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Seabed Soil Classification, Soil behaviour and Pipeline design

N. I. Thusyanthan, Cape Group Pte Ltd

Abstract

Geotechnical survey and the resulting soil classification is one of the fundamental design inputs for any subsea structure or pipeline design. Yet, details of soil classification and its limitations for predicting soil behaviour under various scenarios are not fully understood by pipeline design engineers. As soil classification is often used by pipeline engineers to predict pipe-soil interaction behaviour for a given scenario, lack of fundamental understanding of soil classification often leads to problems later in projects. This paper aims to provide some soil mechanics fundamentals to pipeline engineers. This paper presents a comprehensive summary of how soil classification is carried out based on commonly used standards; ASTM D-2487, BS 5930 and ISO 14688. The paper highlights the fundamental limitations in the classification systems and shows how the use of these different standards can result in different soil classification for very similar soils. The paper brings out an important point that the soil behaviour in a given application is not always in accordance with its soil classification. Examples such as ploughability assessment results and pipeline on-bottom stability assessment results are highlighted to show that when particle size distribution falls near the classification boundary of coarse/fine soils, then soil classification alone may not fully capture the soil behaviour for particular aspects of design and operation.

Introduction

Seabed soil classification is a key step in any offshore project. The soil classification is then used by the pipeline design engineers to assign appropriate design parameters for soil/structure interaction and also to predict soil behaviour (soil resistance, soil deformations) under various operations such as piling, ploughing, jetting etc. Thus understanding the fundamentals of soil classification is vital for pipeline design engineers.

Generally, soil behaviour is categorised as “drained” or “undrained”. Soil behaviour depends on the rate of loading (i.e. the rate at which force is applied to the soil). If the rate of loading is greater than the rate at which pore water (water that is present in the inter-particle voids) is able to move in or out of soil inter-particle voids, then the soil is said to behave in an undrained manner. The volume change of the soil is zero, and the behaviour of the soil is independent of inter-particle forces. If the rate of loading is slower than the rate at which pore water is able to move in or out of soil inter-particle voids, the soil is said to behave in a drained manner.

In summary, whether a soil (sand or clay) behaves in a drained manner or undrained manner, depends on the rate of loading with respect to the permeability of the soil. CLAY behaviour is commonly considered to be undrained, because the rate of loading is usually much greater than the rate at which pore water can move in or out of inter-particle voids (i.e. the permeability of CLAY is very low ~10^{-9}m/s). Hence, the strength of CLAY is given as “undrained shear strength”, denoted by symbol S_u or C_u, and measured in kilopascals (kPa). SAND behaviour is commonly considered drained, because pore water can move in or out of inter-particle space at a greater rate than the rate of loading. Hence, the SAND strength is given in terms of friction angle using the symbol ϕ. It is to be noted that if CLAY is sheared at a very slow rate (~ 0.001 mm/min), such that enough time is allowed for the pore water to move in or out of the inter-particle voids, then it will not exhibit undrained shear strength. Instead, it will behave more like sand with applicable clay friction angle. Similarly, if SAND is sheared at a very fast rate, such that the pore water does not have enough time to move around, then SAND can exhibit undrained behaviour.

For any given soil type (i.e. SAND, CLAY or SILT), the soil behaviour is determined primarily by the following factors:

- particle size distribution of the soil
- soil state (loose/dense for sand; normally consolidated/overconsolidated for clay)
- stress history and current stress state

- water content
- rate of loading applied (drained vs undrained)

The particle shape distribution and chemical composition of the soil also plays are role in its behaviour.

The Relative Density (D_r) of SAND and the Overconsolidation Ratio (OCR) of CLAY

SANDs can have varying degrees of particle packing. A well packed state will give rise to dense sand, while a very loosely packed state will lead to loose sand. Relative Density is a measure of soil packing in relation to standardised loose and dense soil states. Relative Density D_r is a measure of soil packing in relation to standardised loose and dense soil states,

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}}$$

Where

$e_{\max}$ is defined as the voids ratio achieved in quickly inverting a measuring cylinder containing dry soil

$e_{\min}$ is defined as the voids achieved under optimal vibration of a compactive mass under saturated conditions and without causing crushing.

When sands are sheared, loosely packed sands tend to contract i.e. the volume decreases, while densely packed sands tend to dilate i.e. the volume increases.

CLAY that has not experienced a higher vertical load than it is currently experiencing is referred to as “normally consolidated” CLAY. If CLAY has experienced higher vertical loads in the past than the current vertical load, the CLAY is referred to as “overconsolidated”. The level of overconsolidation is given by the overconsolidation ratio (OCR), which is the ratio of the highest stress experienced to the current stress level in the soil.

General overview of soil classification

Soil in general can be classified as CLAY, SILT, SAND, GRAVEL or COBBLE, based on the particle sizes of the soil. However, SANDs, GRAVELs and COBBLEs all behave in a similar fashion whereas CLAYs behave quite differently. The behaviour of SILTs depends on the percentage of the finer content i.e. SILTs can behave like CLAYs or SANDs depending on the particle size distribution and plasticity.

