

Boulder displacements along rocky coasts: A new deterministic and theoretical approach to improve incipient motion formulas

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ABSTRACT

Several impacts of high-energy marine events – tsunamis and storms – which have occurred along the Mediterranean coasts, have determined boulder displacements in different ways, spanning from sliding and overturning to saltation. The dynamics of these transport modes to the incipient motion of boulders, strictly connected to the pre-setting scenarios, has been extensively studied considering the boulder size and the hydrodynamic parameters of high-energy marine events, such as the wave flow velocity. Notwithstanding this, known hydrodynamic relationships provide some unrealistic flow values concerning the real wave flow velocity registered along the Mediterranean coasts. In this work, a new deterministic and theoretical approach has been developed to assess the minimum flow velocities required to move coastal boulders. The proposed approach is based on the introduction of modified parameters, which consider the real dimensional features of the boulders assessed by means of modern geophysical survey techniques, into the incipient motion formulas. To accurately define these parameters, we created a database composed of boulders located along the coasts of Apulia and Sicily (Italy) that were surveyed in previous studies through photogrammetric and Terrestrial Laser Scanner techniques. Results highlighted that the incipient motion formulas, revised with the new proposed parameters, provided minimum flow velocity values for boulder transport initiation, which were significantly lower compared to those calculated using the previous approach. Thus, the proposed modifications are a step forward towards defining the dynamics of boulder displacement.

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1. Introduction

Earth surface processes are gradually becoming a predominant threat to human settlements and economic development. Among these, water-related disasters (high-energy events) play an important role because global warming is probably increasing the occurrence frequency and magnitude of these events (IPCC, 2021, 2019; Scicchitano et al., 2021). Furthermore, owing to ongoing global warming, a general mean sea-level rise is expected for the 21st century with a likely range between 0.61 and 1.10 m at 2100 (IPCC, 2021, 2019) or even greater (Bamber et al., 2019; López-Dóriga and Jiménez, 2020; Rahmstorf, 2007). These sea-level rise projections imply that in the near future many coastal areas could be submerged, thereby changing the areas influenced by

flooding processes of high-energy events, such as storms, cyclones, and Mediterranean Hurricane (Medicane) (Cavichia et al., 2014; Conte and Lionello, 2014; Lionello et al., 2017; Mattei et al., 2021; Nastos et al., 2018; Scicchitano et al., 2021). Although along the Mediterranean coasts the occurrence of common storms has caused many boulder detachments and displacements (Biolchi et al., 2019a, 2019b; Mastronuzzi and Sansò, 2004; Piscitelli et al., 2017; Scardino et al., 2020), establishing the relationship between storm wave magnitude and boulder size is a difficult task.

Using boulders as “markers” to predict the local magnitude of modern and past high-energy hydrodynamic events, such as tsunamis (Paris et al., 2010a; Pignatelli et al., 2009; Scicchitano et al., 2007, 2012; Vacchi et al., 2012), large storms including extra tropical cyclones, hurricanes and typhoons (Cox et al., 2018; Hall et al., 2006; Hall, 2011; May et al., 2015; Scicchitano et al., 2020; Terry et al., 2016), water sprouts (de Lange et al., 2006), and extreme river floods (Alexander and Cooker, 2016), is common in geosciences. As well, coastal boulders

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were used as markers for establishing past frequencies and timing of extreme marine events (Hansom and Hall, 2009). These reconstructions are in high demand for coastal hazard assessments, especially for those areas where no local magnitude records of past events are available. Here we present 3D models reconstructed in previous studies (Mastronuzzi and Pignatelli, 2012; Pignatelli et al., 2010b; Scicchitano et al., 2012, 2020) for several boulders located in two areas of the Mediterranean coast (Sicily and Apulia regions). These models were used to develop a new deterministic and theoretical approach to better estimate the wave flow velocity at the time of boulder displacements. A sensitivity analysis of the minimum flow velocity/transport mode to the various parameters of the formulas (drag, lift, friction, and density) was conducted and compared to the recorded data of a Medicanne that impacted the coast of south-eastern Sicily, and shows the movements of several boulders (Scicchitano et al., 2020). Results highlighted that the boulder shape strongly influences the type of movement, and that the new formulas can describe better the movements of cubic/cuboid boulders.

2. From rational development to the theory of incipient motion formulas

2.1. Revisiting theory

The energy transmission from the impacting wave to the boulder has been conceptualized with different mathematical relationships to describe the whole transport process through the key stages of dislodgment: i) incipient motion (Nott, 2003a), ii) transport (Imamura et al., 2008), iii) deposition (Goto et al., 2009). The incipient motion formulas have been recently revisited and upgraded by correcting the physics behind the original Nott formula concept (Nott, 2003a), and distinguishing each incipient transport mode against the flow velocity (Nandasena et al., 2011a, 2013; Nandasena, 2020). In situ cementation of boulders to the substrate (Kennedy et al., 2019) together with crack propagation and block detachment (Hansom et al., 2008) appear to play key roles in order to assess the wave flow velocity for irregular boulder shapes considering additional forces in the force/moment balance equations (Noormets et al., 2004). When applying the formulas to predict the minimum flow velocity needed to transport a boulder, some assumptions are made (Nandasena et al., 2011b): i) the shape of the boulder is cubic or cuboid to simplify the calculation of the areas and volumes for fluid and body forces; ii) the boulder is detached and isolated to conserve the momentum from the fluid to the boulder; iii) the boulder is fully submerged by the flow when the motion starts to simplify the calculation of fluid forces and moments to the boulder; iv) flow velocity is depth-averaged and uniform over the depth to neglect flow turbulence contributions around the boulder. In their experiments, some authors, Bressan et al. (2018) and Lodhi et al. (2020), observed that boulders

started moving when submerged at least partially if not completely. This observation has been confirmed through the analysis of a video recording of Medicanne Zorbas that impacted south-eastern Sicily. Indeed, it shows that most of the boulder displacements occur when they are submerged (Scicchitano et al., 2020). Furthermore, no matter at what orientation the flow strikes the boulder, the boulder begins to move with the long axis perpendicular to the fluid flow (Imamura et al., 2008; Nandasena and Tanaka, 2013; Oetjen et al., 2020)(Fig. 1).

