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ORIGINAL ARTICLE

Combining coastal geoscience mapping and photogrammetric surveying in maritime environments (Northwestern Iberian Peninsula): focus on methodology

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Abstract Digital photogrammetry and GIS-based mapping are increasingly recognised as powerful tools in littoral issues. This paper considers the interoperability framework for high-resolution imagery acquisition and the development of coastal geoscience maps. The layered system architecture of the cartographic methodology is also explained. Moreover, it highlights a new approach to assessing heterogeneous geologic, geomorphological and maritime environments. The main goal of the present study was to test a new concept for photogrammetric images in order to assist modelling techniques, spatial analysis and coastal conceptual models. This approach proposes a methodological approach to coastal zone monitoring and to maritime forcing conditions evaluating. This approach will allow: (1) the acquisition of a large archive of high-resolution imagery; (2) the development of a coastal database including the entire data field and in situ assessments; (3) the study of coastal dynamics and shoreline evolution; (4) the assessment of the rock platforms and hydraulic structures; (5) the production of coastal geosciences maps. An integrated coastal geoscience and engineering methodology was outlined in NW of Iberian Peninsula (South Galicia and North/Central Portugal regions). This paper reports on the increased knowledge of the studied regions, providing essential data concerning coastal geo-morphodynamics. The overall assessment revealed additional evidence of erosion issues, which contributes to a better understanding of the hydraulic conditions. The main results are presented in regional coastal geoscience maps and local approach-outputs that could help government, local authorities and stakeholders to develop coastal management plans and to recommend strategies.

Keywords Maritime environments · Coastal geoscience mapping · Photogrammetry · NW Iberian Peninsula

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Introduction

Geographical information systems (GIS) represent an outstanding technology that is in constant development in mapping science. GIS applications are gradually becoming part of many scientific or technical studies, hence several open source software tools are available that are operational, fast and accessible (e.g., Goodchild 1992; Chacón et al. 2006; Liu and Mason 2009; Green 2010). According to Goodchild (2004, 2010) GIScience is an emerging concept dealing with the recognition and characterisation of the natural and/or social components to understand the mechanisms or processes toward an interaction level among geographic database systems. In fact, GIScience has an established history in coastal and marine applications (e.g., Wright and Bartlett 1999; Green and King 2003;

Bartlett and Smith 2004). In some studies the geoscientific context aims to summarise the techniques and principles that are useful in GIS applications within or connected with other fields (e.g., Liu and Mason 2009; Yu and Peuquet 2009; Green 2010; Reitsmaa 2013). Several studies have pointed out the value of merging various GIS techniques such as: image analysis and cartographic systems, geodatabase systems, photogrammetry and high-resolution imagery based mapping, global monitoring and 3D modelling techniques (e.g., Chandler 1999; Thumerer et al. 2000; Moore 2000; Lim et al. 2005; Genz et al. 2007; Addo et al. 2008; El-Hakim 2008; Addo 2013; Jordan 2015). There are a growing number of contributions on innovations and applications of GIScience in several scientific and technical branches (e.g., aerial surveying, urban geography, geosciences, water resources, engineering and military operations).

All these research fields connect with the real essence of this study, which is intrinsically related to engineering geoscience applications in maritime environments. The approach was closely followed by a transdisciplinary trend addressed by some authors such as Wickson et al. (2006); Kuhn (2012) and Wright (2012). A coastal GIS methodology needs to be an integrated coastal geoscience and engineering approach, with GIS and photogrammetric surveying of dynamic maritime environments. Such approaches should be established in a multidisciplinary and holistic context (e.g., Drummond et al. 1997; Buckley et al. 2002; Vallega 2005; CIRIA et al. 2007; Rogers et al. 2010; Pires et al. 2013, 2014a, b, 2015).

The conceptual framework described in Fig. 1 proposes the theoretical basis for a geoengineering approach in Integrated Coastal Zone Management (ICZM), which is related to this research. The coastal or maritime environment is one of the most dynamic and energetic interfaces between human society and environmental sustainability (e.g., Green and King 2002; Fröhle and Kohlhase 2004; Populus et al. 2004; Wang 2009; Addo 2013). In this GIS-based project all elements and processes considered are taken into account in the mapping framework. The proposed methodology is essential to anthropic intervention including hydraulic structures, and particularly the armour layer component (superficial and visible part of the structures), as described in Fig. 1. The relationship between all the processes, elements and forcing conditions allows the creation of several thematic geoengineering maps, as well as a better understanding of coastal morphodynamics. This holistic approach is inspired by the concepts, terminologies and methods proposed by Woodroffe (2003) and Pavlopoulos et al. (2009), associated with coasts and engineering geomorphology. In addition, GIS coastal mapping is also related to beach management and maritime engineering approaches presented in CIRIA et al. (2007) and Rogers et al. (2010). Likewise natural rock

(armourstone) and artificial blocks (concrete) are important elements to take into account throughout the development methodology for geomaterials evaluation in hydraulic structures (Latham et al. 2006; Ciria et al. 2007; Pires and Chaminé 2009; Pires et al. 2009a).
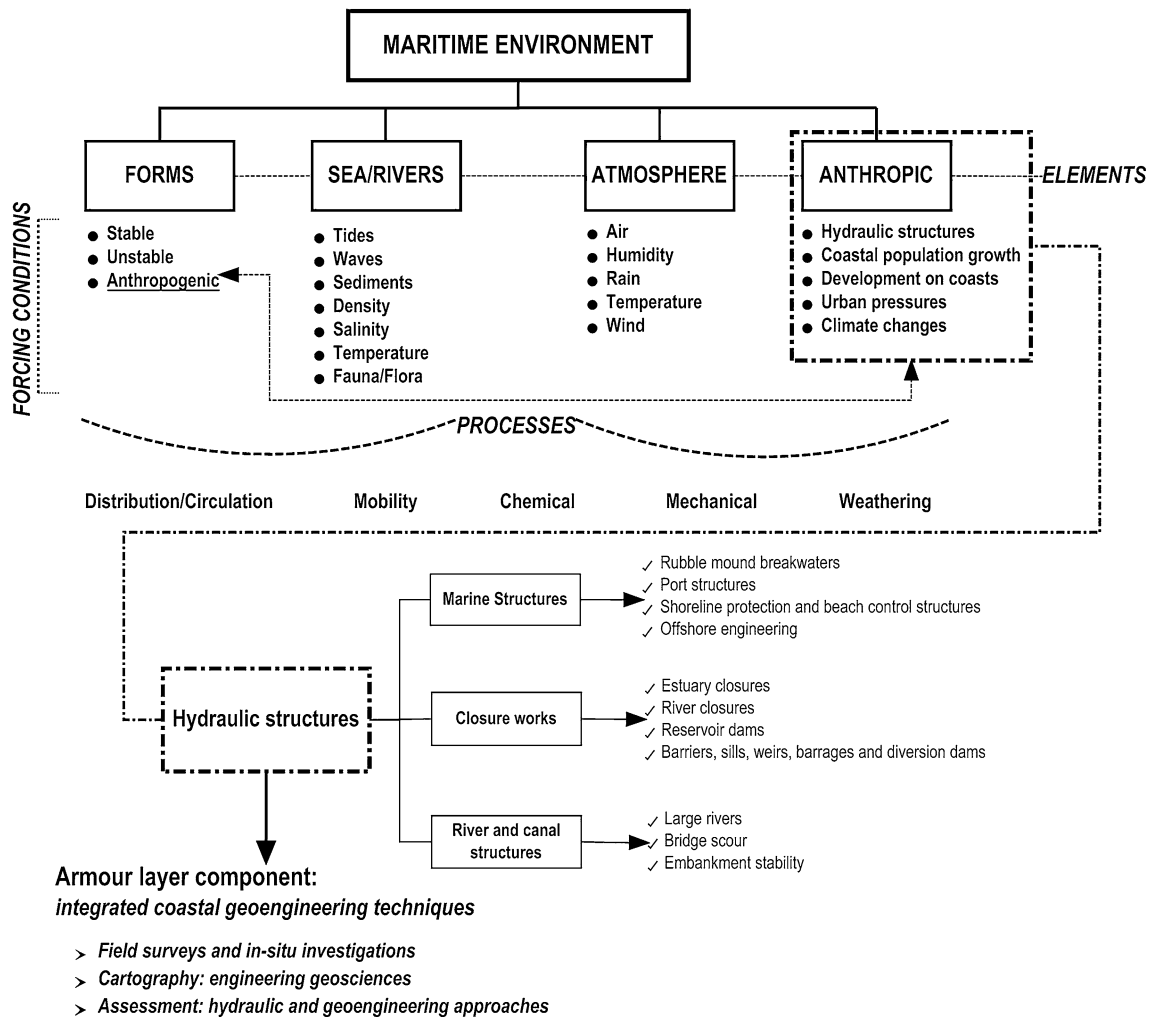
The integrated coastal geoengineering methodology involves the quality of geospatial data and imagery acquisition. Recent evolution in such technologies has improved the assessment, monitoring and know-how in coastal studies. Mapping coastal features requires the combination of different techniques, such as photogrammetry, remote sensing and aerial imagery (Falkner and Morgan 2002; Pires et al. 2013). Digital photogrammetric techniques are frequently used to compare images and detect changes during a specific time period. There are various application fields: glacial movement, rock slide movement, long-term construction sites, advancing vegetation pathogens, wetlands evolution, urban growth charting, floods monitoring, erosion monitoring and natural hazards assessing (e.g., Chisholm 1990; Gillie 1992; Welch and Jordan 1996; Pérez-Alberti et al. 2013).

