

Undrained shear strength of marine clays based on CPTU data and SHANSEP parameters

Résistance au cisaillement non drainée des argiles marines sur la base des données CPTU et des paramètres SHANSEP

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ABSTRACT: A database of CPTU data in marine clays, including index parameters and preconsolidation stresses from oedometer tests is established. Correlations between CPTU data and preconsolidation stress or OCR were developed based on data from 7 offshore and 1 onshore marine clay sites. Laboratory data on SHANSEP parameters of clays are collected. The CPTU data and SHANSEP parameters can be used together to estimate in-situ undrained shear strength of clays. One case study on a clay site from the Norwegian sea is presented.

RÉSUMÉ: Une base de données CPTU dans les argiles marines, comprenant les paramètres d'indice et les contraintes de préconsolidation issues de tests oedometer a été établie. Des corrélations entre les données CPTU et les contraintes de préconsolidation ou l'OCR ont été développées à partir de données provenant de 8 sites d'argile marine (8 offshores et 1 terrestre). Les données de laboratoire sur les paramètres SHANSEP des argiles sont collectées. Les données CPTU et les paramètres SHANSEP peuvent être utilisés ensemble pour estimer la résistance au cisaillement non drainée in situ des argiles. Une étude de cas sur un site argileux de la mer de Norvège est présentée.

Keywords: CPTU, undrained shear strength, SHANSEP, Oedometer tests

1 INTRODUCTION

It is well-recognized that the preconsolidation stress, p'_c , affects the undrained shear strength (s_u) of clays significantly (e.g. Ladd and Foott, 1974; D'Ignazio et al., 2016). A number of theoretical and empirical correlations that relate CPTU parameters to preconsolidation stress, p'_c , or overconsolidation ratio, OCR, have been proposed in the geotechnical literature. These

include correlations between OCR and pore pressure ratio (Wroth, 1984), OCR and normalized cone resistance (Wroth, 1984), between p'_c and pore pressure change (Mayne and Holz, 1988), p'_c and net cone resistance (Tavenas and Leroueil, 1987). Chen and Mayne (1996), Leroueil et al., (1995), Mesri (2001) and Powell and Lunne (2005) have found that the overall best

correlation existed between p_c' and net cone resistance:

$$p_c' = k q_{\text{net}} = k (q_t - \sigma_{vo}) \quad (1)$$

where q_t is the corrected cone tip resistance and σ_{vo} the total overburden vertical stress. OCR can be derived from p_c' as:

$$\text{OCR} = p_c' / \sigma_{vo}' = k (q_t - \sigma_{vo}) / \sigma_{vo}' \quad (2)$$

where σ_{vo}' is the effective vertical stress.

The parameter k is generally clay or site-specific. Based on 205 clay sites all over the world, Chen and Mayne (1996) found on average $k=0.31$. For eastern Canada clays (Leroueil et al., 1995), $k=0.28$ was found. Further, for organic soft clays and silts, $k=0.24$ was suggested (Mesri, 2001). Powell and Lunne (2005) found $k=0.25-0.4$ for Onsøy, Lierstranda and Drammen clays from Norway. Based on data from 36 clay sites, Mayne and Holz (1988) observed that a good correlation existed between OCR and measured excess pore pressure from CPTU:

$$\text{OCR} = (0.42 * \Delta u / \sigma_{vo}')^{1.35} \quad (3)$$

The quality of the data used to derive the existing correlations may vary significantly among the different studies. Test results may not always be of high quality and often sample quality is not discussed. There are, however, studies where high-quality samples (e.g., block samples) were used, e.g. in Powell and Lunne (2005), and the quality of the tested specimen assessed using qualitative methods (e.g. Lunne et al. 2006).

The "Stress history and normalized soil engineering properties" (SHANSEP) concept by Ladd and Foott (1974) is frequently used to evaluate the undrained shear strength of clays. The SHANSEP approach consists of performing a series of laboratory tests (triaxial, direct simple shear) on samples with different OCR, in order to establish a relation between the normalized

strength (e.g. s_u / σ_{vo}' , s_u / p_c') and the OCR. The concept can be extended to a range of stress-paths, and it allows to study the variation of anisotropic strength with OCR. The curves obtained from laboratory tests are then used to model s_u in the field.

