Portable Meter System for Dry Weight Control in Dredging Hoppers

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Abstract: A real-time system for monitoring the dry weight contained in the hopper of a given dredge has been both designed and tested. Among the system's most outstanding features, the following may be mentioned: it is of economical acquisition, can easily be set up in a brief period of time, and works independently from any other control systems incorporated into the dredge by the contractor. Moreover, its displacement is determined uninterruptedly. Ultrasound transducers are located on deck for the precise monitoring of cargo volume, and the data are collected through a personal computer and sent, via modem, to the client. The difference between automatic measuring and the standard manual system appeared to have a mean value of 5%. The content of solid matter in the hopper was 53%. Although this system has proven itself fully operative, certain protective measures have to be taken to shield those components exposed to rough maneuvering before the technical supervisors and controllers leave off.

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Introduction

The economic importance of beaches and their direct link to tourism in some countries has already been studied (Houston 1995, 1996; King 1999; Muñoz-Pérez et al. 2001). On the other hand, a need for the regeneration of beaches in general does exist in Spain. This necessity is due to the erosion undergone by most of our coast, which is attributed to sea level rise, retention of sand in dams, occupation of dry beaches by urbanized areas, removal of sand as a material for building construction, and so on. Hence in the 1980s what was once known as the National Ports and Coastal Authority (Dirección General de Puertos y Costas), a subsidiary of the Ministry of Public Works, began a beach nourishment campaign using the sand extracted through the dredging of submarine deposits.

These sediment deposits were located thanks to an exhaustively carried out geophysical and vibrocoring campaign throughout the Spanish littoral, at depths of approximately 15 to 35 m [Esgemar (1991); Geomytsa (1991a, b), among others]. The minimum limitation was established at such a depth as not to interfere with the active beach profile itself, and it still stands as such up to the present. Yet the technological advances seen in trailing suction hopper dredgers have doubled and tripled the capacity of those ships built only a decade ago. The *Vasco da Gama*, with its 33,000 m^3 capacity, will be able to operate up to a 130 m depth (Riddell 2000).

Notwithstanding, the Spanish government lacks a dredging park capable of handling the sand renourishment needs of national beaches. Even in the tasks of maintaining local ports the option of employing a contractor has been preferred on the whole. This tendency is not exclusively adopted by the Spanish government, but is also the norm in other countries as well. For example, only 20% of the ports operating in England and Wales, from a group of more than 100 harbors that completed a questionnaire, operate their own vessels to carry out the dredging process (Sullivan 2000).

The three main criteria on which the payment decisions are based are the following:

- Calculation of volume dredged through a comparison made between profiles taken before and after the work is completed in the area under consideration;
- Total amount of dredged volume transported to final destination; and
- Total amount of hours put in by the dredge.

Rullens et al. (1994) were of the opinion that the employer should be responsible for the specific site conditions with regard to sedimentation, and therefore the method of taking a pre- and postdredging survey would be impractical, and the most feasible way for remuneration of dredged quantities is measurement by means of conveyance.

Nevertheless, a decision was made in Spain, during those first projects, to base payments upon the real quantity of sand placed on the beach; that is, this amount would be based on a comparison between pre-and postnourishment beach profiles.

One contracting company, upon stating that this assessment was unfair, referred to this matter by adducing that they were not to be held responsible for any possible erosion that may happen on the beach deposits caused by wave or tidal activity. The final

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Fig. 1. Detail of sounding lead used to measure distance between deck and sand surface. Flat shape allows device to lie directly on top of sediment surface, avoiding penetration.

decision was to their advantage, and to this day payment has been made on the hopper measurements taken before the sand sediment is pumped onto the beach.

It is worthy of notice that the dredgers employed for this task—that of noncohesive sediment extraction from the sea floor—are trailing suction hoppers as opposed to cutter suction vessels. Of course, today the bucket ladder dredger has become a rare machine, replaced by the former, which are able to dredge greater volumes of material in shorter periods of time and at lower costs (Vanderostyne and Cohen 1999; Riddell 2000).