2.2. Rational development

The incipient motion formulas (Nandasena et al., 2011a; Nandasena and Tanaka, 2013) have been derived by considering the forces acting on the boulders (Fig. 2) and their moments on a cubic/cuboid boulder such that the area of drag force $A_d = ac$, area of lift force $A_l = ab$ and volume of the boulder $V = abc$.

Drag and lift forces act to move the boulder, reduced-gravity forces (boulder weight minus Buoyant force) and friction forces resist when the waves impact the boulder.

When the incipient motion formulas are applied to no cubic/cuboid boulders, the forces are overestimated because the theoretical size of the boulder is greater than its actual size (Fig. 3). Hence, the minimum flow velocity from the formulas could be overestimated (Cox et al., 2020; Rovere et al., 2017; Scicchitano et al., 2020). In this study, we replace the theoretical boulder with the actual boulder by introducing the new parameters to the coefficient of drag and lift, and the volume of the boulder such that:

$$\text{Virtual drag coefficient } C_{dv} = \frac{A_d}{ac} C_d \quad (1)$$

$$\text{Virtual lift coefficient } C_{lv} = \frac{A_l}{ab} C_l \quad (2)$$

$$\text{Virtual volume coefficient } C_{vv} = \frac{V}{abc} \quad (3)$$

The virtual coefficients (Eqs. (1)–(3)) model the real volume and projected area of the boulder. Thus, they improve the accuracy of the forces in the incipient motion formulas. The incipient motion formulas for a boulder with any shape is reported in Table 1.

3. Study cases of recent high-energy events and their effects on boulder displacements

Over the last decades, boulder movements have occurred during very strong storm events in the Mediterranean, e.g. Storm Vaia (Biolchi et al., 2019a, 2019b; Delle Rose et al., 2020; Ferrarin et al., 2020) and Medicane Qendresa and Zorbas (Scicchitano et al., 2021, 2020).

In order to test the use of the virtual parameters in the incipient motion formulas (c.f. Section 2), we selected two areas of the Mediter-

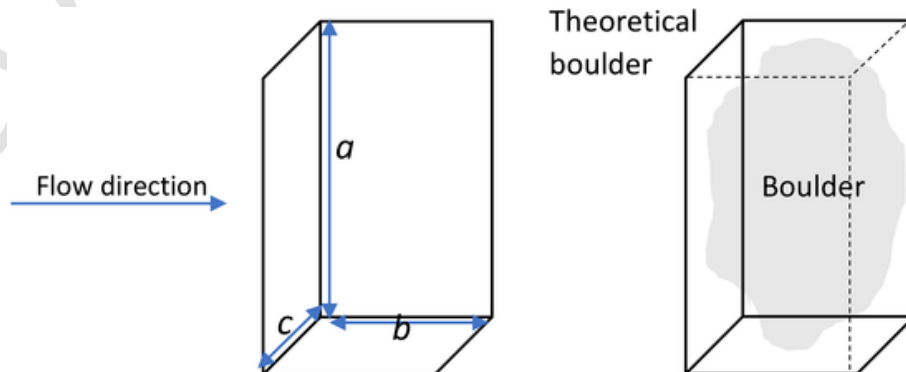


Fig. 1. Theoretical representation of the boulder (Nandasena et al., 2011b). Lengths a , b , and c are measured in the long, intermediate, and short axis of the boulder ($a > b > c$); – the volume of a theoretical boulder ($a \cdot b \cdot c$) is greater than the actual volume of the real boulder.

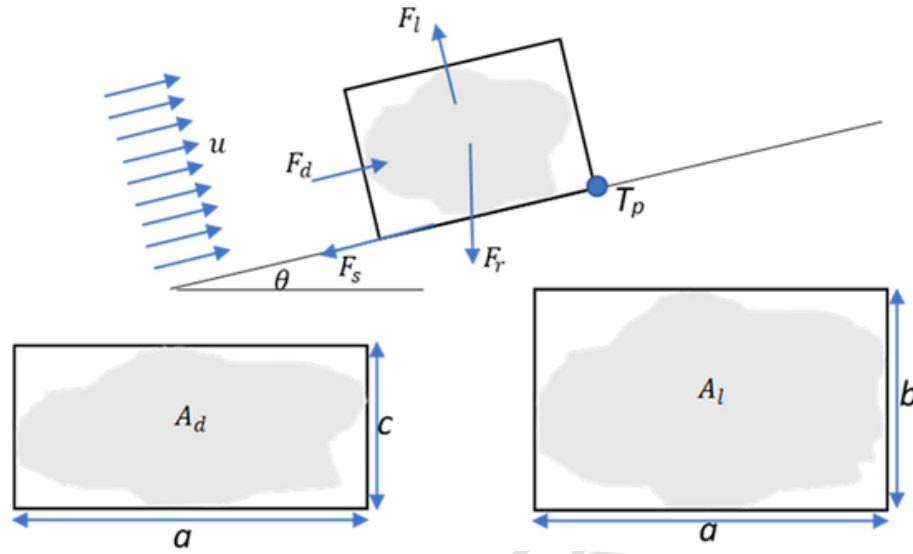


Fig. 2. Top: scheme of forces acting on a boulder on a sloping bed; u is the averaged depth flow velocity, F_d the drag force, F_l the lift force, F_r the reduced-gravity weight (weight of the boulder minus Buoyant force), F_s the static friction force between the bottom surface of the boulder and substrate, T_p the theoretical point of rotation of the boulder, θ the bed angle of the boulder at the pre-transport location. Bottom Left – actual drag area (shaded part A_d) and theoretical drag area (ac) of the boulder. Bottom Right – actual lift area (shaded part A_l) and theoretical lift area (ab) of the boulder.

