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A Review of PSD and Soil Classification of DMS: Characterization Challenges

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ABSTRACT

Dredged marine soils (DMS) are variable sediments excavated for navigation and development. Initially poor in geotechnical quality, their composition reflects diverse geological and anthropogenic influences. Dredging and pre-treatment also alter particle size distribution (PSD). The Unified Soil Classification System (USCS), designed for more homogeneous soils, struggles to accurately classify complex DMS mixtures, hindering predictive capability for engineering behavior. A comprehensive characterization of DMS presents significant geotechnical challenges, particularly regarding the accurate determination of PSD and appropriate soil classification. This study synthesizes extant literature and contemporary geotechnical analyses to interpret the inherent limitations of conventional classification framework, including the USCS. Effective beneficial reuse requires moving beyond traditional classification towards comprehensive, performance-based evaluations and site-specific investigations to fully understand and utilize these complex materials.

1. Introduction

Dredged marine soils (DMS) are defined as sediments that have been excavated and removed from the beds of marine or estuarine water bodies, such as harbors, navigation channels, and river mouths [1] as shown in Figure 1. The primary purpose of dredging is typically to maintain or increase water depth for navigation, flood control, or coastal construction [2]. Consequently, DMS originates from a variety of geological and anthropogenic settings. The composition and inherent properties are highly variable, reflecting the seabed's parent material, the depositional environment's

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hydrodynamic conditions, and the extent of human-induced inputs from surrounding waterways and maritime activities [2]. Initially, DMS is commonly found in a slurry or liquefied form after the dredging and characterized DMS as having high water content and poor geotechnical quality with low shear strength, high compressibility, and low permeability.

The comprehensive characterization of DMS presents significant geotechnical challenges, particularly regarding the accurate determination of particle size distribution (PSD) and appropriate soil classification. This study synthesizes extant literature and contemporary geotechnical analyses to elucidate the inherent limitations of conventional classification frameworks, including the Unified Soil Classification System (USCS), when applied to the inherently heterogeneous nature of DMS. Furthermore, the research undertakes a comparative analysis of PSD determination techniques, investigates the ramifications of dredging processes on soil properties, and evaluates diverse classification methodologies through an examination of geographically varied case studies. Understanding DMS is crucial for effective geotechnical assessment and beneficial reuse in engineering projects. Traditional classification methods often fail to fully capture the complexity of mixed soils, leading to misinterpretations in engineering applications. This study emphasizes the need for alternative frameworks beyond USCS to ensure more accurate predictions of DMS behaviour.

Fig. 1. DMS sample retrieved during dredging activity at Kuala Muda, Kedah, Malaysia

2. Particle Size Distribution (PSD) Analysis of DMS

The determination of PSD is a cornerstone of geotechnical site characterization, providing essential data for soil classification and the prediction of engineering behaviour. For DMS, which can range from coarse sands and gravels to fine silts and clays, a combination of techniques is typically employed to cover the full spectrum of particle sizes.

2.1 Typical PSD Ranges and Characteristics for DMS

The primary methods for determining the PSD of soils, including DMS, are sieve analysis for coarse-grained fractions and sedimentation analysis (typically hydrometer or pipette) for fine-grained fractions [3]. DMS exhibits a wide range of PSDs, largely dependent on the source environment (i.e., river mouths, estuaries, coastal areas, offshore) and local geology. Particularly, those from inactive harbor and estuarine environments are predominantly fine-grained, consisting of silts and clay [4]. For example, DMS from New York and New Jersey harbors showed a median size range of 6 – 20 µm [5]. A study by Yang *et al.,* [6] on remediation research on DMS indicated that the particle size is predominantly below 75µm. Marine clay samples from various Malaysian waters were found to be composed primarily of fine particles (<0.002 mm), followed by silt and then sand [7] and supported by Rosman and Chan [8], DMS was composed of 13 % of sand, 69% of silt, and 18% of clay.