The data for these measurements were collected at the end of each loading phase by two technicians, representatives of the contractor and the government, respectively. Placed at strategic points on the hopper, and through the use of a sounding lead (Fig. 1), the exact distance between the deck and the sand surface was measured. Once this information was applied to the vessel *ullage table* or *ullage chart*, the precise load sediment volume was calculated. Hence, a preprinted logging form was signed by both parties establishing the exact cargo, leaving no room for any doubt or lack of agreement that might arise when completing monthly payments.

It is also worthy of attention that only the total sediment volume, mixed with water, was known with the earlier process, but not in which proportions. Therefore, regretfully, the real net content of valid and useable matter to be placed on the beaches— the sand—was left ignored. Be it known that, *a priori*, porosity in the hold and on the beach itself is not necessarily the same. Furthermore, the pumping of material into a hopper may ‘‘fluff’’ it up somewhat, temporarily increasing the total volume (Scott 1994). All the above-mentioned factors reinforce the hypothesis presented of a need for a better control and measuring system of dredged sediments.

The main aim of this paper is to show an independent and portable system that lets us distinguish between the dry matter and that which corresponds to seawater. Though the dredging vessel occasionally may be equipped with a control system, the one hereby presented allows the contracting administration itself to establish working evidence of quantity and quality control of dredging data, even dispensing with on-deck personnel. This would also be helpful in detecting any accidental dumping or loss of dredged material in unauthorized locations, which naturally could affect the marine environment.

Antecedents

The problem of calculating the total load of the dry weight dredged on board any given vessel has been studied previously, though with different objectives. Van Bochoven et al. (1988) compiled the results of a joint research project in ‘‘Minimizing the Cost of Dredging Operations for Maintenance Purposes,’’ which was undertaken by the city of Rotterdam and the Dutch Department of Public Works. A hopper measuring system was developed to determine the precise amount of silt extracted, that is, to determine the quantities of spoil contained in the hopper of trailing suction dredgers and to assess the performance of such vessels during dredging operations (bearing in mind that hopper contents are used as the basis for calculating the chargeable amounts of dredged material removed).

Two methods were finally selected as feasible techniques on which to base an automated hopper measuring system. The first was a radioactive density meter employing four backscatter sensors, while the latter consisted of a draft-monitoring system combined with a level-measuring device. A practical trial carried out in 1985 demonstrated that measuring rods (electrical conductivity meters) could operate over long periods of time, even though damaged during unloading on that specific occasion. Nevertheless, another prototype capable of withstanding the hostile hopper environment was developed for measuring the density of dredged material in hopper bins.

Formerly, sediment density as a function of a formation factor (sediment bulk resistivity divided by the water resistivity) was empirically derived in comprehensive laboratory tests (Scott 1992a). This system could be fitted as standard equipment on trailing suction dredgers and now is fully operational. Another testing and evaluation of a hopper dredge automated load monitoring system was developed under the Dredging Research Program by the U.S. Army Corps of Engineers (USACE) (Scott 1994). Probabilistic calculation methods were also used to assess the accuracy of the system (Rullens 1993; Scott 1993), and a summary of initial experiences of the USACE, with use of the tons dry solids measurement method has been presented in a technical note (Welp and Rosati 2000).

Nevertheless, dredging companies are not too enthusiastic about commenting on specific details of their measuring systems with ‘‘unrelated parties,’’ clients included. In a poll carried out by the USACE (Pankow 1990), survey submittals were mailed to 197 dredging organizations in the United States (including all USACE district offices) and 472 in the rest of the world. It is noteworthy that just 56 of them responded, and of those, only 32 claimed to use some type of production-monitoring instrumentation on the 72 dredgers they operated.

The need to install a separate draft-measuring system instead of using quality assurance measures to obtain believable data from the contractor sensors is a matter of controversy. In Spain, we are working not only with the latest developments in dredging technology, such as those often implemented in Belgian and Dutch dredging vessels, but with old Spanish and Russian dredges as well. Therefore, the implementation of an inexpensive and portable system would be very useful *per se*. Furthermore, this paper only intends to emphasize the need for cross-checking the available information, which is clearly an important factor when dealing with contractual obligations.