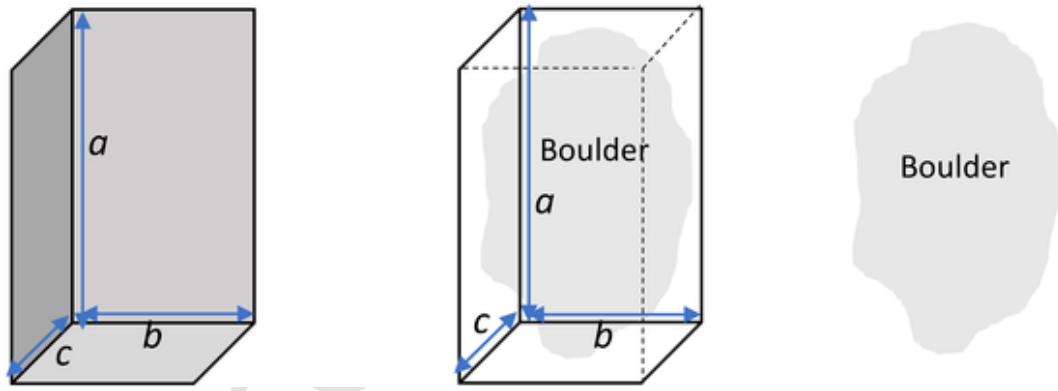


Fig. 3. Scheme of the actual boulder in the incipient motion formulas. Left – the formulas take the cube/cuboid shape based on axis lengths a , b , and c , despite the actual shape of the boulder (Nandasena et al., 2011b; Nandasena and Tanaka, 2013). Middle – the formulas take the actual boulder in terms of its volume and projected areas through the virtual coefficients (Eqs. (1)–(3)), but trapped in an imaginary frame of axis length of a , b , and c . Right – Actual boulder.

Table 1

Incipient motion formulas for the assessment of the square of flow velocity (u^2) in different pre-setting conditions: submerged/subaerial (SB/SA); joint-bounded boulder (JBB); cliff-edge boulder (CEB).

Type of movement	Pre-setting conditions		
	SB/SA	JBB	CEB
Sliding	Eq. (4) $\frac{2C_{vy}(\rho_s/\rho_w-1)gc(\mu_s \cos \theta + \sin \theta)}{C_{dy}(c^2/b^2)+\mu_s C_{lv}}$	–	–
Overturning	Eq. (5) $\frac{2C_{vy}(\rho_s/\rho_w-1)gc(\cos \theta + c/b \sin \theta)}{C_{dy}(c^2/b^2)+C_{lv}}$	–	Eq. (8) $\frac{2C_{vy}(\rho_s/\rho_w-1)gc}{C_{lv}-C_{dy}(c^2/b^2)}$
Saltation/ lifting	Eq. (6) $\frac{2C_{vy}(\rho_s/\rho_w-1)gc(\cos \theta)}{C_{lv}}$	Eq. (7) $\frac{2C_{vy}(\rho_s/\rho_w-1)gc(\cos \theta + \mu_s \sin \theta)}{C_{lv}}$	Eq. (9) $\frac{2C_{vy}(\rho_s/\rho_w-1)gc}{C_{lv}-\mu_s C_{dy}(c/b)}$

ranean in the Italian regions of Apulia and Sicily where extensive boulder fields have been detected and accurately surveyed in previous studies (Mastronuzzi and Pignatelli, 2012; Pignatelli et al., 2010a; Scicchitano et al., 2012). More specifically, we identified three areas in Sicily and three areas in Apulia (Fig. 6) which satisfied these particular conditions: i) boulder fields surveyed with high-resolution systems, such as Terrestrial Laser Scanner (TLS) or photogrammetry, allowing

for a 3D reconstruction with a resolution of about 0.5 cm grid; ii) surveyed boulders, cuboidal in shape and showing clear evidence of movement owing to the specific high-energy event; iii) boulder fields monitored for at least the past 10 years. The selected boulders were compiled in a database (Table 2) that was used to demonstrate the application of virtual coefficients (Eqs. (1)–(3)), modelling the real volume and projected area of each boulder (Figs. 4 and 5).

In Sicily, three sites located along the coast of south-eastern Sicily (Augusta, La Maddalena, and Vendicari) were selected. Along the coasts extending from the towns of Augusta to Siracusa, the occurrence of out-of-size calcareous and calcarenitic boulders was detected (Scardino et al., 2020; Scicchitano et al., 2007) (Fig. 7). Boulder fields in south-eastern Sicily were surveyed along rocky promontories slowly uplifted during the late Quaternary and the Holocene (Spampinato et al., 2012, 2011), using TLS and GPS RTK techniques (Scicchitano et al., 2012) in order to estimate the maximum flooding of the event responsible for the displacements of the largest boulders (Table 2). Moreover, one of the three sites has been under monitoring, since 2009, with Unmanned Autonomous Vehicle (UAV) photogrammetry and video systems (Scicchitano et al., 2020). Indeed, along the coast of the Maddalena Peninsula, there is a currently active surveillance camera system, managed by the Marine Protected Area of Plemmirio, which, in

Table 2

Location, size, and pre-transport setting of the boulders surveyed in south-eastern Sicily and along the Adriatic and Ionian coasts of Apulia.