Historically, photogrammetric applications have relied upon aerial photographs as a basic tool. Their early development was mainly driven by military uses (e.g., Mikhail et al. 2001; Fleming et al. 2009; Jones and Reinke 2009). Later they became widely applied in civil use for applications including environmental issues, climatology, agriculture, engineering, cartography, water resources, coastal management, land planning and geohazards (e.g., Fleming et al. 2009; Wang 2009). The research procedure takes advantage of high-resolution imagery by means of an airborne platform. Although airplanes, helicopters, and lighter-than-air craft are employed as aerial photography vehicles, fixed-wing aircraft are the primary aerial photographic platform (Falkner and Morgan 2002; Cunha et al. 2006; Pires et al. 2009b) and also unmanned aerial vehicles the so-called micro drones (e.g., Jordan 2015; Pires et al. 2015).

The main goal of the paper is to propose a multidisciplinary framework approach that enables geo-professionals to pursue an innovative coastal geoscience and engineering methodology. Moreover, the integrated approach presented herein is important for proposing environmental strategies. The final target of this research would be to support regional authorities with reference to coastal or shoreline management concerns.

Study area

The sites studied embrace a long stretch of coastline and involve a broad region of the north-west of the Iberian Peninsula (Spain and Portugal). The study comprises six main areas, two in Spain with eight specific sectors and

Fig. 1 Conceptual framework and theoretical basis for coastal geoscience and engineering approach in integrated coastal zone management (ICZM)

four in Portugal with ten sectors (Fig. 2; see detailed description in Tables 1, 2). The Southern Galicia region (NW Spain) and the coastal stretch between Caminha and Figueira da Foz (north and central Portugal) extend more than 300 km. The region's coastline is very energetic, changeable and heterogeneous in terms of coastal dynamics. After the choice of the six studied areas (Fig. 2) the next stage of the research comprised the collection of aerial imagery for the GIS-based platform using digital photogrammetry. Three flight operations were made: (1) areas 1–3; (2) areas 4 and 5 and (3) area 6. Tables 1 and 2 display some examples of the high-resolution imagery acquired and also summarise the extent of the studied area, a description of each sector, as well as the ground control points used for image georeferencing. In this type of operation it is important to characterise the coastal region framework and the features of the site, such as physical behaviour, hydraulic constraints and forcing conditions.

The results presented here are for two areas, Ribeira (Spain) and Espinho (Portugal), [1] and [5], respectively. Different GIS coastal applications were displayed for five sectors, including two rocky coasts (Laxe Brava and Corrubedo, in Spain) and three groynes (Aguiño, in Spain, and Carreira de Tiro and Casa Branca, in Portugal).

Galicia and NW Portugal coastline: a general overview

The NW Iberian coastline is depressed by several rivers, inlets and bays. The shoreline has a very dynamic, heterogeneous and mixed coastal environment in terms of its coastal geology and geo-morphodynamics (e.g., Trenhaile et al. 1999; Dias et al. 2000; Pérez-Alberti et al. 2012). Ranging from a rocky shore or platforms to a diversified environment, the region also comprises sandy beaches and coastal protection works (Pires et al. 2013).
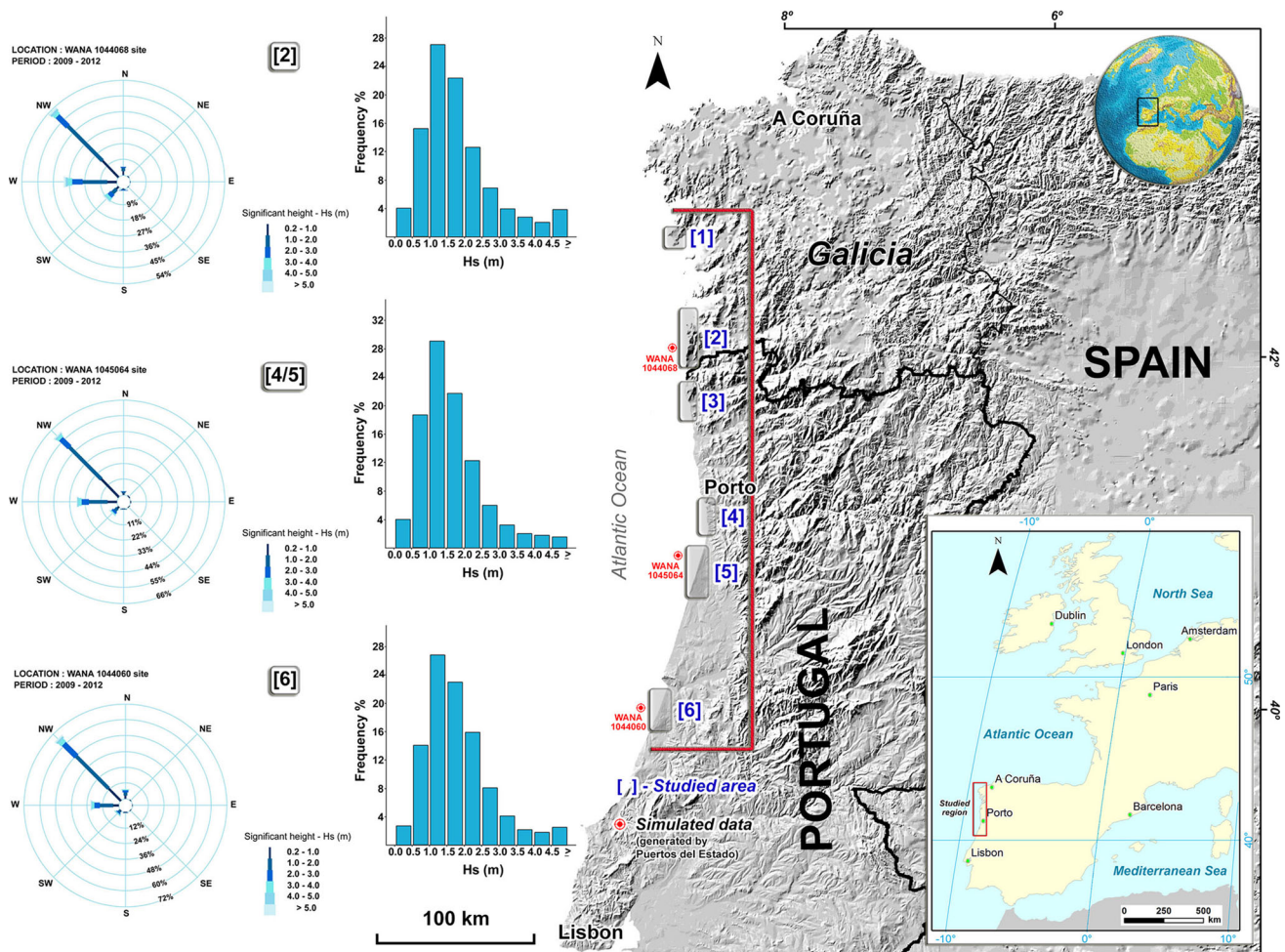
Fig. 2 Studied sites—southern Galicia, Spain and north/central Portugal—and selected sectors for the photogrammetric assessment and GIS applications in NW Iberian Peninsula coastline (more details in Tables 1 and 2)