Methodology

System Description

Trailing suction hopper dredgers are employed in beach nourishment to transport a heterogeneous mix of sand and water. The main function of the system herein described is to pinpoint the exact proportion of each of these components to expressly distinguish the useful amount of the load, the sand.

The total load weight (W_c) is equal to the sum of the sand weight (W_s) and that of the sea water (W_w).

$$W_c = W_s + W_w = \rho_s V_s + \rho_w V_w \tag{1}$$

where ρ_s and ρ_w are densities of sand and sea water, respectively, and V_s and V_w are the respective volumes. To calculate the total load weight, the automated measuring process of the draught is put into nonstop use. The maximum values coincide with those at the very moment the vessel is loaded, whereas the minimums coincide with those of a completely unloaded hopper. The difference found between both values and upon application of ullage charts is given as the loaded displacement (V_d). Knowing that seawater density is (ρ_w), we proceed to compute $W_c = \rho_w V_d$. The actual measuring of the draught is carried out with the use of four pressure transducers welded along both sides of the vessel hull, allowing for frequent data readings in less than half a second. With this approach, the average sea water level is calculated with software developed for filtering any interfering wave action noise.

Simultaneously, the actual load level is monitored in the interior of the hopper through ultrasound transducers placed on deck. Through a process similar to the one previously mentioned (by application of ratified ullage charts), the precise load volume (V_c) is known. Yet this volume is but a composition of the sand volume (V_s) and that of the seawater (V_w) in which it is partially suspended.

$$V_c = V_s + V_w \tag{2}$$

Of course, in cases where the hopper load is not covered 100% with water, the calculations would not reflect the real conditions.

In order to calculate the sand density (ρ_s), two samples were taken after each complete load so that the loss of fine grains after the overflow could be taken into account properly. Sieve analyses were performed by means of standard 11-mesh sizes used consistently for all tests in the Andalucia-Atlantico District Office of Coastal Authority (ASTM 5-10-18-25-35-40-45-60-70-120-230).

Carbonate content was determined by using a Bernard calcimeter. Assuming that the largest fraction of sediment is of silicyclastic origin, composed of quartz and bioclasts or pieces of shell (Gutierrez-Mas et al. 1994), the grain density of each sample is computed as $\rho(\text{sample}) = \%(\text{quartz}) \cdot \rho(\text{quartz}) + \%(\text{CaCO}_3) \cdot \rho(\text{CaCO}_3)$ where ρ (quartz) is 2.65 g/cm^3, and $\rho(\text{CaCO}_3)$ is 2.72 g/cm^3. The difference between sediment densities computed in this way and those obtained by dividing the dry weight of the sample by its volume did not exceed 1 kg/m^3 (Gutierrez-Mas et al. 1998).