ID Boulder	Location	Coordinates		Pre-setting scenario	Axis length (m)		
		Latitude	Longitude		a	b	c
A	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	4.73	2.6	1.3
BN	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	1.76	0.95	0.3
B2	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	1.54	1.1	0.4
B3	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	1.9	0.96	0.45
B4	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	1.5	0.97	0.4
K	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	5.46	4.3	1.3
D	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	2.04	1.84	1
F	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	1.81	1.74	0.6
H	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	2.85	2.08	0.9
L	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	2.18	1.88	1.6
N	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	2.47	2.22	2.2
J	Eastern Sicily - La Maddalena	37.034 N	015.31 E Gr	Subaerial/ Submerged	2.54	2.17	1.25
A1	Eastern Sicily - Augusta	37.24 N	015.25 E Gr	Joint Bounded	7.14	4.19	0.6
TS1	Apulia - Torre Santa Sabina	40.76 N	017.7 E Gr	Joint Bounded	2.77	1.7	0.61
TS2	Apulia - Torre Santa Sabina	40.76 N	017.7 E Gr	Joint Bounded	2.61	1.64	0.5
TS4	Apulia - Torre Santa Sabina	40.76 N	017.7 E Gr	Joint Bounded	1.73	1.3	0.5
TS5	Apulia - Torre Santa Sabina	40.76 N	017.7 E Gr	Joint Bounded	1.84	1.33	0.4
V1	Eastern Sicily - Vendicari	36.8 N	15. 1 E Gr	Subaerial/ Submerged	1.84	0.97	0.47
SV1	Apulia - San Vito Polignano	41.02 N	017.18 E Gr	Subaerial/ Submerged	1.6	1.49	1
SV2	Apulia - San Vito Polignano	41.02 N	017.18 E Gr	Subaerial/ Submerged	2.64	1.98	0.53
SV6	Apulia - San Vito Polignano	41.02 N	017.18 E Gr	Subaerial/ Submerged	2.12	1	0.56
B06	Apulia - Torre dell'Ovo	40.29 N	017.5 E Gr	Subaerial/ Submerged	2.18	1.16	0.8
B11	Apulia - Torre dell'Ovo	40.29 N	017.5 E Gr	Subaerial/ Submerged	2.26	1.64	0.3

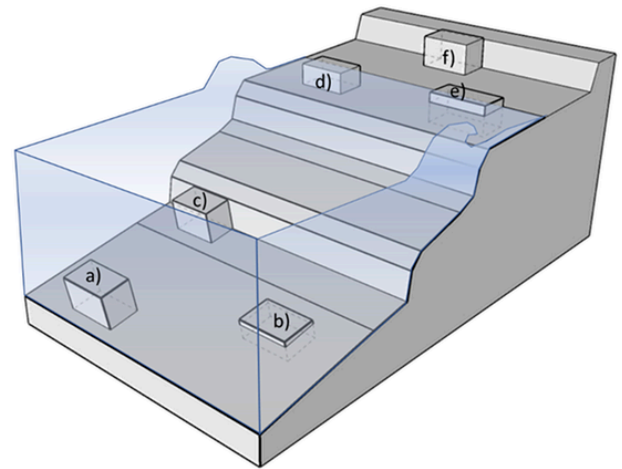


Fig. 4. Pre-setting scenario for incipient motion formulas (Eqs. (4)–(9), Table 1). a – submerged and isolated boulder, b – submerged joint-bounded boulder (part of the rock body, but detached along fractures and strata surfaces), c – submerged and isolated cliff-edge boulder, d – isolated sub-aerial boulder; e – sub-aerial joint-bounded boulder (part of the rock body, but detached along fractures and strata surfaces), f – sub-aerial and isolated cliff-edge boulder at the pre-transport locations.

Video analysis was performed by means of Tracker software (Doug Brown, Cabrillo College, CA, USA) using accurate metric references extrapolated from the TLS data (Scicchitano et al., 2012) and recognized in the video. With this method, flow velocities for the boulder reported in Table 3 were measured. During the entire said boulder movement, wave flow acquired a turbulent motion with main directions from SE and E, with subsequent backwash flow detected in different directions.

In the Apulia region, calcarenitic and biocalcarenic boulders were detected both on the Ionian and Adriatic sides (De Martini et al., 2021; Sansò et al., 2020). Furthermore, the impact of storm events in recent years has increased in intensity and frequency, thereby determining evidence of boulder transportations onto the Apulian coasts with displacements of about 50 m from the coastline (Delle Rose et al., 2020; Mastronuzzi and Sansò, 2004). In Apulia, three sites were selected along the Ionian rocky coast (Torre dell'Ovo) and the Adriatic rocky coasts (Torre Santa Sabina and Monopoli coasts) (Fig. 7). The choice of these sites was based on the same aforementioned conditions as for the Sicily coasts: i) the boulder sizes were surveyed through TLS with a 0.5 cm resolution; ii) the shapes were cuboidal and the movements (sliding, overturning, saltation/lifting) were observed in-field; iii) boulder fields have been monitored for at least the past 10 years. Many boulders, which showed bioencrustations of subtidal environments, are sited on the emerged rocky platforms, scattered or accumulated in berms. The exact position of the cuboidal boulders was assessed using a GPS-RTK techniques; in many cases, it was possible to identify the original positions of the boulders from the movement traces detected in-field. The meteo-marine regime and hydrodynamic estimations highlighted that most of these boulder movements occurred during intense storm events (Delle Rose et al., 2020).

4. Methods: processing data for Incipient motion formulas

The data obtained through photogrammetric and TLS surveys were treated to reconstruct the polygonal models that are representative of the boulder size parameters. Boulder data, 3D Model (0.5 cm grid resolution), and volume have been treated in the Cloud Compare environment to extrapolate the parameters needed to accurately calculate the virtual coefficients. The boulder density was assigned to each boulder on the basis of results of bulk density measurements following the Water Immersion Method (Pepe et al., 2018), as well as considering its thickness and lithology.