Soil, unlike most engineering materials which are man-made (e.g. steel, concrete), is part of nature and is variable (at micro and macro levels) and irregular. Within a localised area, several soil types can be encountered, depending on the geology of the area. Soil behaviour depends mainly on its particle size distribution and the packing of its particles but chemical composition of the soil particle also plays a part. Theoretically, we can predict soil behaviour when it is either “sand” or “clay”. However, when soil constitutes of a combination of sand, clay and perhaps other materials which exist in nature (e.g. organic material such as peat and decayed forestry), there is need for specialist interpretation. The behaviour of the soil also depends on how external forces are applied to it and how fast the forces act on the soil.

A soil description in “BORING LOGs” describes the as-observed soils in the Vibrocore, with some description of the variation and other contents of the soil. The soil classification, according to BS (British Standards) or ASTM, is then carried out based on the laboratory test results and the guidelines given in the BS or ASTM. The soil description recorded in the “BORING LOGs” (as observed from the Vibrocores) is usually updated after the laboratory testing, but this may not be the case always. Thus, the soil description noted in “BORING LOGs” may not exactly match the soil description based on the soil classification. This may cause some confusion among pipeline design engineers and could lead to incorrect soil description taken forward for the pipeline design stage.

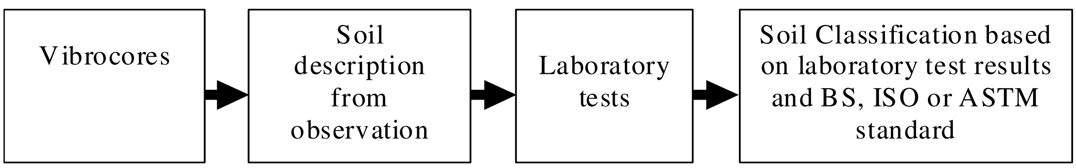

Figure 1: ASTM D2487 Soil Classification Summary

ASTM D2487 Standard Practice for Classification of Soils for Engineering Purposes

This is the ASTM version of the Unified Soil Classification System. The basis for this classification system in the Airfield Classification System developed by A. Casagrande in early 1940's. It is important to note three points with regard to the use of this document and this has been stated clearly in 1.7 in the document;

- *"the document cannot replace education or experience and should be used in conjunction with professional judgement."*
- *"This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service be judged, nor should this document be applied without consideration of a project's many unique aspects"*
- *"The word Standard in the title of this document means only that the document has been approved through the ASTM consensus process".*

The laboratory determination of the particle-size characteristics, liquid limit, and plasticity index is used by this standard to classify the soils. The soil is categorised into three major divisions; coarse-grained, fine-grained and highly organic soils. These three divisions are further subdivided into a total of 15 basic soil groups. If more than 50% of the soil is retained on No. 200 sieve (0.075mm), the soil is classed as Coarse-grained soils, and if 50% or more passes the No. 200 sieve, the soil is classed as Fine-grained soils. Coarse-grained soils are sub-divided based on percentage of fines, and c_u (D_{60}/D_{10}) and c_c [$(D_{30})^2$ /($D_{10} \times D_{60}$)]. Fine-grained soils are sub-divided based on liquid limit (LL), plasticity index (PI) and percentage soil passing sieve No.200 (0.075mm).

Coarse-grained Soils More than 50% of the soil is retained on No.200 sieve (0.075mm)	
GW	Well-graded gravel
GP	Poorly graded gravel
GM	silty Gravel
GC	Clayey gravel
SW	Well-graded sand
SP	Poorly graded sand
SM	Silty sand
SC	Clayey sand

Fine-grained Soils 50% or more passes No.200 sieve (0.075mm)	
CL	Lean clay
ML	Silt
OL	Organic clay
OL	Organic silt
CH	Fat clay
MH	Elastic silt
OH	Organic clay

Highly Organic Soil (PEAT PT)
composed of vegetable tissue in various stages of decomposition and has a fibrous to amorphous texture, a dark-brown to black colour, and an organic odor. If desired, classification of the type of the peat can be made according to D 4427.

Figure 2: ASTM D2487 Soil Classification Summary

The fine-grained soils are classified as summarised in Table 1. Furthermore, the following points are to be noted.

- The soil is *inorganic clay* if the plasticity index vs liquid limit falls on or above the "A" line or the plasticity index greater than 4 and the presence of inorganic matter does not influence the liquid limit.

- The soil is *inorganic silt* if the plasticity index vs liquid limit falls below the "A" line or the plasticity index is less than 4 and the presence of inorganic matter does not influence the liquid limit.

- The soil is organic silt or organic clay if organic matter is present in sufficient amounts to influence the liquid limit (i.e the soil is organic silt or clay is the liquid limit after oven drying is less than 75% of the liquid limit of the original specimen before oven drying (procedure B of Practice D 2217).

Silt is defined as fine-grained soil, or the fine-grained portion of a soil, with a plasticity index less than 4 or if the plot of plasticity index versus liquid limit falls below the "A" line (Figure.3).