In contrast, DMS from higher energy environments or specific geological settings can be predominantly sandy or gravelly. DMS from the Pussur River in Bangladesh consisted mainly of fine sand [9]. Similarly, DMS from Savannah Harbor, USA, were classified as poorly graded sands [10]. It is also common for DMS to be a heterogeneous mixture of sand, silt, and clay, sometimes with organic matter and debris [2]. The relative proportions of these components dictate the overall PSD curve shape (i.e., well-graded, poorly graded, gap graded) as shown in Figure 2. The shape of the PSD curve, such as the steepness or presence of multiple modes, also provides insights into the sorting and depositional history of sediments. Well-graded soils, containing a wide range of particle sizes, generally exhibit better engineering properties (i.e., higher density, lower compressibility when compacted) than poorly graded soils, which consist of a narrow range of sizes.

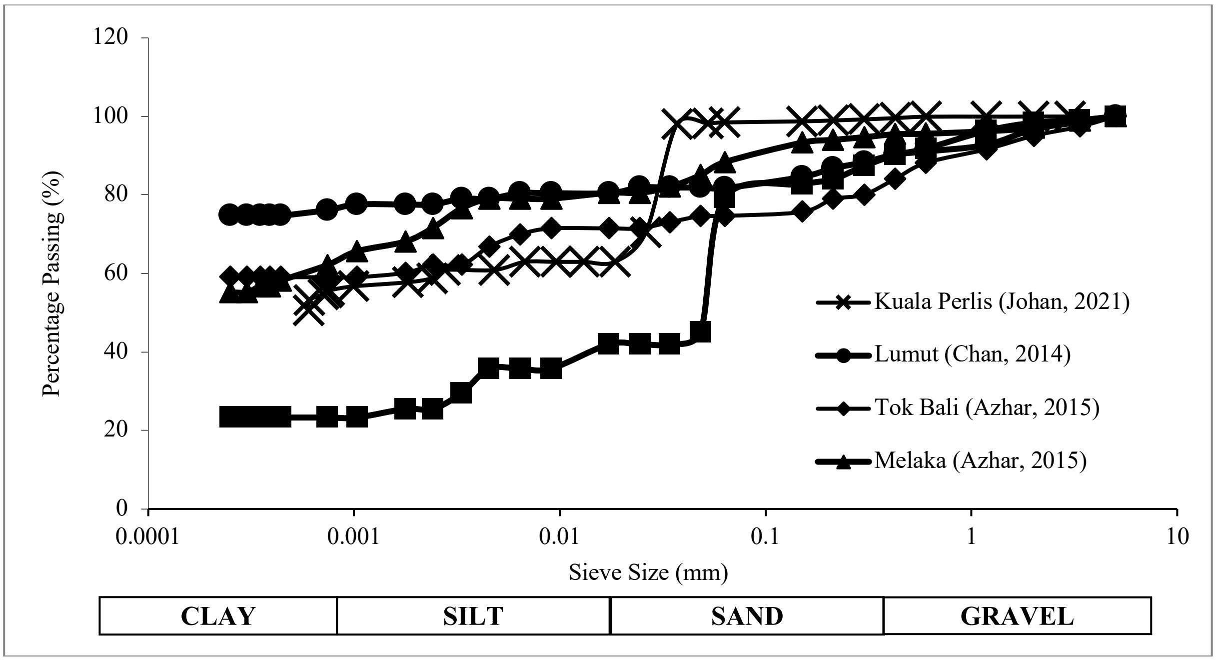


Fig. 2. Compilations of DMS from PSD analysis [1,4]

2.2 Influence of Dredging Techniques and Pre-Treatment on PSD

The dredging method and any subsequent pre-treatment can significantly alter the PSD of the material compared to its in-situ state. Mechanical dredgers (e.g., backhoes, clamshells) excavate sediment with relatively lower water content, largely preserving the in-situ particle associations, though some mixing and segregation can occur during handling [11]. Hydraulic dredgers (e.g., cutter suction, trailing suction hopper) mix the sediment with large volumes of water to form a slurry for transport. This process can break down weakly aggregated particles, leading to particle segregation during transport and initial deposition if flow velocities vary. The high-water content in hydraulically dredged slurries facilitates easier screening [12].