The wind factor is an important physical parameter in terms of wave direction or speed and must be taken into account when studying coastal dynamics and forcing conditions of the region. Generally dominant winds on the coast of Portugal are between N and NW, except in the winter, when the prevailing wind regime direction is from SW and is stronger than in the summer. Similarly, along the Galician coast the wind system in winter usually has a SW trend, while in spring and summer the wind has predominantly N and NW directions (NGA 2011; Puertos del Estado 2012). The forcing conditions, including mean wave height (Hs) and frequency (%), for the simulated data available along the study areas can be found in Fig. 2. Concerning the records, they were divided in two basic types: WANA and SIMAR 44 were both generated and distributed by *Puertos del Estado* (for more detail see Mendoza-Ponce and Quintana 2009, and references therein).

The maritime works that can be found along the coast between Portugal and Spain include a wide range of structures, such as harbours, breakwaters, groynes, jetties, seawalls or mixed solutions (Fig. 1). On rocky shores several geoforms were described along the coast and platforms, including boulders which in some places of Galicia have a very energetic and dynamic performance (e.g., Trenhaile et al. 1999; Blanco-Chao et al. 2007; Pérez-Alberti et al. 2012; Gómez-Pujol et al. 2014); the Laxe Brava site is an example of this (Area [1]). Vigo, Leixões, Aveiro and Figueira da Foz are the main commercial ports throughout the study area. There are other small ports for protection and fishing which are used by small craft and fishing vessels.

The Galician mainland adjacent to Area [1] is dominated by a mesotidal environment with a mean tide length of 2.5 m and a spring tidal range between 3.75 and 4 m (Pérez-Alberti et al. 2012, 2013). The Ribeira is mainly a rocky coast with a few mixed systems along the littoral such as sandy beaches and dunes. The Galician coast is about 2100 km long, including several islets and more than 380 hydraulic works along the coast (POLGalicia 2010).

Table 1 Galicia (Spain) studied areas: description and characterisation with two examples of the high-resolution aerial imagery

Country	Studied sites [ID]	Type of coast	Studied sectors Nr.	Extension (km)	Maritime structures	Control points	Photo (example)
Spain	Laxe Brava, Ribeira [1]	Rocky coast and boulder beach	*1* boulder beach	0,2	-	45	
	Corrubedo, Ribeira [1]		*3* rocky platforms I – Faro Corrubedo II – Punta Corrubedo III – Punta Couso/Corrubedo	3	-	40	
	Aguiño, Ribeira [1]	Mixed coast	*1* groyne *1* rocky platform I – Aguiño groyne II – Aguiño platform	1	1	40	
	Baiona, Pontevedra [2]	Rocky coast with boulders	*1* rocky coast	2	-	35	
	Oia, A Guarda [2]		*1* rocky coast	1,5	-	30	

Table 2 NW Portugal studied areas: description and characterisation with two examples of the high-resolution aerial imagery

Country	Studied sites [ID]	Type of coast	Studied sectors Nr.	Extension (km)	Maritime structures	Control points	Photo (example)
Portugal	Vila Praia de Âncora [3]	Mixed coast	*1* breakwater *1* rocky platform I – V.P.Âncora groyne II – Caminha rocky coast	4	1	35	
	Lavadores, V.N. Gaia [4]	Rocky coast with boulders	*1* rocky platform	1,5	-	45	
	Espinho, Aveiro [5]	Sandy coast	*4* groynes *1* seawall I – Marinha II – Marinha seawall III – Carreira de Tiro IV – Casa Branca V – Paramos ETAR	5	5	200	
	Cova and Lavos, Figueira da Foz [6]	Sandy coast	*2* groynes I – Lavos II – Cova	4	2	75	

INTEGRATED COASTAL GEOENGINEERING TECHNIQUES

PHOTOGRAMMETRIC IMAGE ACQUISITION

INTEGRATED COASTAL GEOENGINEERING MAPS

Light aircraft
Model CESSNA C172 or similar

UAV's
Unmanned aerial vehicle

HIGH RESOLUTION GPS
Trimble Explorer® or equivalent

Digital Camera
CANON EOS-1DS MKII or equivalent

System architecture

High accuracy *GIS* data collection system

> High-end digital
> Single lens reflex (D-SLR)
> 21 Mega pixels
> Camera lens 135 mm; f/2.0
> Ground resolution: 2cm - 5cm

✓ Rugged incorporated or embeded PC
✓ GPS / IMU data interpretation
✓ Camera orientation
       - camera attitude
✓ Human operator
       - acceleration
       - angle rate

CONTROL POINTS ON THE GROUND

Transversing Micro-Erosion Meter (TMEM) in selected sites

GEOREFERENCING AND ORTORECTIFYING

> Shore platforms evolution
> Accuracy of erosion and wear rates in geomaterials
> Control points measurements

GIS **PLATFORM**

LAYERS

✓ Topographic features
✓ Geological background
✓ Tectonic lineaments
✓ Coastal dynamics
✓ Forcing conditions
✓ Maritime structures
✓ Coastal boulders
✓ Coastal geoforms

✓ **Visual inspection and field survey**

> Surveys data
> Geomechanical evaluation
> Geological assessment
> Additional data

IN-SITU EVALUATION

■ Rebound / Hardness stations
    Schmidt hammer and Equotip (PROCEQ®) or equivalent
■ Scanline surveys

GIS **MAPPING**

INPUT

✓ High resolution aerial imagery
✓ Structural geology analysis
✓ Coastal geomorphic features
✓ Geomaterial recognition
✓ In-situ geomechanical testing
✓ Weathering/Degradation grade
✓ Deterioration level of the structure

GEOMETRY:
● Point
● Line
● Polygon
● Raster

THEMATIC OUTPUT MAPS

✓ Engineering geosciences cartography
✓ Interactive coastal database
✓ Revetment geomaterial status
✓ Geomaterial zoning cartography
✓ Present condition of the structure
✓ Coastal geomophologic/dynamics maps
✓ Stability of rocky coasts (shore platforms and coastal boulders)

MODELLING TECHNIQUES

Development of spatial analysis

Coastal conceptual models

3D maritime structure's modelling

> R2 TOTAL STATION (Stonex®) or similar
    - Reflectorless; 350 meters
> GRID maplayers:
    - digital elevation model
    - hillshades (90°, 270°)
    - slope gradient
    - slope aspect

> Dynamics
> Energetic conditions
> Stability evaluation
> Geomorphic features
> Geostructural analysis

■ Oblique photos of the coastline

◄**Fig. 3** Workflow implementation: relationship between different methodologies and outputs for achieving an integrated coastal geoengineering techniques approach

Forcing conditions along the Atlantic coast system in Portugal are characterised by semi-diurnal tides (with amplitudes of 2–4 m). In general, significant wave heights range from 2 to 3 m and maximum significant wave heights are greater than 8 m. The wave directions are dominated by W and NW, with some events from SW (Pires et al. 2009a, 2013). The total length of the Atlantic coast of mainland Portugal is more than 800 km. There are about 290 hydraulic works along the coast, 70 % of which are groynes and seawalls (Pires et al. 2009a). Area [5] is also characterised by a mixed coastal system comprising sandy beaches and groyne fields of approximately 5 km in length.