Table 1: ASTM D2487 Soil Classification Summary

Name	Symbol	Description
Lean clay	CL	If the liquid limit is less than 50
Fat clay	CH	If the liquid limit is 50 or grater
silty clay	CL-ML	If the plasticity index is 4-7 and plasticity index vs liquid limit plot falls on or above “A” line.
Silt	ML	If the liquid limit is less than 50
Elastic silt	MH	If the liquid limit is 50 or greater
Organic silt or organic clay	OL	If the liquid limit (not oven dried) is less than 50%
Organic silt	OL	If the plasticity index is less than 4, or the plasticity index versus liquid limit plot falls below the “A” line.
Organic clay	OL	If the plasticity index is 4 or grater and the plascity index vs liquid limit plot falls on or above the “A” line.
Organic clay of organic silt	OH	If the liquid limit (not oven dried) is 50 or grater.
Organic silt	OH	If the plasticity index vs liquid limit falls below the “A” line.
Organic clay	OH	If the plasticity index vs liquid limit falls on or above the “A” line.

Addition to main classification

If less than 30% but 15% or more of the test specimen is retained on the No.200 (0.075mm) sieve, the words “with sand” or “with gravel” (whichever is predominant) is added to the group name. If sand and gravel percentages are equal, then “with sand” is used.

If 30% or more of the test specimen is retained in the No. 200 sieve, the words “sandy” or “gravely” shall be added to the group name (depending on what is predominant in the coarse-grained portion). If sand and gravel percentages are equal, then “sandy” is used.

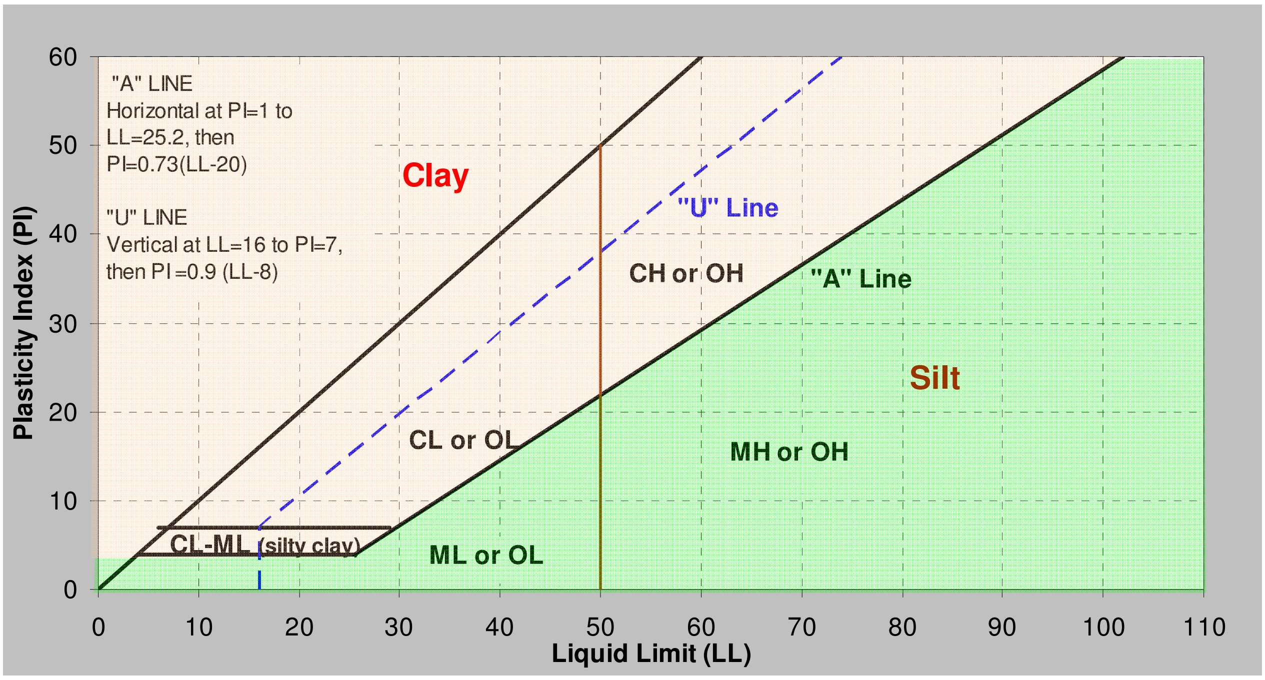

Figure 3: Plasticity Chart

BS 5930

BS5930 states that the soil name is based on particle size distribution of the coarse fraction and/or the plasticity of the fine fraction as determined by the Atterberg Limits. These characteristics are used because they can be measured readily with reasonable precision, and estimated with sufficient accuracy for descriptive purposes. In BS5930, the boundary for coarse-fine fraction size is set at 0.063mm compared to ASTM's 0.075mm. The soil description provides a general indication of the probable engineering characteristic of the soil at any particular moisture content.

BS5930 states that where a soil (omitting any boulders or cobbles) ''sticks together when wet'' it often contains about 35 % or more of fine material, and it is described as a fine soil (''CLAY'' or ''SILT'' dependent on its plasticity). With less than about 35 % of fine material (when it does not stick together), it is usually described as a coarse soil (''SAND'' or ''GRAVEL'' dependent on its particle size grading). The code further states that the 35 % boundary between fine and coarse soils is approximate and primarily depends on the plasticity of the fine fraction and the grading of the coarse fraction (i.e although the 35 % limit is often reasonably appropriate, soils with the boundary as low as 15 % are not unknown). Thus the 35% fine content is not a fixed boundary for classifying fine soil.