FRTR [12] reported that screening is often performed to remove debris and oversized materials or to separate dredged material into different size fractions for specific beneficial uses or subsequent treatment. This process directly modifies the PSD of the output streams. For instance, screening can remove coarse gravel and debris, leaving a finer material, or separate sand from fines. Screen openings can range from 150 mm to about 5 mm, with finer screening being more challenging for sediments rich in silts, clays, and organic matter due to screen blinding. Hydro cyclones may separate smaller sand particles (e.g., 5 mm to 0.08 mm) using centrifugal force. Screening can also occur at the point of dredging, with unwanted fractions returned to the seabed, potentially altering the local sediment composition [13]. The inherent nature of dredging as an excavation and transport process means the material is inevitably remolded, distinguishing its properties from the undisturbed in-situ sediment [11]. This remolding, combined with potential alterations from dredging method and screening, underscores the importance of characterizing the DMS in the state relevant to its intended management or reuse.

3. Unified Soil Classification System (USCS) Application to DMS

Soil classification systems provide a standard for describing soils and predict engineering behavior based on index properties derived from PSD and plasticity. The Unified Soil Classification System (USCS) is widely used internationally for engineering purposes. Application of USCS to DMS reveals a spectrum of soil types, for example, the common fine-grained classifications. The high plasticity clay (CH) indicates a predominantly clayey soil with high plasticity ($LL \geq 50$, plots on or above the "A" line on the plasticity chart). Referring to the Table 1, DMS from Kuala Perlis and Lumut, Malaysia, and at the Confined Disposal Facilities (CDFs) were classified as CH equivalent with USCS term [1,2,14]. In the case of high plasticity of silt (MH), it signifies a silty soil that has high plasticity ($LL > 50$) and plots below the "A" line. Nordin and Chan [15] reported DMS Kuala Perlis classified as MH as well Melaka, Malaysia [2]. Other researchers reported at Milwaukee Harbor, USA [16], and a base sediment used in a pavement material study [17] were also MH.

Low plasticity of silt denotes silty soils with low plasticity ($LL < 50$, plots below the "A" line or $PI < 4$). As reported by Shahri and Chan [2], DMS from Kuala Muda, Tok Bali in Malaysia, and some dredged material from Busan Port, Korea [18] fall into this category. Small cases found for OH (organic clay or silt) in the DMS. As mentioned earlier, some DMS can be classified as coarse-grained. For example, DMS from the Pussur River, Bangladesh [9], and Savannah Harbor, USA [10], were classified as SP. While silty sand (SM) was detected at Ulsan Port, Korea [18]. This indicates sand with more than 12% non-plastic or low plasticity of silt.

Dual symbols (i.e., GW-GM, SP-SM) are used for coarse-grained soils with 5-12% fines, where both grain size distribution and plasticity characteristics of the fines significantly influence engineering properties [19]. The widespread use of USCS in reporting DMS characteristics, as seen in these examples, likely stems from its broad acceptance and utility in general geotechnical engineering practice.

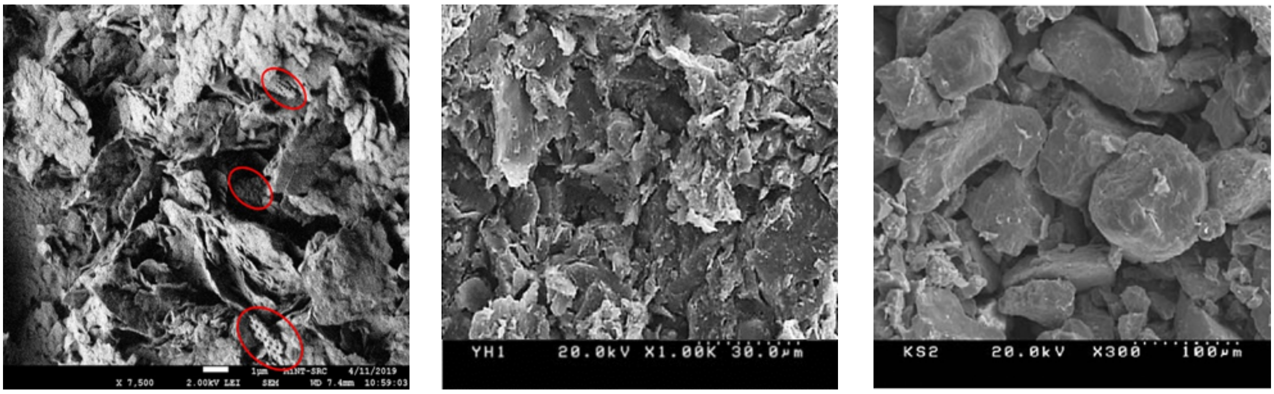
Table 1
Summary of USCS classifications and PSD characteristics of DMS worldwide