September 2018, recorded several boulder displacements during the Mediane Zorbas impact. Analyses of this video, coupled with a seasonally conducted UAV photogrammetric survey, in the area, allowed Scicchitano et al. (2020) to accurately assess the wave flow during the boulder movements (Table 3). It detected several distinct boulder movements, including those inside an ancient Greek quarry.

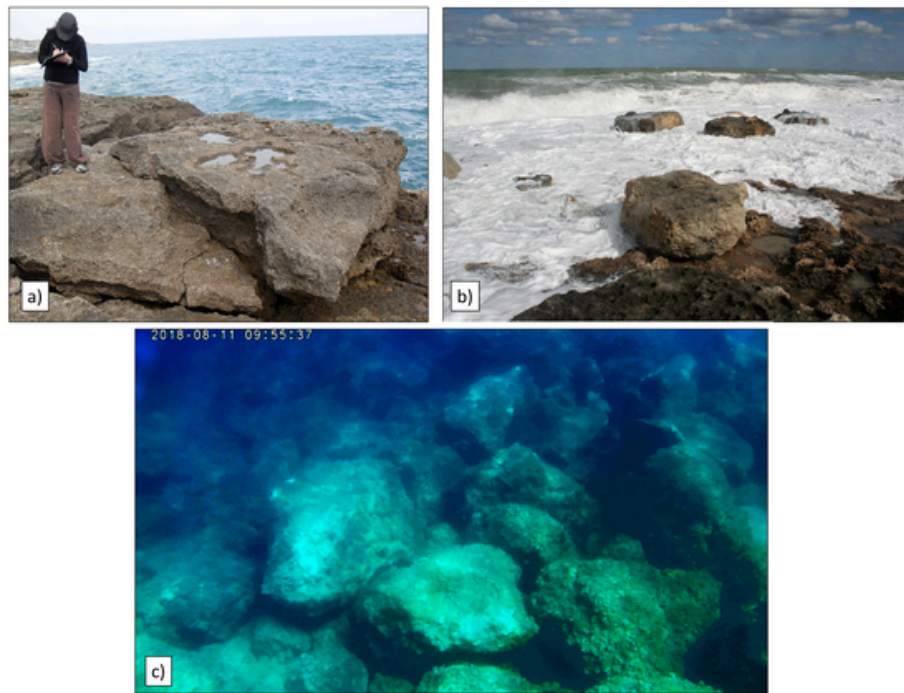


Fig. 5. Examples of pre-setting transport scenarios: a) sub-aerial joint bounded boulder detected in Calabria; b) Isolated sub-aerial boulder on the rocky platform of Torre Santa Sabina (Apulia); c) submerged boulders located in the rocky platform of Torre dell'Ovo (Apulia)



Fig. 6. Locations of the boulders surveyed in south-eastern Sicily and in the Apulia region.

In this work, the new deterministic and theoretical approach considers the assessment of the “ab” and “ac” surfaces reported in Fig. 7. The ab and ac boulder surfaces were extrapolated by point clouds in Cloud Compare, and converted into meshes to reconstruct the polygonal models (Fig. 8). The polygonal models were geometrically reported on the planar projections to assess the ab and ac areas, and to measure the axis lengths ($a > b > c$). Furthermore, processing was performed in Cloud Compare to automatically detect the actual volumes from the polygonal model (Table 2, Supplementary Material: Boulder size parameters).

5. Coefficients of incipient motion formulas

The coefficients of drag, lift, and static friction contribute to the magnitude of the forces considered in the incipient motion formulas, and influence the accuracy of the minimum flow velocity and incipient transport modes of the boulders (Nandasena, 2020). These coefficients are functions of the flow characteristics (fundamentally Froude number, Fr and Reynolds number, Re), the boulder morphometry, and the nature of the bed (Hoerner, 1965). To date, no direct studies have been performed to estimate these coefficients. As a consequence of this gap, researchers were compelled to use proxies from indirect studies (Cox et



Fig. 7. Boulders surveyed in Southern Italy; a) calcarenitic boulder on the Greek quarry of Maddalena Peninsula (SE Sicily); b) mega boulder on the rocky platform of Maddalena Peninsula (SE Sicily); c) sparse boulders on the rocky coast of Torre Santa Sabina (Apulia, Adriatic coast); d) boulders located in the rocky coast of Torre dell'Ovo (Apulia, Ionian coast).

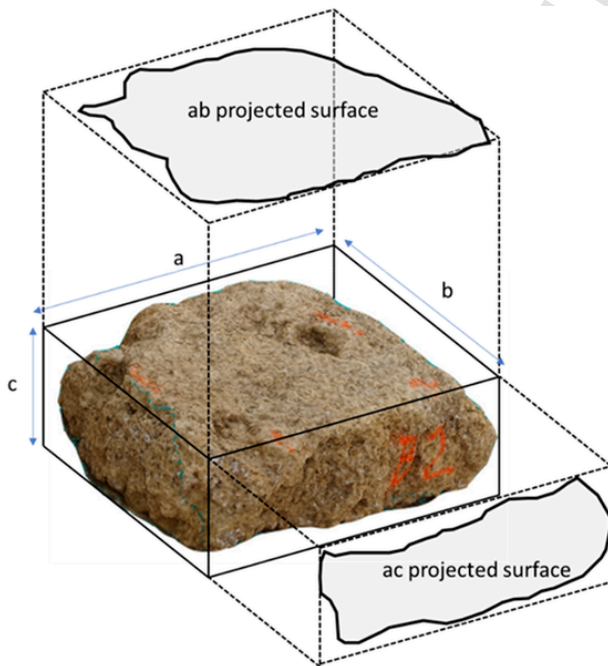


Fig. 8. Polygonal model of a boulder located in the Maddalena Peninsula (south-eastern Sicily, Italy); dimensional features are shown: a - b - c axis lengths and ab-ac projected surfaces.

al., 2020; Rovere et al., 2017; Scicchitano et al., 2020; Watanabe et al., 2019), and this resulted in a matrix of values ranging between 1.05 (Imamura et al., 2008), referring to a 3-dimensional cube in a wind tunnel study with Reynold numbers between 10^4 and 10^6 , and 2.0 (Nott, 2003a) referring to the ratio of bore height to still water depth (Noji et al., 1985).