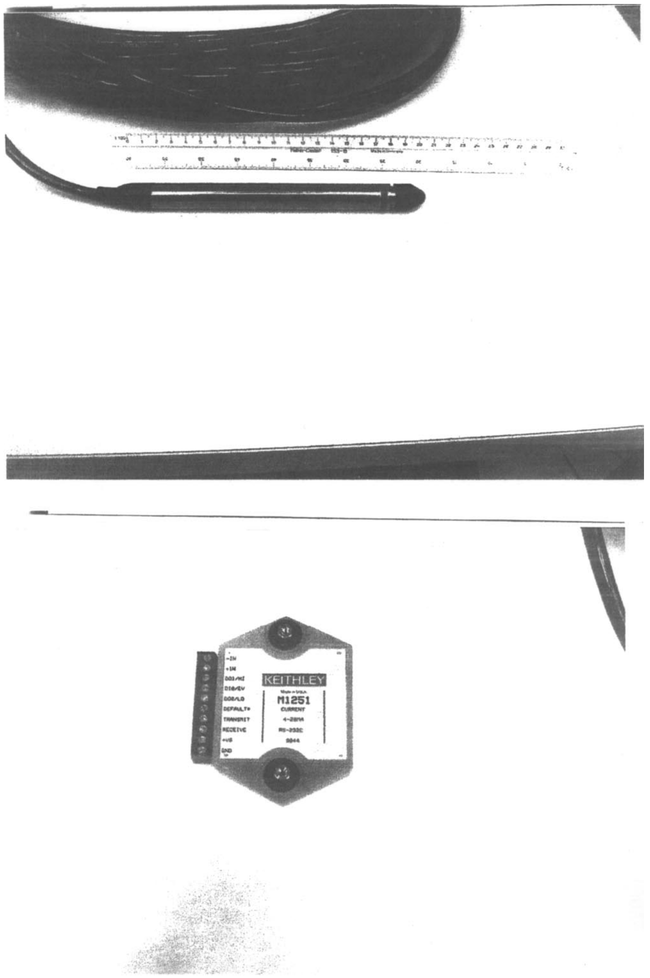

Fig. 2. Pressure transducer and digital-analogical signal converter (RS-232)

All data are transmitted to an on-board computer, though naturally the relevant measures are taken to avoid the noise induced by the vessel motors. These data are processed through the use of the appropriate software, and the aforementioned Eqs. (1) and (2) are solved, giving the exact proportion between sand and seawater. Thereafter, results are filed in a protected hard drive and sent, via modem and in real time, straight to the office of the promoting client.

Equipment Features

The different parts and characteristics of the equipment required are described below.

- Pressure transducers, submerged and welded to the vessel hull for measuring the draft at all times (Fig. 2). Pressure transducers are preferred to the ultrasound type when measuring from the deck due to their simplicity and to the difficult accessibility of the latter, which requires in addition a steel structure to be flagged from the deck. Four transducers were strategically and symmetrically placed (fore and aft, port and starboard), whose average value would compensate for the pitch and roll of the ship;
- Ultrasound sensors for the measuring of total load volume in the hopper (Fig. 2). In this case, pressure transducers were not put into use due to the unavailability of reasonably priced units on the market, which also met the following demands: a

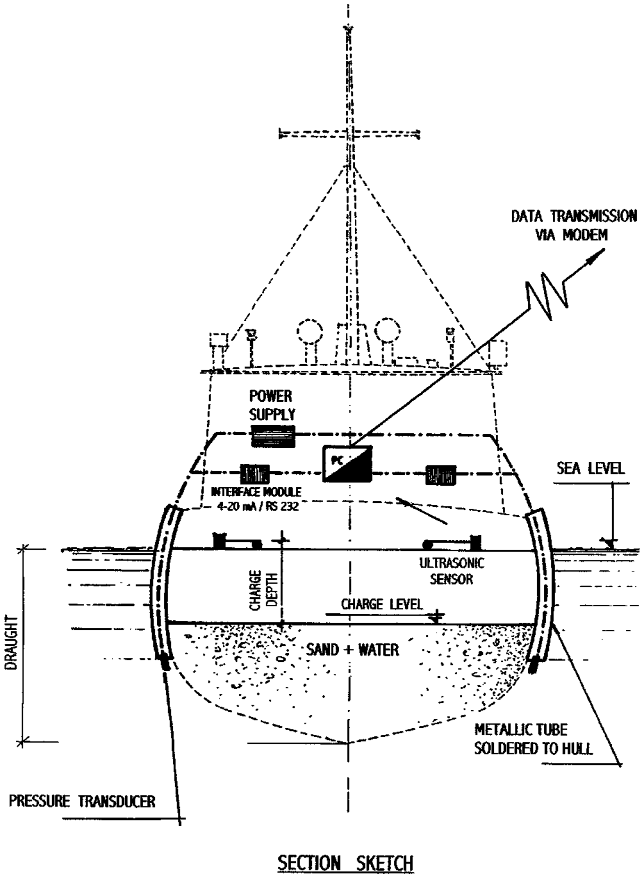

Fig. 3. Section sketch of dredger, showing every one of equipment components needed to measure hopper dry weight

pressure-measuring capacity of a solid material, such as sand, with a range of up to 2 kg/cm^2; resistance to abrasive environments; and ability to send the mean signal to a given destination where it is to be registered and situated at several dozen meters away. For further orientation on the matter, it is important to remark that the output capacity of existing sensors is registered in millivolts and that the immediate surroundings of a dredger, with highly powerful engines, is one of high sound disturbance seen from an electrical point of view. The ultrasonic sensors were calibrated by measuring a metallic plate placed at known distances (every 0.5 m) in order to be confident with the sensor output over the whole measurement range.