Locations	USCS classification	PSD	Dominant material	Ref.
Kuala Perlis, Malaysia	CH	Fine-grained, Low permeability	Clay	[1]
	MH	Fine-grained	Silt	[29]
Kuala Muda, Kedah, Malaysia	ML	Fine-grained	Silt	[2]
Kawasaki Port, Japan	CH	Fine-grained	Clay	[30]
Osaka, Japan	CH	Fine-grained	Clay	[30]
Lumut, Perak, Malaysia	CH	High Plasticity	Clay	[2]
Kakinda Sea Coast, India	CH	Fine-grained	Clay	[31]
Marina, Melaka, Malaysia	MH	High plasticity	Silt	[2]
Busan New Port, South Korea	ML/CL	Silt/clay 80-81.6%	Silty/clay	[18]
West Southern Coastal, South Korea	CL	Fine-grained	Clay	[32]
Iran	ML	Fine-grained	Silt	[33]
Tok Bali, Kelantan, Malaysia	ML	Low Plasticity	Silt	[2]
Pasir Gudang, Johor, Malaysia	ML	Fine-grained	Silt	[2]
Pussur River, Bangladesh	SP	Fine sand, fineness modulus 0.58 – 0.72	Sand	[9]
New York/New Jersey Harbor, USA	Not specified	Fine-grained	Silt/clay	[5]
Milwauke Harbor, USA	MH	96.6% fines, 9.8% OM, LL=61.5%, PL=42.2%	Silt	[16]
Savannah Harbor, USA	SP	Poorly graded sands, little silt/clay	Sand	[10]

4. Challenges in Characterization and Classification of DMS

4.1 Limitations of the Existing Classification System

The unique nature of DMS, particularly their heterogeneity and often mixed composition (Figure 3) presents significant challenges for traditional characterization and classification methods like the USCS. Despite being a foundational element of geotechnical engineering, it faces significant limitations when dealing with the complexity of highly heterogeneous and mixed DMS. Heterogeneity and mixed composition, USCS is primarily designed for relatively homogeneous soil deposits. DMS, however, are frequently highly heterogeneous, containing mixtures of gravel, sand, silt, clay, varying amounts of organic matter, shells, and anthropogenic debris. The predictive capability of a single USCS group symbol is limited when applied to complex mixtures, as it often oversimplifies and inadequately describes the bulk engineering behavior. This is evident in DMS materials used for land reclamation, where assessing engineering properties is inherently problematic due to their heterogeneity [20,21].



(a) (b) (c)

Fig. 3. SEM image of DMS (a) Kuala Perlis, Malaysia; (b) and (c) South Korea [34]

The behavior of soils containing significant fractions of both coarse and fine particles is complex. The discrete thresholds used in USCS (e.g., 50% fines to distinguish coarse from fine-grained; 5-12% fines for dual symbols) may not fully capture the nuanced interactions between the coarse and fine fractions that govern overall behavior [21]. The standard soil classification systems, like USCS, do not have specific provisions for classifying materials based on the content or type of anthropogenic debris or large natural inclusions like shells or cobbles. These components can dominate mass behavior, affecting compressibility, shear strength, permeability, and handling characteristics in ways not predicted by the soil matrix classification alone. Research on soil-rock mixtures [22] highlights the challenges posed by such non-homogeneity. While USCS includes categories for organic soils (OL, OH, PT), the system does not fully detail the wide range of engineering behaviors resulting from different types and concentrations of organic matter within these broad groups [23]. The influence of organic matter on plasticity and compressibility can be substantial. Other alternative approaches by using PIANC classification system for the DMS [24], attempt to provide a more holistic framework by considering factors directly relevant to the dredging process (excavation, transport, disposal, reuse) and include provisions for describing heterogeneity [25]. This may offer a more practical approach for dredging-specific applications.

