ACTA IMEKO
ISSN: 2221-870X
June 2018, Volume 7, Number 2, 10-15

Grain size of marine sediments in the environmental studies, from sampling to measuring and classifying. A critical review of the most used procedures

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ABSTRACT
The knowledge of sediment texture is a main issue in the marine environmental research. Studies on sediment contamination, ecology of benthic communities, seismic studies, remote sensing surveys and beach nourishment are among the research areas which benefit of information on sediment grain size. In this review, the main methods used for sampling, measuring and classifying marine sediments are critically illustrated in order to highlight their strengths and weaknesses. From this revision it was deduced that it does not exist a single procedure, considered as the best one, to be applied in all the cases for obtaining reliable grain size data. This result can be achieved using as much as possible flexible strategies, and adopting the suitable sampling devices and analytical instruments based on the overall characteristics of the study area and the specific aim of the survey.

Section: RESEARCH PAPER

Keywords: marine sediments; sampling sediments; grain size analyses; classification of sediments

Citation: Elena Romano, Maria Celia Magno, Luisa Bergamin, Grain size of marine sediments in the environmental studies, from sampling to measuring and classifying. A critical review of the most used procedures, Acta IMEKO, vol. 7, no. 2, article 3, June 2018, identifier: IMEKO-ACTA-07 (2018)-02-03

Section Editor: Fabio Leccese, Università degli Studi di Roma Tre, Italy

Received January 15, 2018; **In final form** March 23, 2018; **Published** June 2018

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1. INTRODUCTION

Different marine environments are usually characterized by different sediment types because, in general, coarser sediments are present close to the coast, at shallow water depth, while finer sediments raise with increasing bathymetry.

However, there are exceptions to this general rule, because fine sediments may be found not only in deep water environments but also in enclosed marine and transitional settings, due to the low environmental energy, while sandy sediments may be present offshore, as a result of Quaternary glacial low-stand or gravitational processes.

Hydrodynamics, meteorology, climate and bottom morphology are the main factors influencing the distribution of sediment particles once they are supplied to the marine environment, where they may undergo repeated resuspension, transport and deposition over the continental shelf and slope, before being definitively deposited.

Since sediment texture influences a lot of important biotic and abiotic aspects in the marine environment, this is considered a key factor in many fields. For example, diversity and composition of macro and meio benthic communities [1], [2], as well as organic carbon [3] and contaminant distribution [4], are strongly conditioned by sediment grain size. Consequently, the sediment texture has to be determined not only for sedimentological studies, but also for the ecological characterization of benthic habitats and/or for the environmental assessment of marine coastal areas affected by anthropogenic impact. In this context, grain size is also required for normalization procedures of metal and trace element concentrations [5].

Another important application of grain size data is for the correlation of seismic units, recognized in the profiles, with the corresponding stratigraphic ones [6] or for the calibration of remote sensing data [7].

Another application of sediment grain size is in the field of coastal management; in particular, the beach nourishment requires sediment characterization because the features of the borrow area must be as similar as possible to those of the native beach [8].

Figure 1. Superficial sediment samplers; types of grabs: from the left to the right, van Veen, Eckman-Birge, Shipek.

The activities finalized to the acquisition of grain size data should be planned taking into account the topic of the research, and the methodologies of sampling, analysis and classification of sediments may follow different procedures, according to specific needs. Nevertheless, due the importance of the environmental studies for their repercussions on management policies, there is the need of carrying out accurate and reliable measurements [9]-[11].

Aim of this review was to describe the most used procedures as regards sampling, analysis and classification of marine sediments from a critical viewpoint, in order to offer the conceptual tools to adjust the methodologies for obtaining as most as possible reliable data, according to the specific requirements of the study.

2. SAMPLING

In most cases, surveys finalized to environmental studies comprise the collection of samples for multidisciplinary analyzes, including grain size. Devices and sampling methods are finalized to the collection of undisturbed marine sediments, because the preservation of physical structure and chemical composition of the sample is necessary to obtain reliable data on physical, chemical and biological characteristics. The need to maintain the original sedimentary sequence is related to its chronological significance, which allows attributing to a unique historical moment the analytical data obtained from a specific sediment layer. In addition, the chemical contamination of sediment samples, due to the use of unsuitable devices, sampling and subsampling methods, determines the attribution of unreal chemical properties to the sediment layer deposited during a definite time range.