Soil classification and its behaviour, based on the BS standard 5930 is summarised in Figure 4. Soil classification system in accordance with BS5930 is shown in Table 2. Figure 5 shows a comparison of BS 5930 classification with ASTM D-2487.

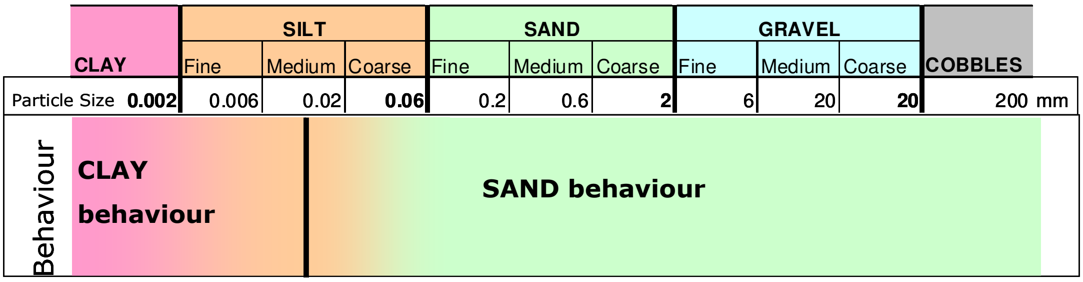

Figure 4: Schematic summary of particle size based on BS5930

Table 2. BS 5930 soil classification summary

Term	Principal Soil Type	Approximate proportion of secondary constituent	
		Coarse soil	Coarse and/or fine soil
Slightly clayey or silty and/or sandy or gravelly Clayey or silty and/or sandy or gravelly Very clayey or silty and/or sandy or gravelly	SAND And/or GRAVEL		<5% 5% - 20% >20%
Very sandy or gravelly Sandy and/or gravelly Slightly sandy and/or gravelly	SILT or CLAY	> 65% 35% - 65% < 35%	

ISO 14688

ISO states that soils shall be classified into groups on the basis of their nature which is the composition only, irrespective of their water content or compactness, taking into account the following characteristics; particle size distribution, plasticity, organic content; genesis. The summary from ISO 14688 soil classification is provided in Table 3.

Table 3. Particle size classification, from ISO 14688

Soil Fractions	Sub-Fractions	Symbols	Particle Sizes (mm)
Very coarse soil	Large boulder	LBo	> 630
	Boulder	Bo	>200 to 630
	Cobble	Co	>63 to 200
Coarse soil	Gravel	Gr	>2 to 63
	Coarse gravel	CGr	>20 to 63
	Medium gravel	MGr	>6.3 to 20
	Fine gravel	FGr	>2 to 6.3
	Sand	Sa	>0.063 to 2
	Coarse sand	CSa	>0.63 to 2
	Medium sand	MSa	>0.2 to 0.63
	Fine sand	FSa	>0.063 to 0.2
Fine soil	Silt	Si	>0.002 to 0.063
	Coarse silt	CSi	>0.02 to 0063
	Medium silt	MSi	>0.0063 to 0.02
	Fine silt	FSi	>0.002 to 0.0063
	Clay	Cl	≤ 0.002

Table 4. Extracted from ISO 14688-2

Fraction	Content of fraction in wt % of material ≤ 63mm	Content of fraction in wt % of material ≤ 0.063mm	Name of Soil	
			Modifying term	Main term
Gravel	20 to40		gravelly	
	> 40			Gravel
Sand	20 to 40		sandy	
	> 40			Sand
Silt + Clay (fine soil)	5 to 15	<20	slightly silty	
		≥ 20	slightly clayey	
	15 to 40	< 20	silty	
		≥ 20	clayey	
	> 40	< 10		silt
		10 to 20	clayey	silt
		20 to 40	silty	clay
		> 40		clay