According to Scott (1992b), the sensors were placed at easy access locations and in such a way that both maintenance and replacement, if needed, could be carried out promptly without delaying dredging operations. This system differs from that of the electrical conductivity measuring rod developed by van Bochoven et al. (1988) and, to our understanding, appears to be less fragile and vulnerable to accidental damage. As before, with pressure transducers, four sensors are equally necessary to compensate for vessel motion;

- A digital-analogical signal converter. These modules amplify the analogical signals sent by the pressure transducer, thus transforming them into units of measure, which are transmitted to a computer with an RS 232 or RS 485 port. The model used was the PTX 1830, DRUCK by brand name, with a power output of between 4 and 20 mA, and naturally thoroughly insulated;

Fig. 4. Aerial view of Camposoto Beach showing two different placement sites assigned to each of dredgers and their respective pumping pipelines

- A power supply unit capable of providing the necessary energy for the voltage appropriately established for each of the components;
- A personal computer capable of processing the information received, calculating the total load and the relative percentages of water and solid matter, and furthermore recording the data collected and results on a protected hard drive; and
- A modem for real-time transmission of information to the onshore client branch offices.

Moreover, and according to Español et al. (1997), the position of the ship is determined by a differential global positioning system and recorded with the rest of the data. Fig. 3 depicts a cross-sectional sketch of a prototype dredger. The submerged pressure transducers, which provide nonstop vessel draught information, are also represented.

The information is transmitted by a cable system coming up through the steel tubes welded to the vessel hull, directly to signal converters. Through these in turn, the information is sent to a personal computer having previously been digitized. This transmission process is also repeated for the information registered by ultrasound transducers, in relation to the level of loaded material within the hopper.

Testing and Evaluation during Practical Case

A series of studies previously carried out on the littoral dynamics (Fundacion 1995), as well as on environmental impact assessment studies (Tecnoambiente 1996), allowed confirmation of a substantial regression on the coastline of the Camposoto Beach (Gulf of Cadiz, S.W. Spain). The placement of more than 747,000 m^3 of sand along a total of 3 km of coastal stretch was put into effect through the service of two trailing suction hopper dredgers pertaining to the TETRAMAR Company, the *Iria Flavia* and the *Atlantida*, with hopper capacities of 1,183 and 1,597 m^3, respectively. Fig. 4 shows two different placement sites, one assigned to each of the dredgers and bearing their respective pumping pipelines.

Taking advantage of the entrance of the *Iria Flavia* into the port (Fig. 5) for maintenance and fuel provision, the independent dry weight control system was installed on an experimental basis and was in full operation until dismantled five days later. The

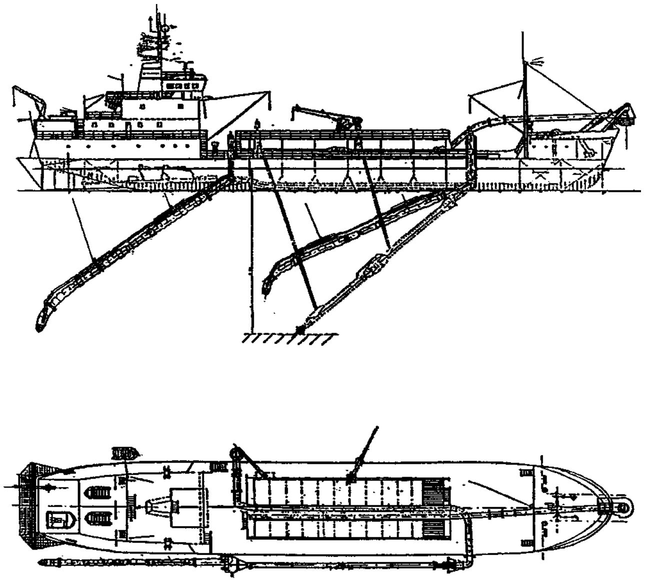

Fig. 5. Sketch showing *Iria Flavia*, trailing suction hopper dredger used in Camposoto Beach nourishment. Sweephead laid on sea bottom can be observed.