In this study, data from projects carried out by the Norwegian Geotechnical Institute (NGI) and from literature is collected. The purpose is to study possible correlations between OCR and CPTU data, then to evaluate the in-situ undrained shear strength of clays by using the SHANSEP framework. The combined CPTU-SHANSEP approach is evaluated for a clay site in the Norwegian Sea and compared to the more traditional approach based on cone factors.

2 INVESTIGATED SITES AND REFERENCE DATABASE

In this study, a database of clays has been compiled, consisting of 178 data points from 8 marine clay sites (7 offshore and 1 onshore): Barents Sea, Norwegian Trench, Norwegian Sea, Vøring basin, Gulf of Guineas (GOG), Indian Coast, Offshore Egypt and Onsøy (onshore). CPTUs for all the sites were carried out according to ISO 19901-8:2014. The 75mm-diameter piston tube sampler was used to collect samples from the offshore sites, whilst at Onsøy site a Sherbrooke block sampler (250mm-diameter) was used.

Typical corrected cone resistance, q_t , and excess pore pressure, u_2 , profiles for the sites in the database are shown in Figures 1 and 2.

All studied sites show very similar cone resistance and u_2 profiles, except for the Barents sea site, where the soil seems to be stronger.

The database includes the following parameters: water content, plasticity index, clay fraction, liquid limit, plastic limit, sensitivity, effective preconsolidation stress (p_c') and, therefore, OCR, recompression volume to the in-situ stress in oedometer tests $\Delta e / e_i$. CPTU data

including net cone resistance, q_{net} , and excess pore water pressure, u_2 , are obtained nearby the borehole locations.

The preconsolidation stress, p_c' , was determined from constant-rate-of-strain CRS oedometer tests using Casagrande's construction. All tested samples in the database showed "very good to excellent" and "good to fair" sample quality, based on the $\Delta e/e_i$ ratio (Lunne, et al., 2006). Sensitivity is less than 12 and OCR is less than 4.5 for the collected data set.

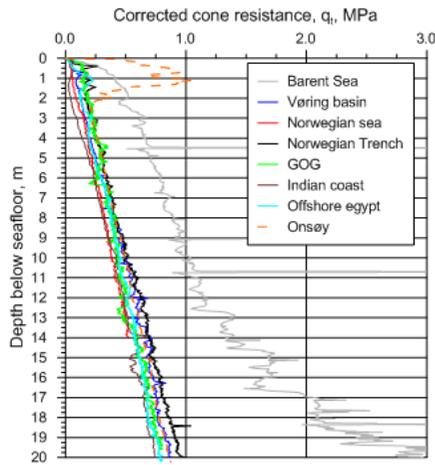


Figure 1. Typical cone resistance profiles for the studied sites

It should be mentioned that the p_c' values found from the CRS tests represent the so-called "rapid p_c' ". Due to rate effect, the p_c' found from 24 h load step IL (incremental load) oedometer tests is expected to be lower. For example, for Eastern Canadian clays Leroueil (1997) found $p_c'_{CRS}/p_c'_{IL}$ to be on average 1.28. Berre et al. (2007) showed that rapid p_c' is 9% to 18% higher than the values from IL p_c' . In this study, p_c' from CRS tests is used as a reference.

Ranges and average values of water content (w), plasticity index (I_p), clay fraction, sensitivity, OCR and $\Delta e/e_i$ for each site are summarized in Table 1.

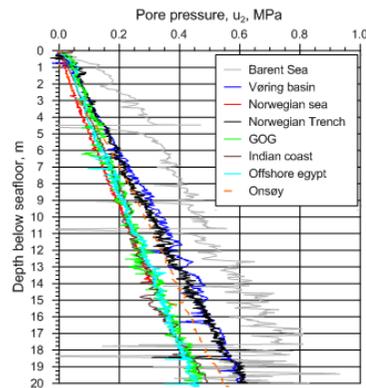


Figure 2. Typical pore pressure profiles for the studied sites

Table 1 Soil parameters for the 8 clay sites included in the database.