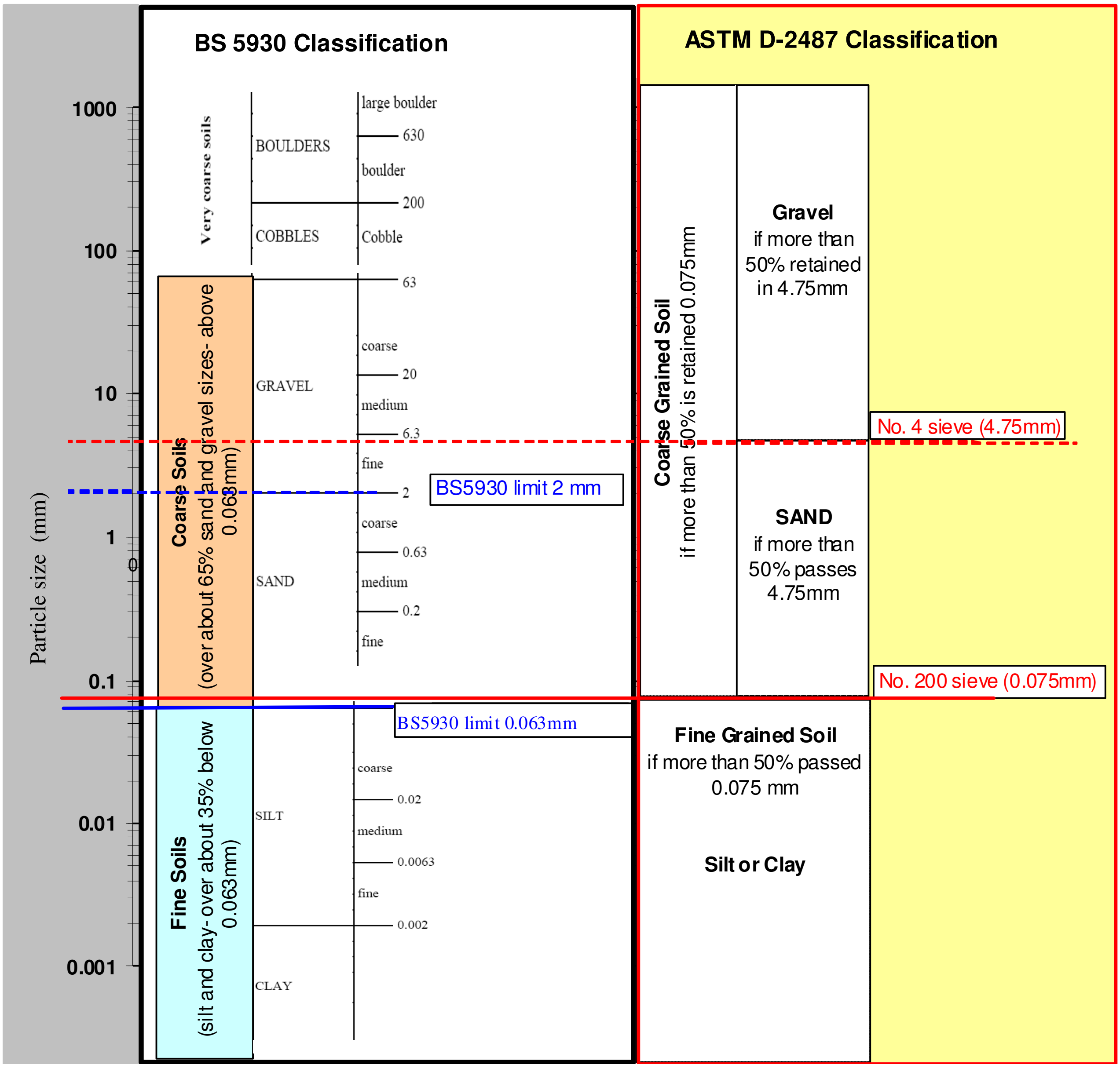

Figure 5: Comparison of BS5930 and ASTM D-2487

Practical Implications of soil classification

Comparison of Table 2 and 3, along with Figure 5, shows BS5930, ISO 14688 and ASTM D-2487 all have slightly different boundary definitions (particle size and percentage) when it comes to classifying coarse and fine grain soil. For example, ASTM requires 50% or more soil to be less than 0.075mm in particle size for the soil to be classed as fine grained soils (Silt or Clay), where as BS 5930 suggests 35% of soil to be less than 0.063mm in particle size for the soil to be classed as fine soils. ISO 14688 has same particle size boundaries as BS 5930 but has different percentages when it comes to classifying silt and clay (Table 4).

Figure 6 shows three real examples of particle size distributions from geotechnical survey reports. A geotechnical survey report classified sample 1, according to BS5930, as "Very silty slightly clayey fine to medium SAND". In another geotechnical report, sample 2 was classified according to ASTM, as "Grey sandy clay" and sample 3 as "Grey clayey fine sand". Samples 2 and 3 did not have particle size distribution below 0.075mm as hydrometer tests have not been carried out on those samples. It is to be noted that sample 1 has >35% of fine material and thus would have been expected to be classed as fine soils and classified as SILT or CLAY based on its plasticity. It is clear that sample 3 is very close to being at the boundary of coarse/fine soils classification according to BS 5930, whereas it clearly falls in the coarse grained soils category based on ASTM D-2487. Thus it is clear that the same soil can end up being classified differently by the standards when the particle size distribution of the soil is near the coarse/fine boundaries as defined by the standards. This has practical implications in offshore pipeline design and operations. This is demonstrated by providing two examples, ploughability assessment and on-bottom stability assessment, in which marginally incorrect soil classification can result in substantially different assessment results thus leading to difficulties in design and operation.