Table 1. Technical Characteristics of the *Iria Flavia*, One of the Trailing Suction Hopper Dredgers Used for Camposoto Beach Nourishment

Characteristic	Specification
Name	Iria Flavia
Owner	TETRAMAR S.L.
Year built	1982
Type	Trailing suction hopper dredger
Flag	Spanish
Length	71.02 m
Breadth	12.00 m
Depth	4.25 m
Draft	3.90 m (operating)
Hopper capacity	1,183 m3
Discharge systems	Bottom doors and piping
Discharge pipe diameter	600 mm
Speed loaded	9.0 knots
Dredging depth	35 m
Propeller power	2×560 kw
Dredge pump capacity power	940 kw
Total installed diesel capacity power	2,630 kw

setting-up process was completed in a matter of less than 6 h. The technical dredging characteristics are shown in Table 1. The sand itself was extracted from Placer de Meca, an underwater sand deposit located in the surroundings of the Cape of Trafalgar and at a distance of 18 nautical miles south of the Camposoto Beach. The complete cycle, including loading, transporting, sand pumping, and return of the vessel to source, lasted approximately 8 h. Hence the maximum daily trips were three. It is relevant to bear in mind that these dredging vessels were disabled from carrying out their job when obstructed with waves with a height larger than 1 to 1 1/2 m due to the obvious risk of sweephead fracture.

The draft transducer calibration was confirmed by comparing sensor output with visual sightings of the vessel hull's draft markings. A water test, filling the hopper with seawater, would have been appropriate to test the accuracy of the system, but due to economical criteria, it could not be carried out. Nevertheless, it is noteworthy that three water tests conducted on the dredge McFarland (Welp and Rosati 2000) gave an average difference of 1.23% between the theoretical and measured values.

Once the basic adjustment operations pertaining to the first few days were completed, the equipment functioned smoothly with the exception of only one minor problem. The ultrasound transducers had undergone positional displacements and had to be refitted by the technical controllers who had been contracted by the administration to supervise these operations. Once all systems were checked and found to be in optimum working condition, the only possibility left to consider was human lack of care.

The computer stores all the raw data in a protected system ready for further analysis or verification, whenever needed.

Results

The dredged sediments consisted primarily of fine sands ($D_{50} = 0.34$ mm). The percentage of carbonate weight ($\rho = 2.72$ g/cm^3) of the different samples analyzed ranged between 22 and 31%, while the remaining quantity of sand was found to be of silicyclastic origin (Gutierrez-Mas et al. 1998). Results are shown in Table 2. The value of seawater density remained almost constant around 1,036.5 kg/m^3, with a standard deviation of 0.2 kg/m^3.

With the exception of certain time lapses in fine-tuning the equipment, five hoppers still remained through which the data collected could be compared with those originating from the standard manual measuring process. The differences found between

Table 2. Results of Sediment Size Analysis of Samples, Including Carbonate Content and Density

Hopper load	D_{50} (mm)	D_{84} (mm)	D_{16} (mm)	Silt (%$<$0.063 mm)	$CaCO_3$ (%)	Sediment density (kg/m^3)
1	0.32	0.82	0.22	0.07	22.6	2,666
	0.31	0.64	0.23	0.14	23.5	2,666
2	0.28	0.39	0.22	0.26	31.4	2,672
	0.28	0.38	0.22	0.35	29.1	2,670
3	0.32	0.53	0.22	0.12	29.7	2,671
	0.33	0.60	0.23	0.23	28.8	2,670
4	0.35	0.90	0.22	0.17	25.9	2,668
	0.37	0.86	0.22	0.31	27.3	2,669
5	0.28	0.36	0.22	0.00	29.1	2,670
	0.27	0.43	0.22	0.00	30.4	2,671
Average	0.31	0.59	0.22	0.17	27.8	2,669

Table 3. Comparison between Load Volumes Obtained Manually and Automatically by Proposed System, and Resulting Load Density and Percentage of Solids