Site	Water content (%)		Plasticity index (%)		Clay content (%)		Sensitivity		OCR		$\Delta e/e_i$	
	range	average	range	average	range	average	range	average	range	average	range	average
Barents Sea	25-48	32	22-42	28.0	33-52	41.0	1.4-2.7	1.8	1.2-4.5	2.0	0.006-0.062	0.034
GOG	79-147	110	64-110	93.0	46-75	59.0	3.4	3.4	1.4-3.4	2.0	0.016-0.055	0.032
Indian coast	48-126	90	34-68	52.0	31-83	61.0	1.1-5.5	3.2	1.3-2.7	1.9	0.003-0.054	0.030
Offshore egypt	80-180	125	32-72	59.0	21-75	61.0	2.4-6.2	4.3	1.2-2.1	1.5	0.016-0.06	0.040
Vøring basin	33-89	63	30-48	39.0	40-63	53.0	1.5-5.6	3.0	1.1-1.8	1.4	0.025-0.068	0.052
Norwegian sea	118-130	123	38-63	53.0	46-63	54.0	6.5-7.3	6.9	1.3-1.4	1.3	0.052-0.058	0.054
Norwegian trench	29-84	63	22-43	33.0	37-67	50.0	2.0-8.0	4.9	1.1-2.6	1.7	0.01-0.066	0.032
Block samples	34-72	60	15-44	34.0	17-44	32.0	8.0-12	10.0	1.2-1.9	1.6	0.027-0.048	0.036

3 CORRELATIONS BETWEEN CPTU DATA AND LABORATORY TEST RESULTS

Three correlation factors, k_1 , k_2 , k_3 , are defined in this study as follows:

$$p_c' = k_1 q_{net} = k_1 (q_t - \sigma_{v0}) \quad (4)$$

$$p_c' = k_2 (u_2 - u_0) \quad (5)$$

$$p_c' = k_3 u_2 \quad (6)$$

Table 2 shows ranges and mean values of k_1 , k_2 , k_3 , B_q , q_{net} , u , and u/σ_{v0}' for each site. Correlations between k_1 , k_2 , k_3 and index parameters did not show any significant trend.

From Table 2, it can be observed how k_1 , k_2 and k_3 vary from site to site. Figures 3 and 4 show

examples from the Norwegian Sea and the Barents Sea sites on the k_1 factor.

Figure 5 shows correlations between p_c' and $(u_2 - u_0)$, and between p_c' and q_{net} for all sites. Figures 6 and 7 show correlations between $(u_2 - u_0)/\sigma_{v0}'$, $(q_t - \sigma_{v0})/\sigma_{v0}'$ and OCR, respectively. Despite the data scatter, there is a general trend suggesting that $(u_2 - u_0)/\sigma_{v0}'$ and $(q_t - \sigma_{v0})/\sigma_{v0}'$ increase with increasing OCR. Moreover, Figure 5b suggests $k_1 = 0.24$, which is lower than the $k_1 = 0.31$ proposed by Chen and Mayne (1996).

Figure 8 shows that good correlation exists between $B_q (= \Delta u / q_{net})$ and OCR from the database. This agrees well with the trend observed from the Mad Dog data (Schroeder et al., 2006) presented in Figure 8

Table 2 CPTU related parameters in the database

Site	k_1		k_2		k_3		B_q		q_{net}		Δu		$\Delta u / \sigma_{v0}'$	
	range	average	range	average	range	average								
Barents Sea	0.14-0.32	0.20	0.25-0.67	0.44	0.21-0.57	0.34	0.31-0.64	0.5	82-685	429	39-340	194	2.4-8.3	4.5
GOG	0.2-0.3	0.20	0.48-0.78	0.60	0.25-0.46	0.30	0.3-0.52	0.4	74-577	351	37-242	145	2.2-4.7	3.3
Indian coast	0.16-0.33	0.20	0.36-0.68	0.50	0.22-0.42	0.30	0.34-0.72	0.5	46-1159	391	25-410	169	2.9-6.6	4.1
Offshore egypt	0.15-0.26	0.19	0.29-0.51	0.38	0.17-0.31	0.23	0.37-0.7	0.5	58-256	156	25-144	82	3.1-5.1	4.0
Vøring basin	0.2-0.41	0.28	0.3-0.57	0.40	0.22-0.36	0.27	0.53-0.8	0.7	78-978	403	51-602	267	2.6-4.8	3.5
Norwegian sea	0.18-0.23	0.21	0.4-0.46	0.43	0.23-0.24	0.23	0.39-0.54	0.5	116-134	125	52-66	60	2.8-3.6	3.1
Norwegian trench	0.18-0.3	0.24	0.31-0.71	0.48	0.21-0.47	0.32	0.39-0.66	0.51	83-629	195	37-247	93	2.7-5.5	3.5
Block samples	0.25-0.34	0.30	0.32-0.52	0.44	0.23-0.39	0.32	0.58-0.77	0.7	228-670	378	139-426	257	3.1-3.8	3.6