Therefore, the drag coefficient showed a high degree of freedom in past studies (1.0 to 2.0) (Imamura et al., 2008; Malavasi and

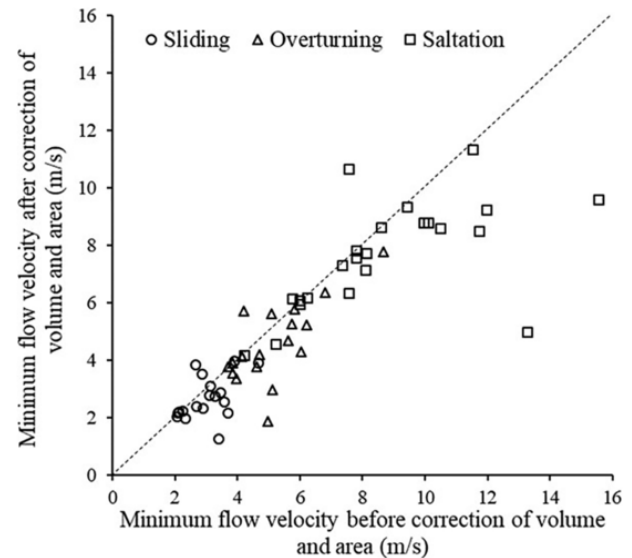


Fig. 9. Comparison between the minimum flow velocity calculated using the incipient motion formulas (Eqs. (4)–(9), Table 1) before and after revision of the volume and projected areas of the boulders (Table 2).

Guadagnini, 2007). To be conservative, in this study, we assigned the value of 1.5 to the drag coefficient.

The 0.178 lift coefficient was common to model the lift force in the incipient motion formulas (Cox et al., 2020; Nott, 2003a; Watanabe et al., 2019), and was referred by Einstein and El-Samni (1949). Nandasena (2017) reported that, for supercritical flows ($Fr > 1.0$), the lift coefficient for cuboid and spherical objects ranges between 0.1 and 0.2. However, for subcritical flows ($Fr < 1.0$), the lift coefficient is equal to 0.8.

The static friction coefficient, estimated by Byerlee (1978) to initiate sliding for a variety of rock types, ranges between 0.6 and 1.0. Nandasena and Tanaka (2013) estimated that the static friction coefficient

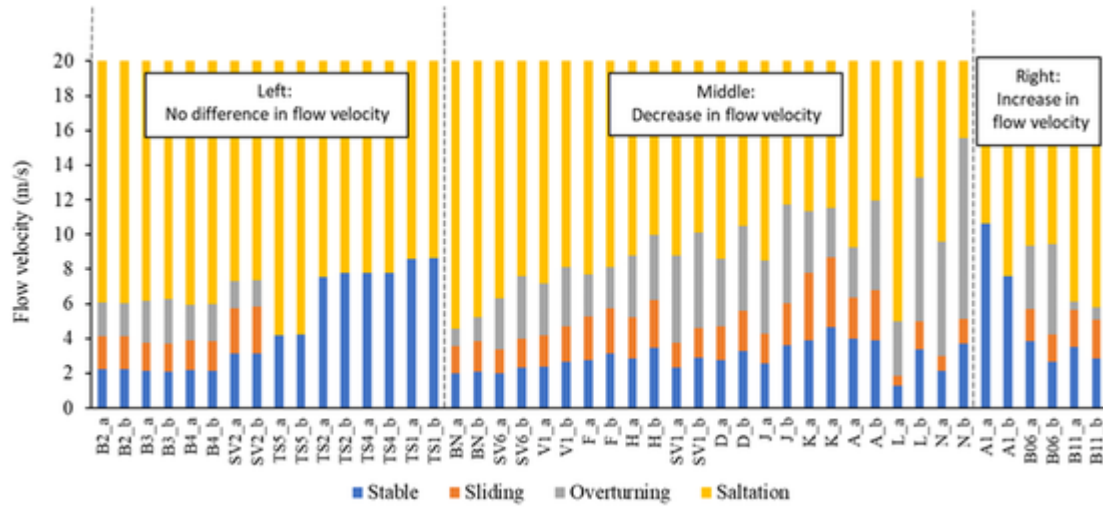


Fig. 10. Transport histograms of the boulders (Table 2). Each boulder has two histograms. The first histogram is based on the flow velocity after the revision (actual area and volume, for example “Boulder ID_a” and the second histogram before the revision (theoretical area and volume, example “Boulder ID_b”). The graph is capped at 20 m/s at the top. Beyond this value, the movement continues with saltation.