Hopper load	Volume by manual surveying (m^3)	Distance deck-load surface (m)	Volume by automatic surveying (m^3)	(2)−(4) (%)	Load (10^3 kg)	Sediment density (kg/m^3)	Load density	Percent solids
1	863	1.84	831	3.8	1,552.5	2,666	1,868.2	51.0
2	881	1.78	842	4.6	1,600.9	2,671	1,901.3	52.8
3	847	2.02	798	6.1	1,520.6	2,670.5	1,905.5	53.1
4	855	1.95	810	5.5	1,532.8	2,668.5	1,892.3	52.4
5	852	1.90	819	4.0	1,564.9	2,670.5	1,910.8	53.4
Average	859	1.90	820	4.8	1,554.4	2,669.3	1,895.6	52.5

both systems ranged from 3.8 to 6.1%, with an average of 4.8% (Table 3). The standard manual approach came up with a measurement figure higher than that of the automated approach. Due to the scarcity of available data, the value dealt with here cannot be extrapolated, but it does thoroughly justify further experiments using the data taken from other dredgers and sediments.

The mean average value of solid volume in the hopper, with an almost inappreciable variability, resulted in 53% (Table 3), which implied an in-place density of the sediments of 1.9 g/cm^3, as opposed to the 1.8 g/cm^3 value found in a test carried out by the USACE, though the dredged sediments there consisted of fine sands with some silt (Scott 1994). Keep in mind that the percentage of solid volume on a beach, and recommended in the *Shore Protection Manual* (CERC 1984) as a typical rate, is about 60%. On the other hand, experiments carried out on the nourished sand itself resulted in average values of 60%, with a varying range that fluctuated between 52 and 69% (Gutierrez-Mas et al. 1998).

The estimated daily rental cost for the weight control equipment, completely installed in the dredger ship, runs to approximately $150 per day.

Discussion and Conclusions

The portable and independent control system presented here has proven both operational and useful when calculating the respective percentages of solid matter and seawater in the dredger hopper. Among other characteristics, the low budget cost, prompt simple setup, and independence from other control systems installed in the dredger by the contractor are worth pointing out.

Equally important is the fact that the data referring to volume and dry weight are collected in real time. This allows not only the full-time monitoring of precise data used in dredging management, but also a thorough discernment of any accidental dumping of the sediment loaded on the dredger. It would be appropriate to point out frequent cases in which mud was dredged instead of sand, and consequently dumped in an authorized zone, normally far away from the coast. These mud escapes, when occurring en route between the dredging site and dumping destination, could very well provoke an elevated level of turbidity in those waters and the burying of existing biota, as well as consequent environmental dangers. By application of this technique, the exact quantity poured and the moment and location where this took place would be indicated.

Currently, the beach nourishment work is being paid for by measuring the cubic meters of material contained in the hopper. No guarantee exists whatsoever of the percentage of water to be found in the load. With this methodology, the useful matter—sand—can be clearly distinguished from that which is not useful—seawater. In this way, in future dredgings a rate per ton of dry sand can be set; that is to say, the sum of all weights of each grain of sand, leaving out all water caught in interstitial gaps.

The estimated rental price for the equipment complete with gear is less than the cost necessary to keep two controlling technicians on board the vessel on 12 h shifts each. Nevertheless, up to the present, human supervision is still required until some type of protection measures can be put into effect for the maintenance of certain mechanisms against involuntary maneuvers caused by unauthorized personnel. Computerized data processing and real-time monitoring allow for better clarity in controlling the actual and subsequent measurements taken.

The percentage of solid matter in the hopper (53%) has turned out to be only slightly higher than that of seawater (47%). On the other hand, the tests carried out on the beach sand itself indicated 60% for the percentage of solid grains, oscillating between 52 and 69%.

As far as the measurements taken in the hopper are concerned, the automatic procedure yielded values of approximately 5% less than those obtained by the standard manual process. This result, though not definite, justifies the need to perform new tests on other dredgers and different sediment types.

Acknowledgments

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Notation

The following symbols are used in this paper:

V_c = total volume;
V_d = displacement volume;
V_s = sand volume;
V_w = water volume;
W_c = total weight;
W_s = sand weight;
W_w = water weight;
ρ_s = density of sand; and
ρ_w = density of water.

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