Minimizing effects on the chemical and physical integrity of the sample is of great importance for studies in the field of the environmental research, because the use of unsuitable devices or sampling procedures may result in the modification of typology and bioavailability of contaminants.

Two main groups of sampling devices, employed for different purposes, are grabs and corers.

Grabs are used for collecting superficial sediment, normally in a large number of stations, to characterize spatially the study area.

Differently, corers, which collect a whole thickness of sediment, supply information along the vertical direction that, according to sedimentation principle, provides the chronological record of past conditions.

2.1. Devices for collecting superficial sediments

An appropriate sampling method for characterizing current environmental conditions of sea bottom as regards chemical, biological and sedimentological parameters implies the use of grab, which is relatively easy and fast to handle and operate, allowing the collection of a lot of samples in a short time.

The most commonly used are: van Veen grab, Ekman-Birge grab and Shipek grab (Figure 1).

The van Veen grab is constituted by two jaws. As soon as the grab comes down to the bottom, the jaws close by holding the sediment inside. Some models have upper doors that allow collecting the nearly undisturbed upper centimeters of bottom sediment, directly inside the device. This kind of grab is used to collect sediment ranging from muddy to sandy.

The Ekman-Birge grab has a box shape with upper windows and lower jaws, and the smaller type can be manually operated by means of a rod that allows the insertion into the sediment. It is mainly used in shallow water environments with muddy sediments like as lagoons or marshes [12]-[14].

The Shipek grab has a bucket that rotates into the sediment when it reaches the sea bottom. It is suitable to collect fine sediments and it can be used even on sloping seabed.

2.2. Devices for collecting sediment cores

Because sediment cores provide chronological information useful to reconstruct the environmental history of the study area, they should be collected when temporal changes of environmental conditions are investigated.

The anthropogenic impact on marine coastal systems may be recognized in sediment cores where by changes of the sedimentary and chemical input, associated to the micropaleontological content. Deeper core levels, deposited during pre-impacted periods, reflect the reference conditions and may be compared to the recent ones for the assessment of environmental status [15].

For this purpose, the collected core must preserve the *in situ* conditions of sediment and any kind of cross contamination, especially in the lower levels, reworking of sediment and alteration of the stratigraphic sequence should be carefully avoided during coring and sub sampling phases.

The corers used for the collection of marine sediment are mainly of two types: gravity and vibro corers (Figure 2). All devices consist of a core barrel, varying in length and diameter, with internal liner used to facilitate the extraction of the core and avoid contamination of the sediment due to the transfer of heavy metals from the core barrel; it also prevents the downward drag of any contaminants during the extrusion of the

Figure 2. From left to right: SW-104, Rossfelder® and Kullemberg corers (photo by ISPRA).

core.

The gravity corer is equipped at the head with dead weight, variable depending on the number of lead ring masses, which provides the kinetic energy needed to penetrate the sediments. A flap valve, at the barrel top, allows water to escape during coring, but it is closed during pullout, ascent and recovery, to prevent sediment being washed out. A sharp cutting edge, at the end of the barrel, bears the core catcher, necessary to hold the core during the ascent. The length of the core barrel can generally vary between 2 and 6 meters.

A wide variety of gravity corers is available; among these, some models, such as the Kullemberg one, may be equipped with dead weight up to 1000 kg, which allows deep sediment penetration, but determine some disturbance, mainly in upper layer and mostly at the water sediment interface. These heavy devices have the disadvantage to need a substantial secondary apparatus due to the difficulty of handling [16].

On the other hand, the SW-104 bears lower weight at the head (up to 90 kg) and penetrates sediments with scarce disturbance, preserving the water sediment interface, also thanks to the wider core diameter. Nevertheless, it allows the recovery of cores shorter than 135 cm [17]. All gravity corers are mainly used to sample fine sediment bottoms in deep water to allow effective penetration and adequate recovery of sediment. In this environment, the coring method with controlled penetration speed (Angel Descent) allows to minimize the sediment shortening and deformation [18].