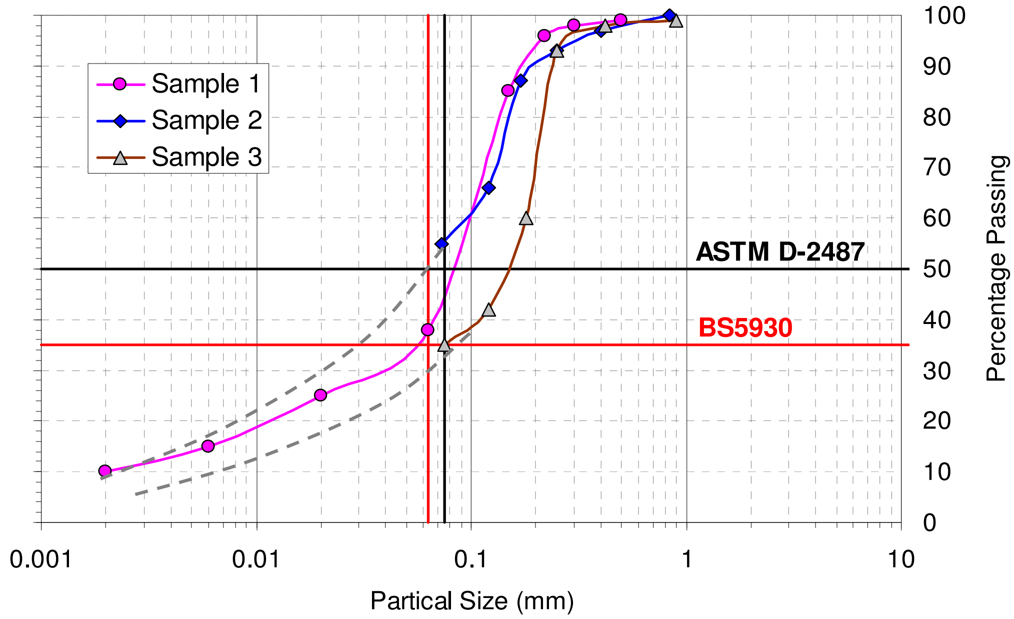

Figure 6: Particle size distribution from seabed samples

Seabed Ploughability Assessment

Pipelines are often buried in the seabed for protection from anchor or fishing gear damage, for stability of the pipeline, for better thermal insulation, or for compliance to national and local regulations. Ploughing is one of the most common methods of burying a pipeline. As part of the planning phase of ploughing operations, a ploughability assessment is carried out to estimate required tow force for a given plough speed. The main aims of a ploughability assessment is to identify the bottom-time required for the ploughing operation, to evaluate the tow force required and to identify any associated risks (i.e very slow ploughing or sinkage). Thus the results of the ploughability assessment are key to proper planning of offshore operations. The ploughability assessment results are very sensitive to seabed soil classification and soil properties. This is demonstrated by a parametric study based on methodology of Cathie & Wintgens (2001). This parametric study was carried out to provide an insight into how the soil properties affect plough tow force and plough speed. The assessment was done for a trench depth of 1.35m, and tow was limited to 250te and plough velocity limited to 500m/hour. The submerged weight of the plough and weight transfer from the pipeline was taken as 192 te. The submerged unit weight of soil was taken as 1 te/m^3.

The parametric study results in SAND (Figure 7) show the effect of soil state (loose, dense) and particle size (D10) on the plough tow force and speed. The speed of the plough decreases with the soil particle size even when the same plough tow force (maximum) is applied. The plough assessment results in CLAY are shown Figure 8. The results show the effect of increasing undrained shear strength of clay from 25kPa to 400 kPa. As it may be expected, for maximum plough speed to be maintained, the required tow force increases with the shear strength of the clay. At 300 kPa, the maximum tow force is insufficient to maintain the tow speed and the hence the tow speed reduced to 405m/hour and as the seabed shear strength increases further the predicted plough speed decreases.

It should be noted that these results are presented to show trends in plough performance with typical changes in the soil properties, and the results should not be directly used or related to specific projects. The results show the importance of reviewing the full soil data and using the correct soil properties in the assessment. If the assessment is based solely on soil classification and a typical value for the soil classification, then the results would be very misleading as it could be incorrect by many folders. For example, ploughability assessment for seabed of soil sample 2 will be based on CLAY model as it was classified as clay by ASTM standard and plough velocity of 500m/hr is predicted as long as the shear strength of clay is less than 300kPa. However, if the particle size of sample 2 extends similar to that of sample 1 with D_{10} <0.08 (shown in dashed line), then the soil behaviour is likely to be that of fine sand and ploughability assessment should be based on SAND model. This would mean that the expected plough velocity could be less than 100m/hr (Figure 7). Thus ploughability assessment solely based on soil classification can lead to risky results. It is recommended that all soil test data is reviewed in view of the application prior to proceeding with assessment.

It should be noted that the trenching may be slow to very slow in fine silty dense sands. It is recommended that detailed study of grain size distribution and additional sample should be collected if there are only few samples to make reliable estimates. Cathie & Wintgens (2001) stated that any fine sand with D_{10} less than 0.08mm should be scrutinised carefully. For medium dense to dense fine sands where dilation is bound to occur under shear failure, the permeability will play a vital role in determining the ploughing resistance. D_{10} is a good measure of the soil permeability, $k \propto (D_{10})^2$. Hence if soil consists of 10% or more of silts then careful scrutiny may be required in the ploughing assessment.