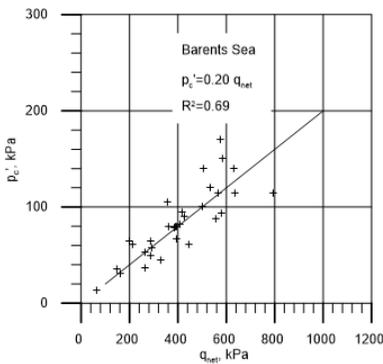


Figure 3 q_{net} versus p_c' for Barents Sea

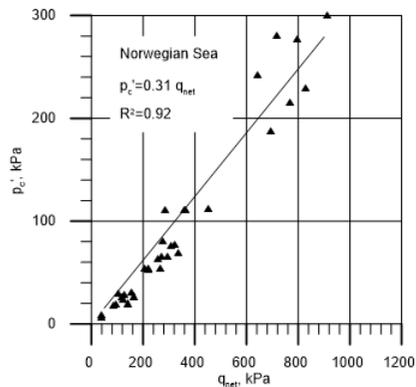


Figure 4 q_{net} versus p_c' for Norwegian Sea

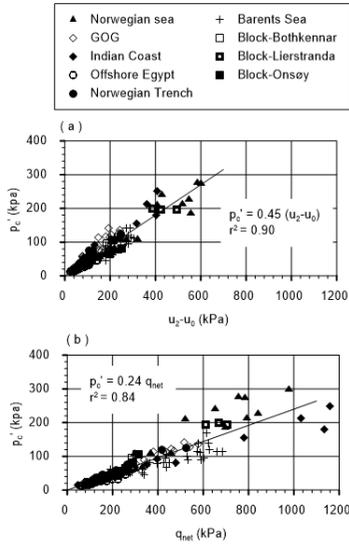


Figure 5 Correlations between p_c' and (u_2-u_0) (a), between p_c' and q_{net} (b), all sites.

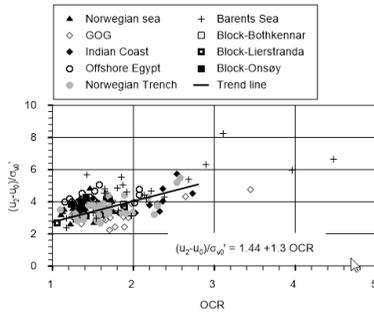


Figure 6 $(u_2-u_0)/\sigma'_{v0}$ versus OCR

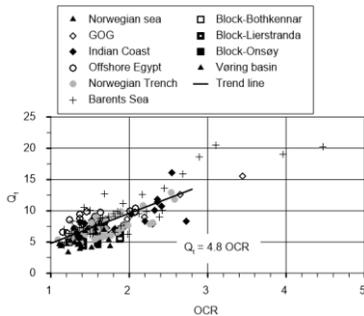


Figure 7 q_t versus OCR

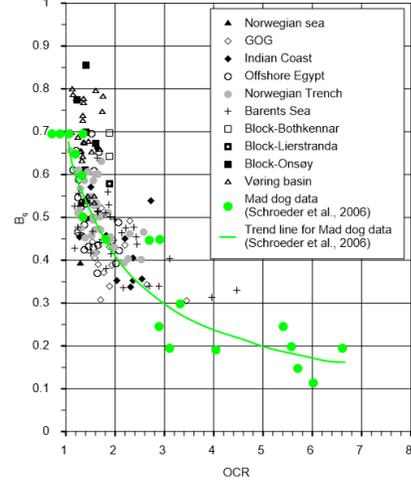


Figure 8 B_q versus OCR

4 SHANSEP PARAMETERS

In the SHANSEP approach, equation (7) is used to describe the undrained shear strength of a soil subjected to a particular stress path:

$$s_u/\sigma'_{v0} = (s_u/\sigma'_{v0})_{nc} \cdot (OCR)^m \quad (7)$$

where: s_u is the undrained shear strength, σ'_{v0} is the in situ effective vertical stress, $(s_u/\sigma'_{v0})_{nc}$ is the strength ratio at $OCR=1$, OCR is the over consolidation ratio and m is a material coefficient.