The vibro corer has a structure similar to the gravity one, but it has a different principle for sediment penetration, because it is equipped with an electric-powered mechanical vibrator at the head, which applies thousand of vibrations per minute, to help the penetration of the sharp cutting edge. This corer is able to recover cores from a wide range of sandy sediments [12].

Another category of samplers, the box corer (Figure 3), is generally used for collecting sub-superficial samples, no more than 30 cm thick, preserving the water-sediment interface. It consists of a stainless steel square box of variable size and a support frame that stabilizes the sampler on the seabed and ensures the vertical penetration. When the box has penetrated into the sediments by means of weights, a scoop cutting the sediment layer and closing the box is released. The large area of sampled sediment allows the recovery of nearly undisturbed samples [17].

A more recent type of sampling device is represented by multicorer (Figure 3). It's a single device constituted by multiple core barrels for collecting cores of undisturbed sediment, including the sediment-water interface. A range of models is available to sample from 4 up to 12 cores in a single deployment. It is widely used for soft sediment sampling in a wide range of environmental applications. The cores are held together by a stainless steel frame. The core tubing (from 300 to 600 mm length) can be manufactured from acrylic, polycarbonate or stainless steel, depending on requirements. The frame is held by a winch that allows a descent and the penetration is due to a hydrostatic damping system that eliminates the typical bow wave. Corer weight ranges from 88 to 735 kg. During the ascent, samples are sealed, being capped both top and bottom.

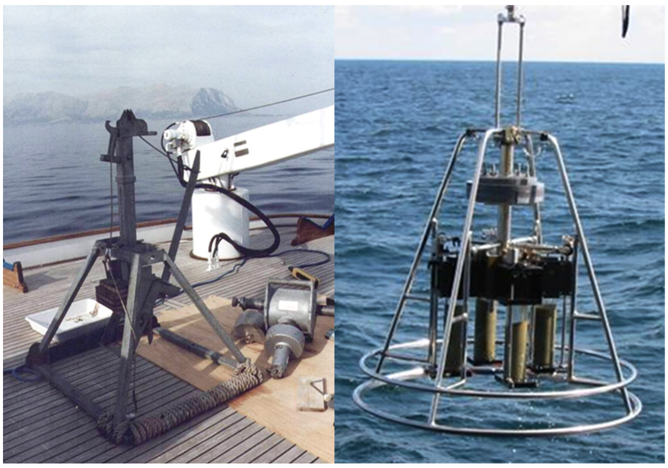

Figure 3. From left to right: box corer (photo by Elena Romano) and multiple corer (*http://osil.com/Home.aspx*).

3. GRAIN SIZE ANALYSES

The accuracy of grain size determination in the environmental studies is of basic importance to obtain reliable data. The main phases of the analytical procedure are described below.

3.1. Pre-treatment

A pre-treatment of the sediment sample is necessary in order to discrete the colloidal aggregates, to eliminate saline content and to remove any organic material. The saline content and the organic material, adhered to the sediment granules can be easily removed by immersing the sample in a solution of distilled or natural water and hydrogen peroxide (30 % H_2O_2) and leaving it for at least 24 hours; if necessary, the operation can be repeated [19]-[21]. Removal of organic material may be necessary to achieve full dispersion of clay and, in sediments with a high organic content (> 3 %), to avoid organic matter being counted in the total weight of the sample, thereby affecting the grain size distribution [22]. The separation of coarse (> 63 μm) and fine (< 63 μm) fraction is carried out by wet sieving.

3.2. Analysis of coarse fraction

The coarse fraction (> 63 μm) can be efficiently determined by dry sieving through set of sieves, whose number and range of coverage depend on the required detail of the grain size classes, placed on a vibro-tilting mechanical stirrer. After sieving, the individual dimensional classes are weighed and recorded, and then their relative abundances are calculated. Data obtained from sieving are normally integrated with those of the fine fraction and, if present, of the gravelly ones.

3.3. Analysis of fine fraction

As regards the analysis of the fine fraction, up to a few decades ago, sedimentation methods such as the pipette or the hydrometer based on the Stokes Law were used. The analysis, assumes the preparation of a homogeneous sample suspension in a dispersant solution, and subsequent particle sedimentation within a graduated cylinder. The procedure is completely manual and requires a high level of precision and competence of the operator [23].