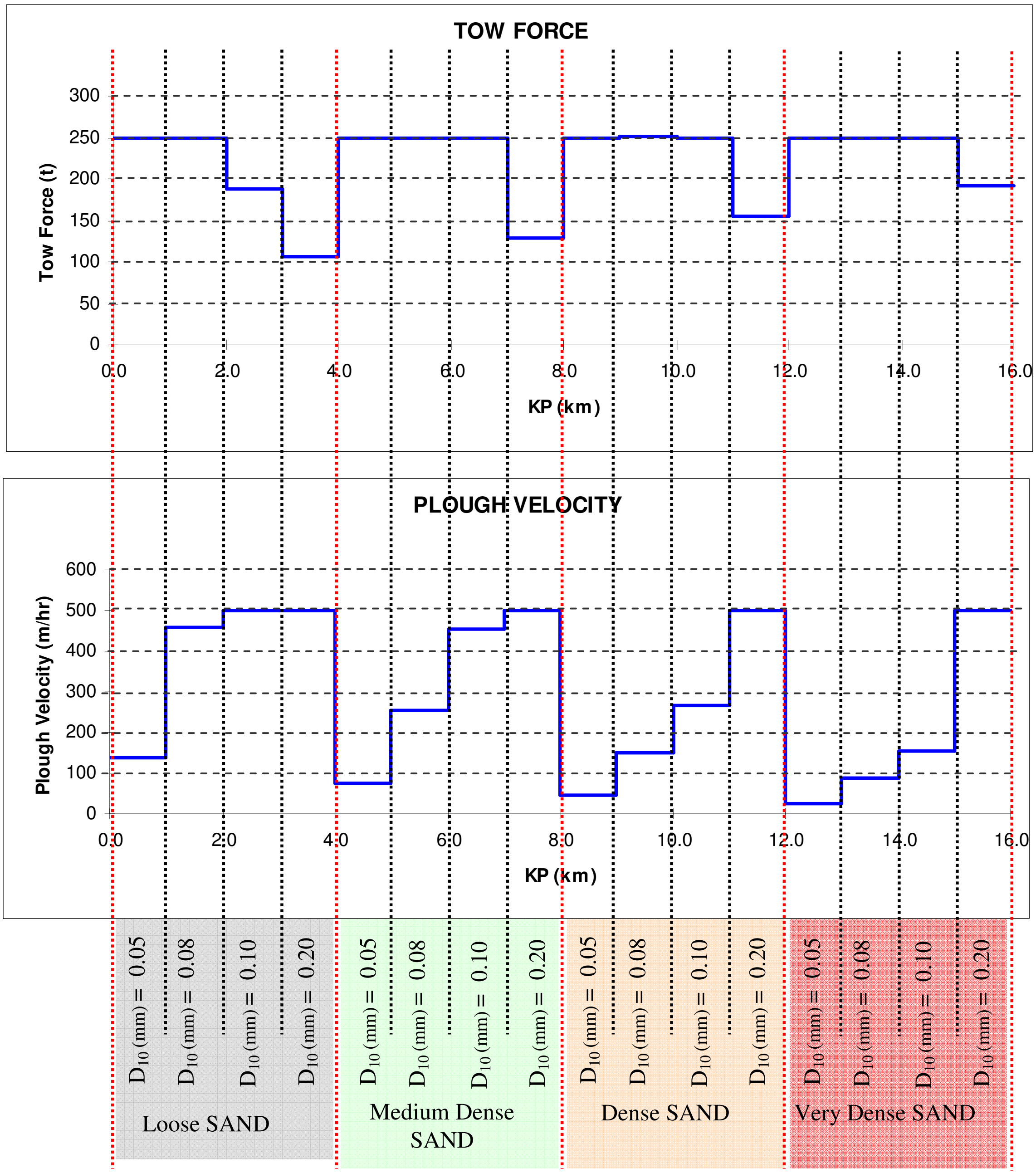

Figure 7: Ploughability assessment results in SAND

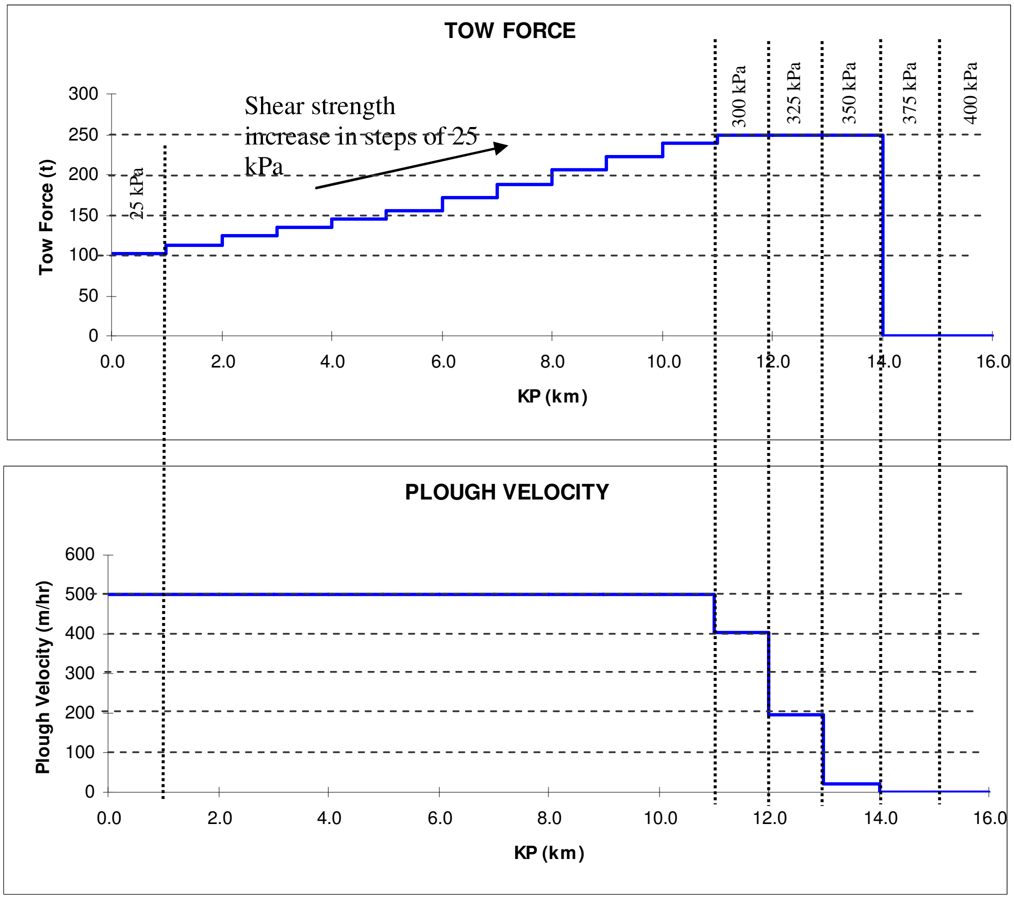

Figure 8: Ploughability assessment results in CLAY

On-bottom stability of pipelines

On-bottom stability of a surface laid pipeline is a key design consideration which drives the concrete weight coating thickness. If the maximum concrete weight coating that is practical is not sufficient to provide the required on-bottom stability, then the pipeline is placed in a trench. The trenching is carried out either pre-lay or post-lay by ploughing.

DNV RP F109 provides the methodology for on-bottom stability assessment. According to DNV FP F109 methodology, the lateral resistance to the pipeline is provided by two parts; frictional part from pipe-seabed interaction and a passive resistance part which depends on pipeline embedment, both of these parts depend on seabed soil condition. Thus seabed classification has double impact on the results of on-bottom stability assessment. This is demonstrated by a parametric study below. A pipeline with outer diameter 1m and SG of 1.1 (without concrete coating) at a water depth of 50m was considered in this study. On-bottom stability according to DNV RP F109 was assessed for 5 different cases, each having increasing wave and current conditions as shown in Table 5. All five cases were assessed for two different seabed soil conditions; fine sand (with seabed roughness 0.00001m), Silt & Clay (with seabed roughness 0.000005m and shear strength of 10kPa). The results of the parametric stability assessment are presented in Figure 7. The results are shown for both absolute stability and generalised 10D stability. It is clear that the required concrete coating