Data from several clay sites studied by NGI and presented in the literature are collected and summarized in Table 3. In general, m seems to vary between 0.70 and 0.98, while the strength ratio $(s_u/\sigma'_{v0})_{nc}$ generally ranges between 0.27 and 0.35 for triaxial compression mode. Exception is made for two clays reported by DeGroot (1999) for which $(s_u/\sigma'_{v0})_{nc}$ is as low as 0.18-0.19.

Table 3 Index parameters and SHANSEP parameters for different sites world wide.

Site	water content %	plastic limit %	Liquid limit %	Plasticity index %	Liquidity index -	Clay content %	Sensitivity -	OCR -	m -	strength ratio at OCR=1 -	Source, reference
Tangawizi	36	27.9	69.9	42.0	0.2	55.0		1.1	0.80	0.29	
Egypt	100	46.1	109.3	63.2	1.2	56.0	4.2	1.3	0.96	0.27	
Egypt	110	43.8	87.5	50.0	1.3	67.7	6.2	1.3	0.87	0.28	
	102	28.8	89.8	61.0	1.2	41.0	4.0	1.2	0.89	0.35	
Shah Deniz	104	30.0	90.0	60.0	1.2	40.0	4.0	1.2	0.98	0.30	
	65	27.3	68.1	40.7	0.9	58.2	3.3	1.5	0.75	0.32	NGI project
	41	28.3	76.3	40.0	0.3	59.8	2.0	1.1	0.75	0.31	
Norwegian Sea	54	27.8	70.0	42.2	0.6	51.1	4.0	1.2	0.77	0.31	
Onsøy	66	27.2	69.9	42.7	0.9	50-65		1.3	0.75	0.31	
Lierstranda	34	21.3	39.9	18.6	0.7	33.0			0.74	0.30	
				12-25		30-40			0.70	0.32	
Ormen Lange				>25		45-65			0.70	0.28	
Bonneville	58-67	23-26	36-47	10-23.5		34-38			0.82	0.32	Bay, et al., 2005
Bangkok	68.0	24.0	65.0	41.0	1.1				0.74	0.27	Seah and Lai, 2003
Klang	66-107	30-45	75-95	41-60					0.78	0.26	Amin et al., 1997
	38-40	20-24	40-47	20-24	0.7-0.9	48-57			0.71-0.77	0.28-0.33	Abdullahi et al., 2012
Boston											
Connecticut		30	45	15	>1				0.73	0.18	Degroot, 1999
Boston		25	45	20					0.75	0.19	Degroot,1999

5 CASE STUDY

The LUVA gas field is located in the Vøring basin of the Norwegian Sea in about 1300 m water depth. The undrained shear strength for foundation design at the LUVA deep water field has been discussed in detail by Lunne et al. (2012).

Figures 9 and 10 show s_u versus depth for the LUVA site from 4 boreholes. Measured s_u from triaxial tests and corrected s_u values are included in the plots. Given the low quality of the samples retrieved from the LUVA site, as a consequence of gas coming out of solution and causing cracking in the samples (Yetginer et al., 2012), s_u was corrected following the method proposed by Berre et al. (2007). Berre et al.'s (2007) correction method was based on a large project on comparison of very high quality and low quality clay samples. The correction procedure can only be justified for clays similar to the ones in Berre et al.'s (2007) database. The data base included clays that have an apparent OCR due to ageing.

Lunne et al. (2012) proposed a cone factor $N_{kt} = 12$ for triaxial compression at the LUVA site, ECSMGE-2019 – Proceedings

based on a very comprehensive evaluation of similarities with the Onsøy test site, where tests were performed on high-quality samples. The use of Berre et al.'s (2007) correction for s_u could be justified for LUVA because of the great similarities between Luva and Onsøy clays (Lunne et al. 2012).