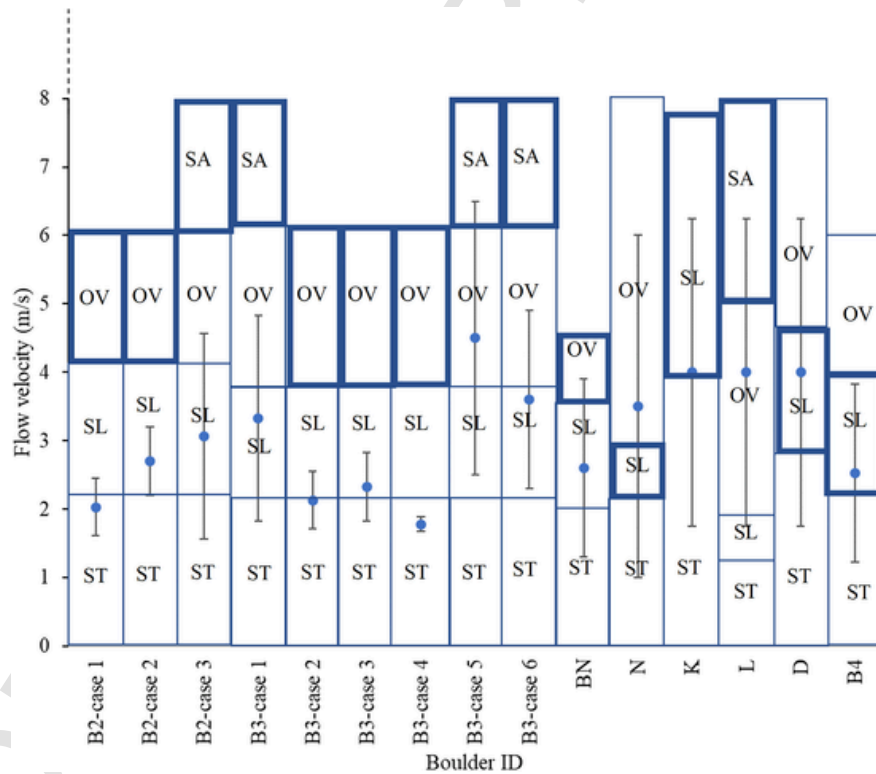


Fig. 11. Comparison between observed transport mode and predicted transport mode by applying the formulas (Eqs. (4)–(9), Table 2). Each histogram shows the range of velocity for each transport mode in the order of stable (ST), sliding (SL), overturning (OV), and saltation (SA). The observed transport mode is shown by the thick box, while the observed mean flow velocity and its accuracy are marked on each point.

cient of smooth limestone and corals on a uniform wooden bed ranges between 0.4 and 0.7. Milella et al. (2018) performed field tests to assess the static friction coefficient of calcarenite boulders on the coast of Apulia, Italy. From two differently-sized boulders, the coefficient of static friction was estimated to be between 0.3 and 0.5. The boulders selected for this study are also from the same region. Therefore, we assigned a mean value of 0.5 to the coefficient of static friction.

6. Results

6.1. Effect of volume and projected area of the boulder on transport potential

A comparison between the minimum flow velocities to start the transport of the boulders (Table 2) in sliding, overturning, and saltation was made before and after revising the projected areas and volumes of the boulders, applying the incipient motion formulas (Fig. 9). The minimum flow velocity showed different values for each transport mode: a general decrease was observed for many boulders, while an increase

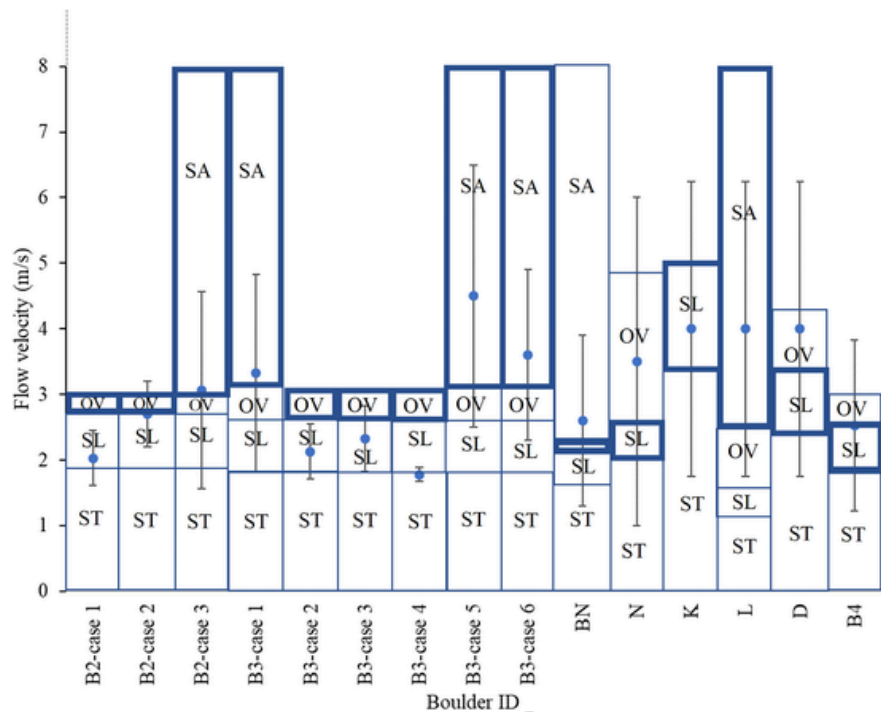


Fig. 12. Best fit of predicted transport mode and observed transport mode. Each histogram shows the range of velocity for each transport mode in the order of stable (ST), sliding (SL), overturning (OV), and saltation (SA). The observed transport mode is shown by the thick box, while the observed mean flow velocity and its accuracy are marked on each point.