Methodology

Integrated coastal geosciences and engineering techniques

This paper deals with a holistic and systematic methodology that encompasses several layers of information obtained from different sources: field data (in situ evaluation) and existing maps, charts and documents. The thematic maps and outputs were developed by using all the layers and inputs. Afterwards all the information was embedded in GIS software and geodatabases. Finally, these outputs and the data analysis will support the framework of modelling applications.

This section presents the system architecture, the map design of the GIS and photogrammetric project. The workflow illustrated in Fig. 3 shows the structural design for the study implementation. It also presents the relationship between the different methodologies/techniques (e.g., light aircraft, unmanned aerial vehicles, high-resolution GPS, traversing micro-erosion meter technology, GIS-based platform) and the outputs (e.g., engineering geosciences mapping, geomaterial zoning mapping, stability of rocky coasts). The conceptual flowchart could be used as a general methodology using several modern techniques and equipment. As stated before the proposed sequence of techniques is intended to contribute to GIS in coastal environments. The workflow shows two important components of the system: (1) digital photogrammetric image acquisition and (2) coastal geoscience mapping, described below in "Geo-morphodynamic mapping: stability of rocky coasts" and "Geomaterial zoning map: marine structures assessment".

Firstly, it is important to effectively prepare the flight operation, which will translate into greater data accuracy

and high-resolution aerial images. This system uses a light aircraft (in this case a Cessna C172, but any similar aircraft can be used) with the right door removed (more details can be found in Cunha et al. 2006; Pires et al. 2009b). This modification led to more accurate photos related to verticality, flexibility or even mobility of the camera operator (Teunissen 1995). Some of the main features of the flight are described in Fig. 3. Three flight operations were planned in order to obtain the aerial images. Several flights are required to obtain an adequate number of images of the coastal sites. Georeferencing information was provided by Trimble GPS GeoExplorer® XH technology, allowing more accurate collection of the control points (see Tables 1 and 2 with the number of control points registered for each sector).

Finally, the GIS platform was a necessary step toward the assessment and analysis of maritime environments to carry out coastal geoscience mapping. ArcGIS v10.1 software (ESRI®) and the available extensions were applied. The results of the photogrammetric mapping produced interesting outputs of the area. Figure 4 exemplifies the four different scenarios necessary to create and develop coastal geoscience GIS mapping from high-resolution aerial imagery acquisition and fieldwork surveys (Fig. 4a, b) to the integration, application and spatial conceptualisation in a GIS-based cartography framework (Fig. 4c, d).

This paper reports on the application of the approach in three types of coastal environment: (1) rocky coasts; (2) sandy coasts or mixed systems and (3) anthropic elements such as hydraulic structures or coastal protection works. The first and second types covered different layers and inputs from the third type, as will be shown in the results. Rocky and sandy coast assessment requires a thorough study of the platform and of mobile elements like boulders and geoforms, but also a good knowledge of the area's geology, tectonics, geomorphology, and coastal dynamics (Pérez-Alberti et al. 2012, 2013). Such background understanding has already been provided by previous works (e.g., Pérez-Alberti et al. 2012, 2013). The hydraulic structures evaluation incorporates several geoengineering methods allowing a new approach to the assessment and monitoring of coastal structures which has been updated from previous studies (e.g., Pires and Chaminé 2007; Pires et al. 2009a, 2009b, 2013 and references therein). GIS mapping, geomorphological features and geomaterials properties were incorporated into the coastal environments research to analyse these features in terms of the behaviour of the structure of different layers and rock/block movement (depending on the type of structure and the type of blocks placed in it, the performance of the different layers of the structure may vary in terms of coastal protection, and the movement of the blocks placed along the structures can differ). An interdisciplinary connection was also
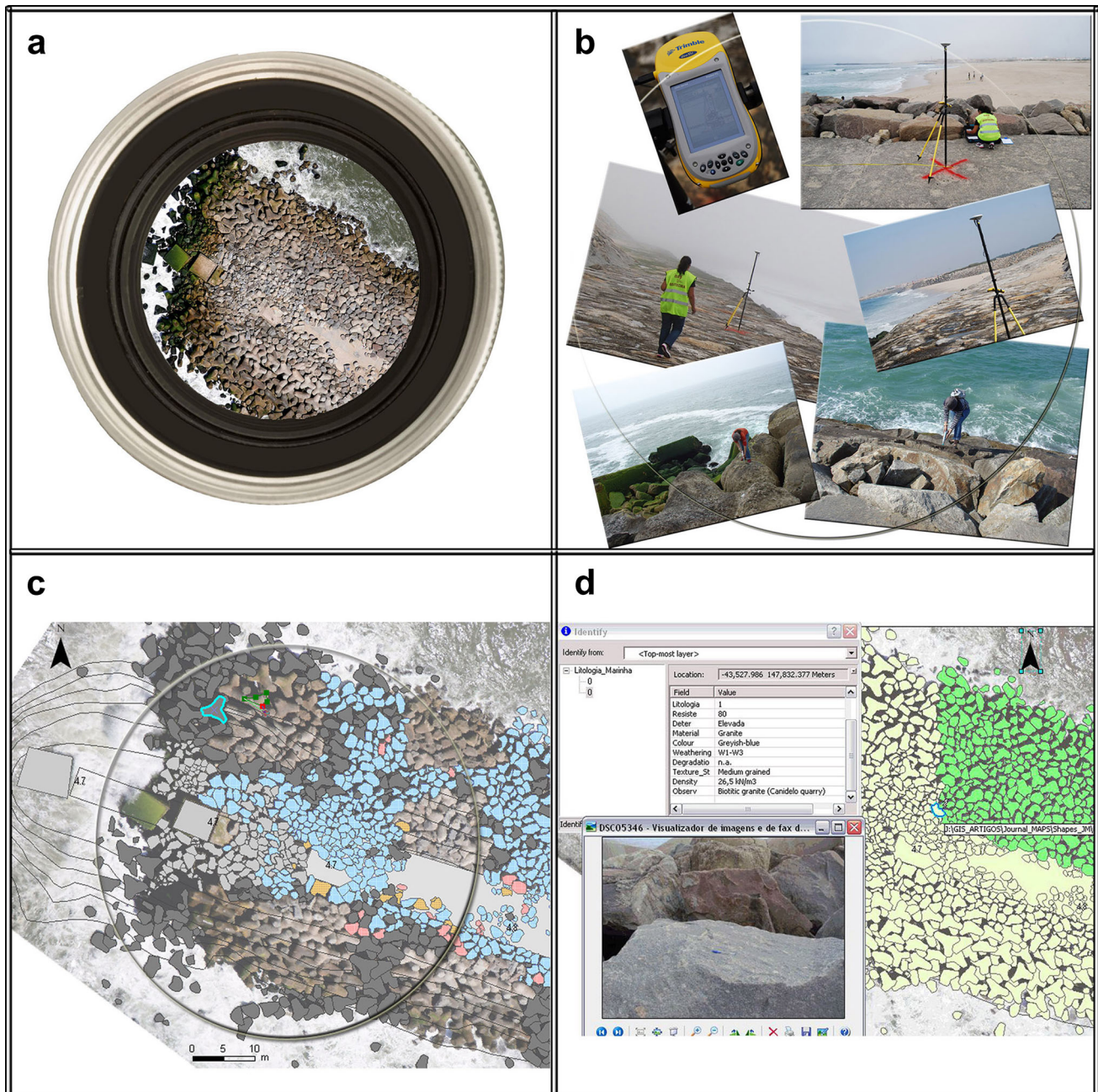
Fig. 4 Applying different scenarios to create and develop coastal geoscience GIS mapping: **a** high-resolution aerial imagery acquisition; **b** field surveys and GPS measurements; **c** GIS integration, application and vectorisation platform or project; **d** spatial conceptualisation of layers, vectorial data, attributes, rasters and interactive geodatabases

established between geoengineering concepts and hydraulic behaviour in the planning process of maritime structures as recommended by Ciria et al. (2007).