In the last decades, several new instruments have been developed; they can characterize variable dimensional ranges based on particle electroresistence (e.g. Coulter Counter), photometric techniques (e.g. Microtrac, Malvern Laser Sizer, Coulter LS) or on automated image analysis (QICPIC).

Instruments based on laser diffraction have become one of the most widely used for determining particle size. The speed of analysis and the possibility of using extremely small sample quantities are the strengths of such instruments. Samples can be analyzed either in a liquid suspension or in a dry dispersion. A small, but representative, quantity of sample is crossed by a laser beam, which is deviated of an angle, inversely proportional to the size of the single particle. Although laser diffraction can theoretically be easily applied in a dimensional range from sand to clay, some studies have shown that it is preferable to limit the analysis to lower grain size classes [24].

Sedigraph, an instrument that utilizes the X-ray attenuation principle, is another widely used for grain size analysis, in particular for the fine fraction. The analysis is performed through an X-ray beam, suitably collimated in a thin horizontal band that allows calculating the concentration of particles in the liquid medium, following the principle of the Stokes Law. It detects the size of the particles according to their sedimentation rate [25].

The problem of comparing grain-size analyses based on different techniques and different physical principles has been discussed by several authors. For example, Goossens carried out a detailed comparative study analyzing four sediment samples with ten techniques indicated that, although the trends were generally similar, minor differences between the results of grain size analyses, attributable to different instruments, were observed [26].

Advantages and limitations of the two main instruments are reported in Table 1.

4. CLASSIFICATION

Sediment classification is necessary to include the analyzed sediments in distinct classes, according to their dimensional ranges, and to compare different types of sediments. Because several classifications are known in scientific literature, the choice of the most suitable one depends on the purpose of the study, type of the studied sediment and accuracy of the analysis.

The Wentworth scale defines limits and names of grain size classes [27]. Range limits are expressed in phi (ϕ), which is calculated as follows:

$$\phi = -\log_2 (D/D_0) \tag{1}$$

where D is the diameter of the particle in millimeters and D_0 is a reference diameter, equal to 1 mm [28].

The binary classification of Nota may be used also in case there is no possibility of analyzing the fine fraction [29]. This classification is given by the ratio between sand and mud (silt + clay):

- Sand: sand > 95 %
- Muddy sand: sand 95-70 %; mud 30-5 %
- Very sandy mud: sand 70-30 %; mud 30-70 %
- Sandy mud: sand 30-5 %, mud 70-95 %
- Mud: mud > 95 %

One of the most commonly used classifications of marine sediments is the Shepard ternary classification [30]. It considers the relative abundance of sand, silt and clay fractions with the identification of 10 sediment classes (Figure 4). It is possible to use this diagram even if small percentages of gravel fraction are present. When a large amount of gravel is recorded, the modified Shepard diagram, is preferable. In this ternary diagram the vertices consist of gravel, sand and mud (silt + clay). The use of this classification is recommendable for studies on contamination assessment, because of the great importance of clay minerals for the accumulation of heavy metals and organic compounds.

Also the Folk classification is suitable for gravelly sediments [31] (Figure 5). The basis of this classification is a triangular diagram on which the proportions of gravel, sand and mud are plotted. Depending on the relative proportions of these three constituents, 15 major textural groups are identified.

5. GRAIN SIZE DATA

Data resulted from the analysis of the coarse and fine fraction should be integrated and processed for the determination not only of percentages of the main grain size fractions (sand, silt, clay), but also to reconstruct the frequency and the cumulative curves and to obtain the main statistical parameters, as defined by Folk and Ward [31].

Figure 4. Shepard ternary diagram.

Table 1. Advantages and limitations of Laser Granulometer (LG) and X-ray Sedigraph (XS).