The primary challenge with applying USCS to DMS lies in its idealization of soils into categories based on the properties of the soil matrix. This often fails to capture the complex reality of highly variable, mixed-phase materials that may contain significant non-soil components. Consequently, relying solely on a USCS classification without substantial engineering judgment and detailed supplementary descriptive information can lead to misinterpretation of the bulk engineering behavior of the DMS.

4.2 Difficulties in Obtaining Representative Samples and Consistent Test Results

The inherent variability of DMS poses significant challenges to obtaining samples that accurately represent the entire volume of material to be managed. As discussed, DMS properties can change dramatically over short distances, both horizontally and vertically. This necessitates a high density of sampling to adequately characterize a site, which can be costly and time-consuming as reported by Lee [11]. Sample disturbance due to soft, sensitive, fine-grained DMS is particularly susceptible to disturbance during sampling, handling, transport, and laboratory preparation. Disturbance can significantly alter the measured strength and consolidation properties. Other than that, laboratory testing issues. This is because the high natural water content of DMS, flocculated fine particles, dissolved salts (in marine sediments), and variable organic matter can complicate standard laboratory tests and affect the consistency and reproducibility of results [26]. For example, salt can influence Atterberg limits and dispersion characteristics.

4.3 Addressing the Impact of Debris and Anthropogenic Materials

Standard geotechnical testing protocols often involve pre-processing samples, such as removing particles larger than a certain size sieve (e.g., material retained on a 2 mm sieve might be excluded from some index tests [27], or particles >75 mm excluded from field classification [19]. While necessary for the applicability of the test methods, this means that the properties determined for the tested soil matrix may not fully reflect the behavior of the bulk DMS if it contains a significant fraction of larger debris or shells. Current classification systems offer limited formal guidance on how to incorporate the influence of such components into the primary classification, relying instead on descriptive notes.

The limitations of USCS for heterogeneous DMS imply that risk assessment and engineering design for beneficial reuse projects must rely more heavily on a comprehensive suite of performance-based tests tailored to the specific application and detailed site-specific investigations, rather than solely on properties inferred from a general soil classification. These points towards a need for more sophisticated characterization approaches, potentially integrating in-situ testing (like CPT, which can provide continuous profiles and help identify layering and variability [28], geophysical methods, and advanced statistical analysis of spatially variable data to better understand the range and distribution of properties within a DMS deposit.

5. Conclusions

In summary, DMS represent a complex and highly variable geomaterial whose accurate characterization is fundamental for effective management and beneficial reuse. While particle size distribution analysis provides essential information on grading, and systems like the USCS offer a standardized classification framework, their application to DMS reveals significant limitations. The inherent heterogeneity of DMS, often containing a mixture of soil types, organic matter, and debris, is not adequately captured by traditional methods designed for more homogeneous soils. This oversimplification can lead to an incomplete understanding of the material's true engineering behavior, complicating assessments for potential applications.

The challenges in characterizing DMS extend to practical difficulties in obtaining representative samples and achieving consistent laboratory test results due to the material's high-water content, fine particles, and variable composition. These limitations underscore the necessity of moving beyond sole reliance on standard classification systems. To facilitate the sustainable and beneficial reuse of DMS, a more comprehensive approach is required. This should involve detailed site-specific investigations, the application of performance-based testing tailored to the intended use, and potentially the adoption of alternative classification frameworks or supplementary descriptive methods that better account for the complex, heterogeneous nature of dredged marine soils.

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