The design of coastal conceptual models was an important aspect of the studied sites. To help conceptualise the 3D models of the hydraulic structures presented here, total station records (Stonex®) and a grid of points were used, with models based on the GIS project displaying the rock/blocks mobility of the maritime structures.

The outputs (thematic maps) are a good starting point to theorise and propose a conceptualisation of the coastal systems framework interaction. GIS mapping has been shown to be a good contribution for the integrated coastal geoscience and engineering approach. Scientific fields such as GIS cartography, engineering geosciences, applied geomorphology, rock engineering, and coastal engineering were applied to the studied areas as shown in the output maps displayed in this work. These maps involve diverse

types of thematic layers and researched fields, previously applied with other perspectives or approaches by several authors (e.g., Fisher et al. 1993; Dykes et al. 2005; ISRM 2007; Ciria et al. 2007; Peterson 2009; Smith et al. 2011; Chaminé et al. 2013).

As a final remark, the study displays an integrative procedure for coupling coastal geoscience GIS mapping and high-resolution digital imagery for maritime environmental evaluation. A low-level aerial survey was conducted from a light aircraft in order to acquire the images in raster format, which were a fundamental part of the GIS platform/project. Finally, GIS mapping enabled 3D modelling and spatial analysis of the studied sites.

Results and discussion

The research results are presented in three sub-sections: rocky coasts and boulder evaluation; marine structures assessment and conceptual model proposal and synthesis of results. Five practical examples will be displayed as an outcome of the GIS platform for data integration. The outputs of the GIS project correspond to different thematic maps according to the main purpose for each studied area. Hence, these final maps are associated with several factors: (1) coastal management issues; (2) type of coastal environment; (3) geologic, petrophysical and geomechanical characteristics of geomaterials; (4) geo-morphodynamics behaviour; (5) hydrographic and physical conditions and (6) data and information availability.

The examples shown here were selected to show the methodology presented. The key sites are located in Ribeira (Area [1], Spain) and Espinho (Area [5], Portugal) and comprise five sectors: Laxe Brava, Punta Couso and Aguiño (Ribeira) in Area [1]; Carreira de Tiro and Casa Branca (Espinho) in Area [5].

Geo-morphodynamic mapping: stability of rocky coasts

Laxe Brava (Ribeira, Area [1]) is characterised by an open beach with boulders along a rocky granitic coast. Figure 5 exemplifies the geostructure vectorisation with a general overview of the drawn polylines and studied profiles for future monitoring, inspection and comparison. Laxe Brava embodies one of the most typical coastal environments found in Galicia (NW Spain). Along this coast, which is particularly unusual and energetic, it was very useful to use GIS tools to assess rocky coast stability. High-resolution imagery was used to vectorise all the geostructures and lithological heterogeneities to several scales, particularly megascale (tectonic lineaments and geological boundaries) and meso and macroscale (faults, fractures, joints, fissures and veins), Fig. 5a. The identification of dominant geostructure patterns can help correlate the orientations with the different rock clasts/boulders sizes along the beach. Moreover, the relationship between lineament directions and wave attack tendencies could also explain the boulders' shape as well as their differential positions along the rocky platform (Pérez-Alberti et al. 2012).

Perpendicular profiles to the beach were also carried out with the aid of high-resolution GPS equipment. The main goal was to determine the movement of boulders and to identify each of the clasts by performing a systematic inspection and survey of the area (Fig. 5b). This detailed task was carried out using aerial images at different periods of time to compare the mobility of the clasts. The profiles were also used to insert the entire data obtained during the fieldwork and to analyse the beach stability due to boulders movement.

Punta Couso/Corrubedo (Ribeira, Area [1]) is also characterised by a rocky platform with boulders and dispersed megaboulders. It is a very active and energetic coast which is sculpted on granitic rocks. In this example the main purpose was to carry out an integrated geologic, geomechanical and petrophysical study along scanline surveys to help systematise the collected data. Therefore, in situ geomechanical testing measures were obtained with a Schmidt Hammer and an Equotip (ISRM 2007, 2015; PROCEQ 2012; Pires et al. 2014a, b) as shown in Fig. 6. It was also possible to register and identify potential boulder pathways with the help of high-accuracy GPS (Fig. 6).

Another example of applied GIS mapping is displayed in Fig. 7. Using the GIS platform it was possible to define a criterion for vectorisation and categorisation of the rock platform joints along the Punta Couso/Corrubedo sector. The field calculator extension was used in order to evaluate the joint degree or density of each polyline: 1 for first-order joints; 2 for second-order joints and 3 for third-order joints (Fig. 7). The implemented hierarchy allows geomorphological corridors to be distinguished and sheds light on the dynamics of boulders along the platform. Using the high-resolution imagery it was possible to vectorise very accurately the tectonic lineaments and/or fracture network, as well as the geoforms (boulders and megaboulders).

The detailed maps suggest that: (1) assessing the degree of fracturing will benefit accurate coastal mapping (e.g., if the distances between joints are larger, this highlights potential boulder corridors); (2) analysing the existence or absence of displacements and the degree of mobility of boulders and megaboulders will allow the study of geoforms and coastal dynamics as well as leading to a better understanding of the consequences of the forcing conditions on the coast (Figs. 6, 7).

Fig. 5 Example of the geostructures vectorisation of Laxe Brava sector (studied area [1]) and boulders stability analysis: **a** general overview of the drawn *polylines*; **b** studied profiles and boulders' marks for future monitoring, inspection and comparison
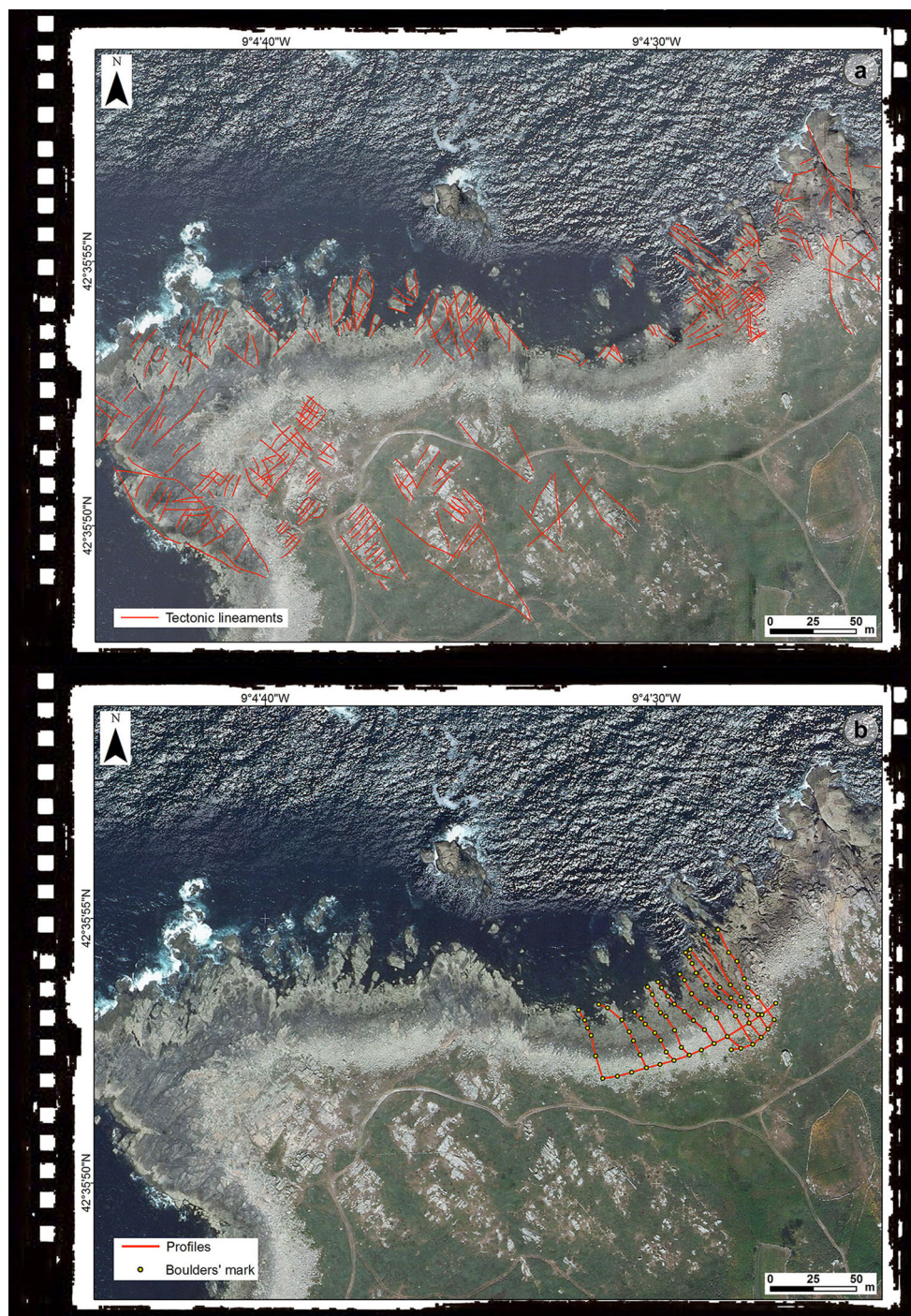