for stability is sensitive on whether the seabed soil is fine sand or silty/clay. Thus if the seabed soil classification is not correctly reflected in on-bottom stability assessment, then the concrete coating requirement resulted from on-bottom stability assessment could be incorrect.

Table 5. Wave and current input data for on-bottom stability assessment

Case	Hs (m)	Tp (s)	Current (m/s) (1m above seabed)
1	5.00	10	0.10
2	6.00	10	0.15
3	7.00	10	0.20
4	8.00	10	0.25
5	9.00	10	0.30

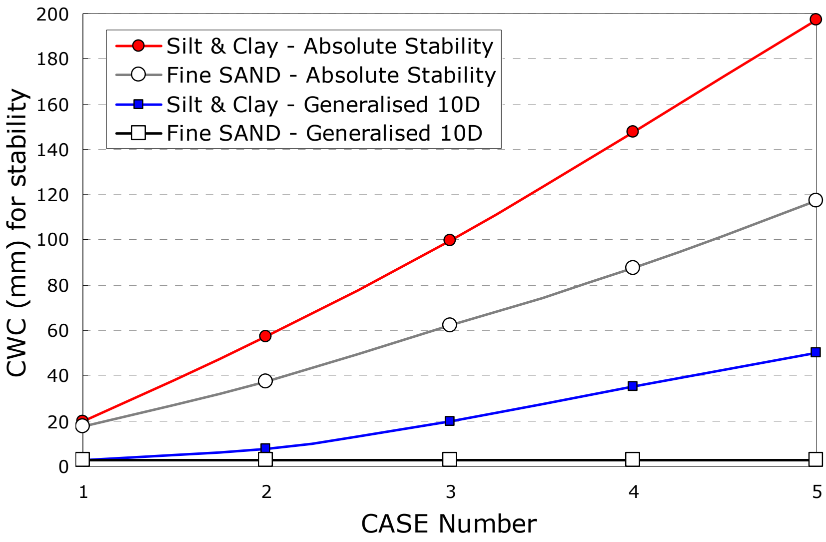

Figure 9: Parametric Stability assessment results

Conclusion

Most commonly used soil classifications standards (ASTM D-2487, BS 5930 and ISO 14688) were reviewed in this paper. While soil classification is useful in categorising the soils, original soil test data should always be reviewed and the soil behaviour predicted based on test data and not solely on the soil classification. In light of the fact that soil classification may not always capture soil behaviour for a particular application, it is recommended that;

- design engineers be aware of the soil classification standards and their limitations in predicting soil behaviour
- the standard followed for soil classification should be clearly stated in geotechnical and design reports
- caution is applied when particle size distribution is close to the boundary of soil classifications (Figure 6)
- original soil test data should always be reviewed when soil properties are being assigned for pipeline design

Proper knowledge of how the soil classification is carried out and its limitations will enable design engineers to use the geotechnical survey data correctly and efficiently.

Acknowledgement

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