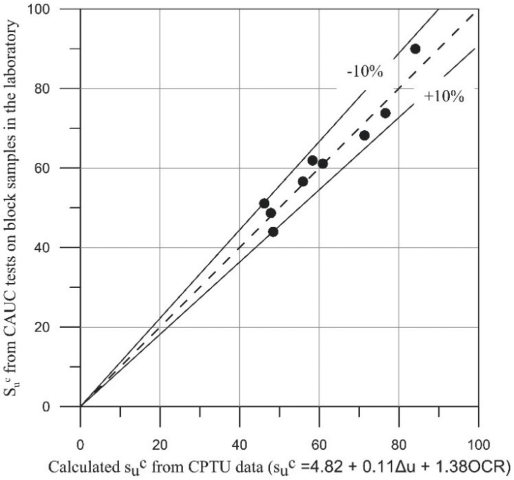

Figure 10. Calculated versus measured undrained shear strength in compression using Eq. 3.

can also be observed in the reference database compared to the larger diameter block samples data set.

To evaluate the most appropriate equation form for the interpretation of s_u^C from CPTU data in the study area, a series of regression analyses were performed.

The two best fits were obtained by using i) the Δu parameter with OCR, and ii) the q_{net} parameter with OCR. The resulting best fit equations are given as follows:

$$s_u = 4.82 + 0.11\Delta u + 1.38OCR \qquad r^2 = 0.93 \qquad (3)$$

$$s_u = 0.39OCR^{-0.17} \cdot q_{net}^{0.83} \qquad r^2 = 0.74 \qquad (4)$$

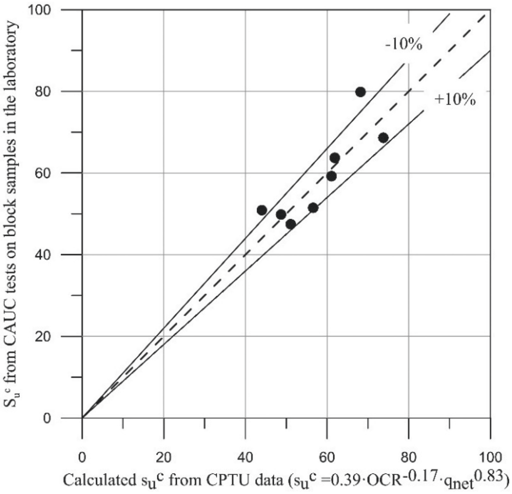

Figure 11. Calculated versus measured undrained shear strength in compression using Eq. 4.

As shown from the r² coefficients above, the best statistical fit is obtained with Equation 3 on the basis of the Δu parameter and OCR data. Figures 10 and 11 shows that both Equations 3 and 4 gives reliable estimates of s_u^C in the study area, within +/– 10% of that measured in the laboratory from CAUC on block samples.

5 DESIGN CONSIDERATIONS

A typical example of the use of Equations 1–4 in the study area is shown in Figure 12 for a CPTU test carried out at location 2371. On this figure, the OCR and s_u^C interpretations are compared to results from other empirical correlations normally used in design in Norway (i.e. Karlsrud et al. 2005) and to correlations based on laboratory results from 72 mm samples. The latter is based on the best fit $N_{\Delta u}$ correlation (i.e. $N_{\Delta u} = \Delta u/s_u^C$) shown in Figure 8.

As expected, a better match with the relationships based on the block sample correlations is obtained. The Karlsrud et al. (2005) relationship seems to underestimate the OCR of Rakkestad clay. The differences are significant throughout the profile (Figure 12).

Differences are also observed in the case of the interpreted undrained shear strength (Figure 12). Here the difference can be up to 30–40% when compared to the interpretation based on the 72 mm reference database. Also, at depths larger than 10 m, the estimated shear strength from Equations 3–4 is generally higher (up to 30%) than that obtained from the Karlsrud et al. (2005) methodology.

The major difference between the undrained shear strength estimated from the 72 mm reference data-

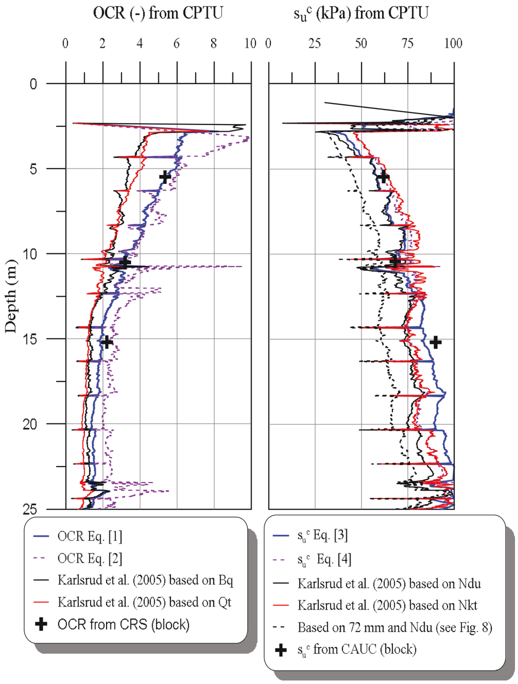

Figure 12. Interpretation of OCR and s_u^C of Rakkestad clay at borehole 2371 based on correlations by Karlsrud et al. (2005) and on the best fit empirical correlations obtained from this study (i.e. both 72 mm and block samples).

base and that based on the block samples is associated with sample quality and sampling technique. Throughout this project, the laboratory results on the block samples showed consistently superior quality than those acquired on the 72 mm samples, which resulted in a notable difference in undrained shear strength. This seems to agree with other studies documenting the impact of sampling processes in soft and sensitive clays (e.g. Berre et al. 2007).

Results from this study show with little doubt that one can use a higher undrained shear strength profile in design for the Rakkestad clay along the planned E16 highway. At some locations along the highway, the difference between the previously recommended design line and the new design criterion from block samples can be important (i.e. up to 40% in active undrained shear strength). The results are expected to lead to important economic savings for the E16 project and highlight the need for local and high quality samples for CPTU correlations in soft and sensitive clays. A first assumption is that the findings will lead to a saving of approximately 30% of costs associated with lime-cement stabilization of road cuttings along the E16 highway project.

6 CONCLUSIONS

A high quality database including results from CPTU and laboratory tests performed on Ø72 mm piston samples and Ø250 mm block samples collected along the planned new highway, E16, from Nybakk to Slomarka, in southeastern Norway was assembled. The laboratory results on block samples show a superior quality compared to 72 mm samples, a higher peak undrained shear strength and less scatter in the other important geotechnical parameters such as preconsolidation stress and overconsolidation ratio.

Based on regression analyses, the database allowed the development of empirical correlations between CPTU parameters and the undrained shear strength and the overconsolidation ratios for the Rakkestad clay. The recommended CPTU correlations in the study area show up to 40% increase in undrained shear strength when compared to previously established CPTU correlations for Norwegian clays, or to correlation based on laboratory tests performed on 72 mm samples.

Results presented herein clearly show the importance of establishing site specific correlations when assessing geotechnical parameters from CPTU tests. In soft and sensitive clays, it is also particularly important that the correlations are established from large diameter samples of very high quality. For the E16 project, a small investment in the field campaign to collect large diameter block samples will lead to cost-effective solutions and savings of approximately 30% associated with the lime-cement stabilization of road cuttings.

ACKNOWLEDGEMENTS

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