Geomaterial zoning map: marine structures assessment

Aguiño groyne (Ribeira, Area [1]) is located in a mixed system. As shown in Fig. 8, it was possible to identify a groyne implemented or established on a rocky platform. The same approach to the rocky platform was made in this sector as described in the previous examples. However,

Fig. 8 shows also the approach to hydraulic structures assumed in the methodology proposed here. A general overview of the studied sector is visible as well as the GIS mapping of the geomaterials surveyed (more than 12,000 vectorised blocks or polygons). Furthermore, this sector is a good example of the application of photogrammetric techniques to assess the armour layer (superficial part) of a groyne. It is also possible to visualise the sequence of high-
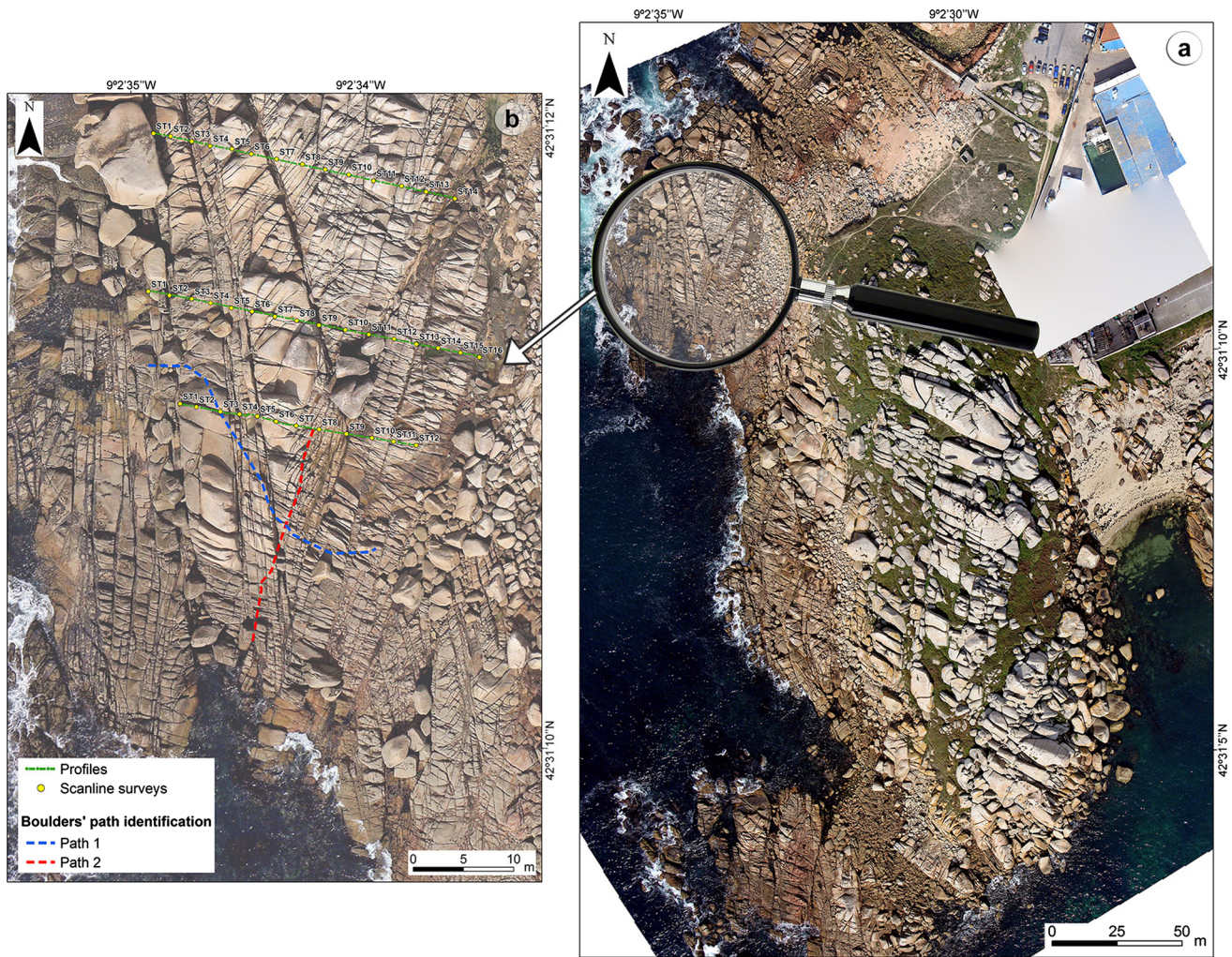
Fig. 6 Punta Couso/Corrubedo sector (studied area [1]): **a** high-resolution aerial imagery of the boulder beach; **b** location of the scanline surveys and geomechanical stations (ST) obtained along the profiles, boulder's path identification and stability analysis

resolution imagery georeferenced along the coastal protection structure (Fig. 8c), which was the basis for the geomaterial delimitation.

Finally, the Espinho (Area [5]) is characterised by a sandy coast with a series of groynes. In the example shown in Fig. 9 it is possible to recognise the overlapping layers from high-resolution imagery to geomaterial recognition, durability and deterioration levels. Examples of the generated 3D models, GIS mapping projects and applied cartography are also displayed. Similarly to the previous example of Aguiño, this approach has been applied to Carreira de Tiro and Casa Branca hydraulic structures (groynes).

Figure 9a shows the first thematic map design concerning geomaterial recognition and characterisation. The second thematic map represents the Schmidt Hammer rebound values determined along the armour layer of the structure (Fig. 9b). The Schmidt Hammer was used to determine the hardness of the geomaterials. In addition,

cross-checking all data and linking the two previous maps led to the last output displaying the structures' zoning, which comprises the deterioration level and current status (Fig. 9c). The deterioration level is based on the fieldwork surveys (data acquisition) and the applied geo-mapping. This evaluation allows a qualitative diagnostic of the actual condition of the superficial blocks forming the armour layer and presents the current status of the structure (for further information see previous works by Pires and Chaminé 2009; Pires et al. 2009b, 2013, 2014a, b and references therein). Espinho GIS mapping shows the layered architecture of the cartographical methodology approach for this type of environment. All the layers are interlocked, but it is possible to visualise features separately.