Instruments	Laser granulometer	X-ray Sedigraph
Advantages	Wide range of measuring (variable depending on the instrument from gravel to clay)	Wide range of measuring (0,1 μm - 300 mm)
	Short analysis times (only few minutes)	Excellent spectrum analysis resolution above 1 μm
	Small amounts of sample	Possibility of serial analysis (using an accessory)
Limitations	Need to make accurate splitting	Long measurement times (25 minutes or more)
	High cost	Relatively high cost
	Greater range of measurements, less accuracy in finer fractions	

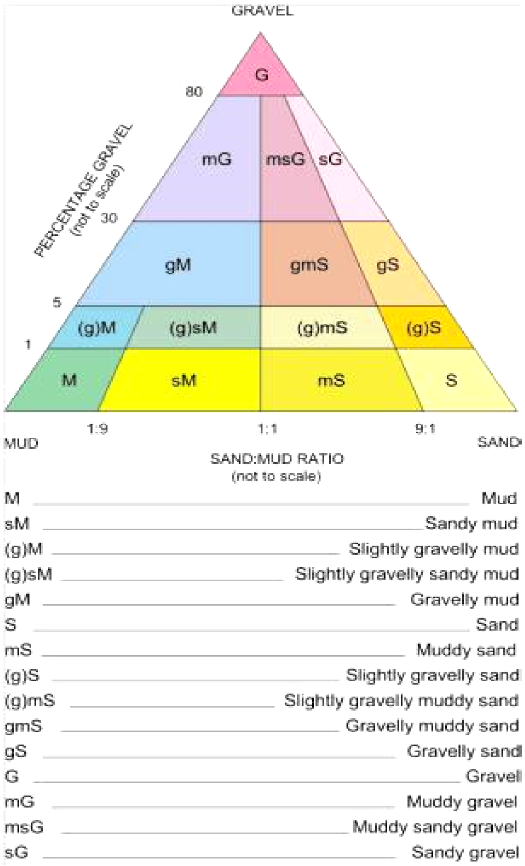

Figure 5. Folk ternary diagram and nomenclature.

For each diameter class, the frequency curve expresses its percentage of the total sample. It could have only one (unimodal curve) or more peaks (bimodal or polimodal curves), indicative of the presence of a mixture of different sediments.

The cumulative curve represents the percentage, referring to the total, of the sediment relative to each diameter class.

In order to compare different sedimentary environments by quantitative viewpoint, it is necessary to calculate measures of average size, sorting, and other frequency distribution properties. These properties may be determined either mathematically by the method of moments or graphically by reading selected percentiles off the cumulative curves [31].

The main statistical parameters are mean size, standard deviation, skewness and kurtosis. Important parameters are also the median (D_{50}) and other significant percentiles (D_5, D_{16}, D_{25}, D_{75}, D_{84}), recognizable in the cumulative curve, and the mode, derived from the frequency curve.

Different environmental contexts are characterized by distinct statistical parameters while the grain size distribution depends on the source rock.

Mean size, mode, median and first percentile diameters give information on transport capacity. In general, coarser sediments indicate greater energy (higher transport capacity) than the finer sediments.

The standard deviation parameter indicates the selective capacity of the medium of transport. A well-sorted sediment is subjected to a constant selection.

6. CONCLUSIONS

This methodological review was carried out considering the importance of grain size in a wide spectrum of marine environmental studies. The acquisition of reliable data is of basic importance in these studies especially because of their consequence on the management policies. This work, highlighted advantages and disadvantages of the most commonly used sampling, analysis and classification methods for marine sediments. Considering this information, it was clear that it does not exist a single procedure to be considered as the best one for the acquisition of reliable grain size data. As regards sampling and sediment analysis, the choice of appropriate instrumentation should be carefully planned. As regards the choice of sampling strategy and device, type of sediment, sea bottom bathymetry and morphology, sample volume, necessity of collecting more or less deep sediment layers and the specific aim of the study should be considered. Concerning grain size analysis, although a standard method of dry sieving is generally adopted for the analysis of coarse sediment fraction (> 63 μm), for the analysis of the finer one (< 63 μm) the instrument should be selected considering several factors such as type and quantity of available sediment, speed of measurement and reproducibility of the results. Finally, for the choice of sediment classification, type of analyzed sediment and availability of silt and clay data should be considered. In conclusion, this review offers the conceptual tools to plan a flexible strategy to obtain the highest reliability of grain size data of marine sediments, considering the most suitable method in sampling, measuring and classifying sediments, in relation to the specific aim of the research.

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