The following three methods are used in this study to estimate the undrained shear strength at LUVA:

1. $s_u = (q_c - \sigma_{v0}) / N_{kt}$, $N_{kt} = 12$ from Lunne et al., (2012)
2. $OCR = p_c' / \sigma_{v0}'$, $p_c' = 0.28 q_{net}$.
 $k_1 = 0.28$ is the average of k_1 values in Table 2 from Norwegian Sea, Vøring basin, Norwegian Trench and GOG.
3. $OCR = [(u_2 - u_0) / \sigma_{v0}' - 1.44] / 1.3$, based on Figure 6

After OCR is determined, the SHANSEP parameters $m = 0.76$ and $(s_u / \sigma_{v0}')_{nc} = 0.31$ reported for the Norwegian Sea (Table 3) are chosen to calculate s_u .

Figures 9 to 11 show 1) measured s_u , 2) corrected s_u according to Berre et al. (2007), 3) estimated s_u based on CPTU data and SHANSEP parameters, and 4) estimated s_u based on $N_{kt} = 12$.

The s_u derived based on SHANSEP parameters combined with the OCR determined from CPTU correlations provides a fairly good estimate of the representative in situ s_u of the soil. These derived profiles are in line with the s_u resulting from the N_{kt} method (Figure 11).

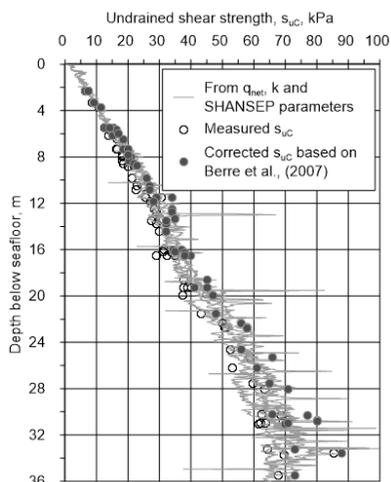


Figure 9 Undrained shear strength profiles based on CPTU cone resistance data and SHANSEP parameters for the LUVA site

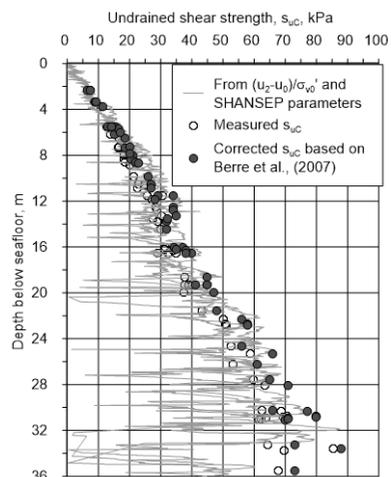


Figure 10 Undrained shear strength profiles based on CPTU pore pressure data and SHANSEP parameters for the LUVA site

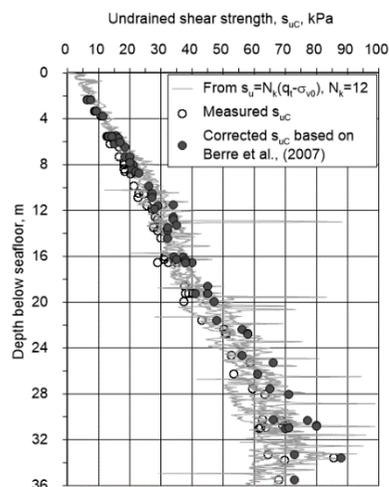


Figure 11 Undrained shear strength profiles based on CPTU data and N_{kt} factor for the LUVA site

6 CONCLUSIONS

Data from CPTU, oedometer tests, index tests and triaxial tests were collected from several sites to study possible correlations between strength of clays with OCR and index parameters. Correlations between CPTU data and preconsolidation stress p'_c and overconsolidation ratio OCR were developed from a database that includes high-quality data from 8 marine clay sites. No well defined correlations to model p'_c from CPTU data and index parameters could be established. Normalized CPTU parameters $(u_2-u_0)/\sigma'_{v0}$ and $(q_t-\sigma'_{v0})/\sigma'_{v0}$ were found to correlate with OCR, increasing with increasing OCR. Once OCR is evaluated from correlations or site-specific data, the in-situ undrained shear strength can be estimated by means of the SHANSEP method. The validity of this procedure was verified for a lightly overconsolidated clay site located in the Norwegian Sea, showing that the combined CPTU-SHANSEP approach agrees with the N_{kt} approach based on high-quality data. The approach described in this study needs to be verified for other clay types and higher OCRs.

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