Conceptual model proposal

The examples presented above show the different approaches that can be used in an integrated coastal

Fig. 7 Illustration for Punta Cousa/Corrubedo sector: **a**, **b** criterion for vectorisation, categorisation and field calculator along the polylines in order to evaluate the joint degree in several scales; **c** final result with different line weights/density as well as different attributes or values
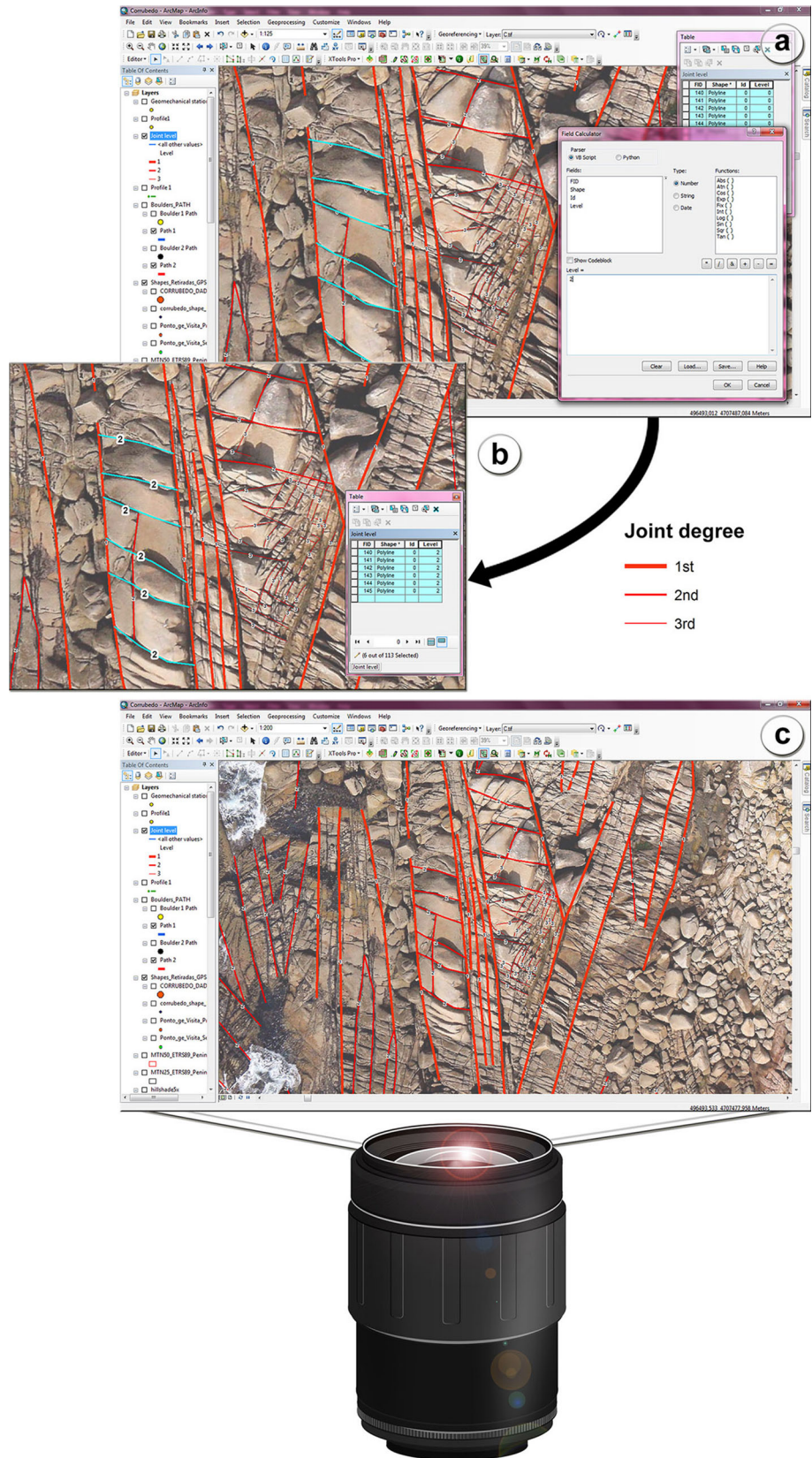
Fig. 8 Example of the mixed coast of Aguiño groyne with rocky platform (studied area [1]): **a**, **b** general overview of the studied sector; **c**, **d** geomaterial zoning GIS mapping (more than 12,000 vectorised blocks)
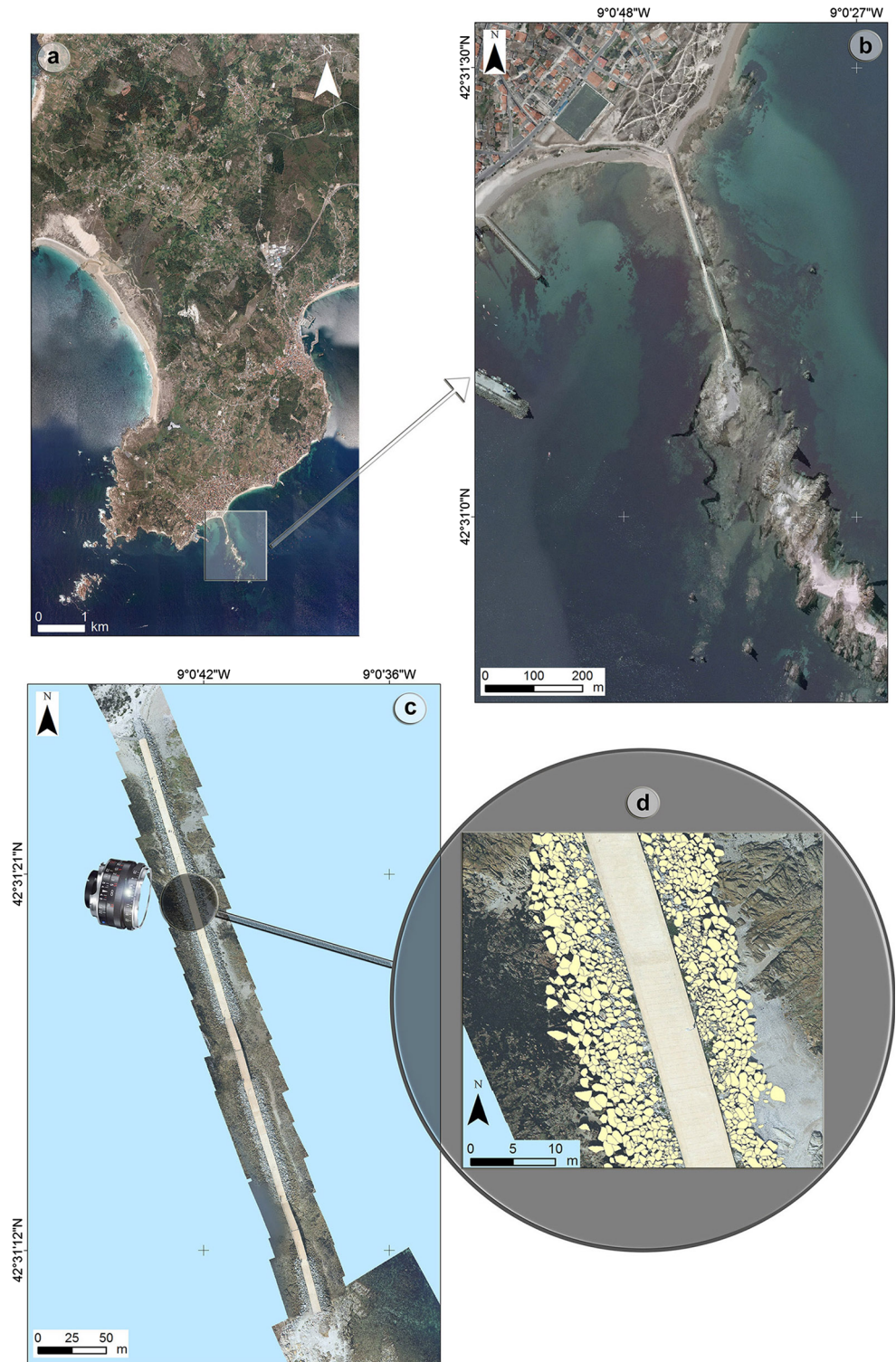
geoengineering methodology. From data collection to GIS project implementation, there is a large variety of thematic maps and applied mapping available. These outputs are described in the workflow of Fig. 3, for instance: engineering geoscience cartography; revetment geomaterial status; present condition of the structure or stability of

rocky coasts. The series of maps for the studied sites incorporates numerous geodatabases and vital information for future coastal studies along the NW Iberian region. Moreover, the maps contain a considerable number of mixed layers, from vectorial features to rasters. This will allow researchers to map coastal geoscience data and to

Fig. 9 Armour layer assessment of hydraulic structures—Carreira de Tiro and Casa Branca groynes from Espinho (studied area [5]) and integrated coastal geoengineering techniques: **a**–**c** overlapping layers from high-resolution imagery to geomaterial recognition, durability and deterioration level; examples of the 3D models generated, GIS mapping projects and applied cartography. (Geomaterial explanation: *1* biotitic granite, *grayish-blue*, medium grained; *2* granite, *reddish-pink*, medium to fine grained; *3* biotitic gneiss, *yellowish-brown*, coarse to medium grained with quartz and large feldspar megacrystals; *4* concrete path along the structure crest or blocks with concrete and aggregates; *5* tetrapods)
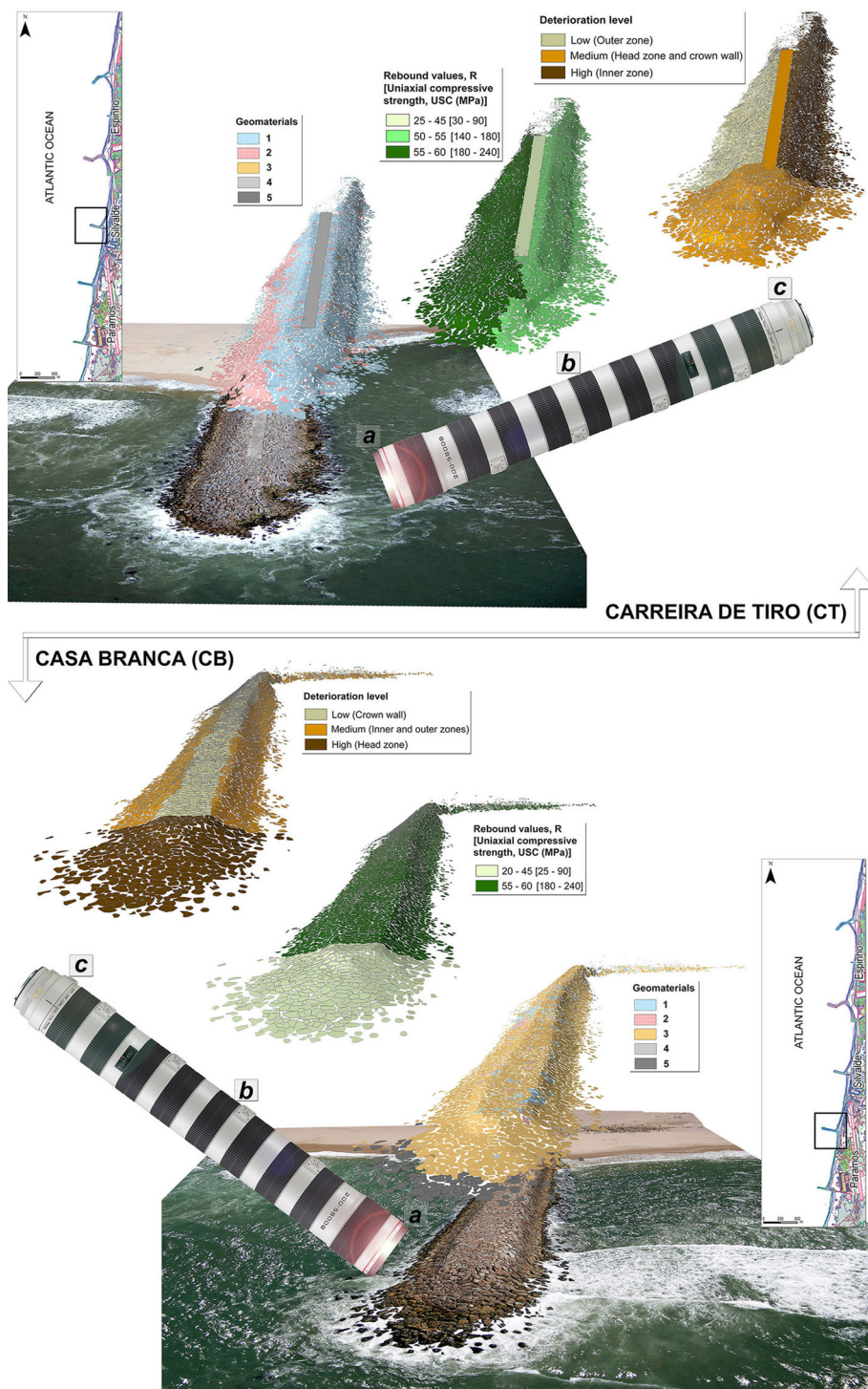
develop conceptual models for each studied sector at different scales (regional and local approaches).

The developed methodology provides an interesting starting point for GIScience cartography in maritime environments. The conceptual model proposed in Fig. 10 not only represents the synthesis of this paper, but also the key elements and requirements for integrated coastal zone management and geoengineering. This model also illustrates the relationship between the acquisition of high-resolution imagery, photogrammetric techniques, high-resolution GPS measurements, basic fieldwork and the applied cartography production. This approach represents an integrated framework (interdisciplinary, multidisciplinary and transdisciplinary) of the studied regions.

Fig. 10 An integrated coastal zone management: a coastal geosciences and engineering techniques approach

Conclusions

The main concluding remarks are as follows:

1. The increased knowledge of the studied regions supplies essential data and inputs. The studied regions highlight some results concerning coastal morphodynamics. The assessment provided further evidence of erosion problems along the studied sectors that can contribute to a better understanding of the hydraulic conditions. The use of regional coastal geosciences maps and local approach-outputs could help the government, local authorities and stakeholders to develop coastal management plans and to recommend strategies;

2. The proposed integrated coastal geoengineering methodology is valid for any type of coast or maritime environment. GIS mapping was the key to promote the interdisciplinary framework that was employed in the NW Iberian region. This paper shows an innovative sequence of techniques and equipment and an efficient approach to easily assess maritime environments. The strength lies in coupling GIS applications with photogrammetric techniques to create applied cartography and thematic maps. The outputs can be represented by maps for rocky coasts or for hydraulic structures, ranging from the stability study of rocky platforms and coastal boulders to the geomaterial zoning mapping and revetment status;

3. GIS-based mapping assessment incorporates an interactive geodatabase that is being updated regularly. Such database merges several amounts of layers, inputs, information and data, as displayed in the output maps. Using GIS applications and extensions it is possible to create 3D models of the maritime structures as well as use spatial analyst extension for several interpretations (e.g., susceptibility or vulnerability maps and statistical studies);

The study provides the backbone for coastal management processes. The development of a general workflow shows the connection between all the stages along these processes. This paper also underlines the importance of the conceptual modelling from a geoengineering perspective which characterises the research framework.

4. The investigations in this region are continuing. This approach was the starting point for GIS platforms relating to coastal zones in the NW Iberian Peninsula. The platform has the potential to create coastal GIS mapping and analysis. The upcoming research involves land use planning strategies and recommending long/short-term actions to coastal management plans, suggesting more adaptive solutions to coastal communities (e.g., Moore 2012; Pontee and Parsons 2012; USACE et al. 2014), taking advantage of coastal geosciences mapping.

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