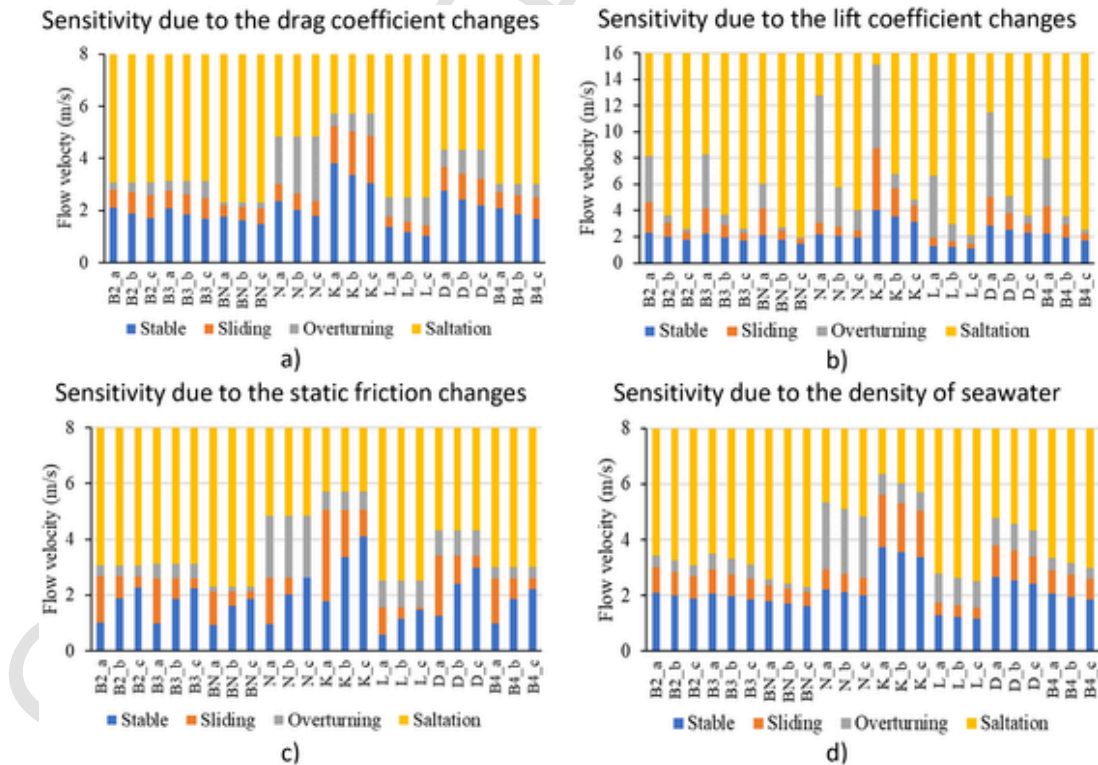


Fig. 13. Sensitivity of flow velocity and transport mode to the coefficients. There are three histograms per boulder. The “a”, “b” and “c” values are: a) the drag coefficient 1.0, 1.5 and 2.0; b) the lift coefficient 0.1, 0.5 and 1.0; c) the static friction 0.1, 0.5 and 1.0; d) the density of the seawater 1025, 1080, and 1140 kg/m³.

was observed for few boulders. The formulas before and after the correction of the volume and area predicted that the boulders are moved with saltation dynamic by high flow velocity and are moved through sliding way by low flow velocity.

Fig. 10 shows the transport histograms for each boulder studied before and after the revision of areas and volumes. Cuboid boulders did not show a significant change in the flow velocity (Fig. 10 Left, Supplementary Material: Boulder size parameters). Because there is not much difference between the actual boulder and the hypothesized

Table 3

Boulders movements and wave flow (velocity and depth) assessed by video analysis during the Medicane Zorbas impacted on the Peninsula Maddalena (south-eastern Sicily); the ID of the boulder is referred to ID reported in [Table 2](#) and Hour UTC field represents the temporal range in which the boulder movements were detected.

Boulder ID	Date	Hour UTC	Scenario	Type of movement	Observed flow velocity (m/s)	Flow depth (m)
B1	28-Sep-18	14:29:44	Subaerial/Submerged Scenario	Sliding	2.012 ± 0.2	0.6 ± 0.15
B1	28-Sep-18	14:31:13	Subaerial/Submerged Scenario	Overturning	1.71 ± 0.2	0.59 ± 0.15
B1	28-Sep-18	14:33:16	Subaerial/Submerged Scenario	Saltation	1.29 ± 0.3	0.59 ± 0.15
B1	28-Sep-18	14:35:36	Subaerial/Submerged Scenario	Overturning	1.588 ± 0.2	0.63 ± 0.15
B1	28-Sep-18	14:41:15	Subaerial/Submerged Scenario	Overturning	2.113 ± 0.42	1.5 ± 0.15
B2	28-Sep-18	15:02:20	Subaerial/Submerged Scenario	Overturning	2.03 ± 0.42	0.63 ± 0.15
B2	28-Sep-18	15:14:00	Subaerial/Submerged Scenario	Overturning	2.7 ± 0.5	0.9 ± 0.2
B2	28-Sep-18	15:51:52	Subaerial/Submerged Scenario	Saltation	3.068 ± 1.5	0.6 ± 0.15
B3	28-Sep-18	15:59:30	Subaerial/Submerged Scenario	Saltation	3.33 ± 1.5	0.82 ± 0.2
B3	28-Sep-18	16:05:16	Subaerial/Submerged Scenario	Overturning	2.131 ± 0.42	1.5 ± 0.15
B3	28-Sep-18	16:05:27	Subaerial/Submerged Scenario	Overturning	2.331 ± 0.5	0.8 ± 0.15

Table 3 (continued)

Boulder ID	Date	Hour UTC	Scenario	Type of movement	Observed flow velocity (m/s)	Flow depth (m)
B3	28-Sep-18	16:16:25	Subaerial/Submerged Scenario	Overturning	1.78 ± 0.11	0.59 ± 0.15
BN	28-Sep-18	16:16:57	Subaerial/Submerged Scenario	Overturning	2.6 ± 1.3	0.59 ± 0.2
B3	28-Sep-18	16:18:30	Subaerial/Submerged Scenario	Saltation	4.5 ± 2	0.7 ± 0.2
B3	28-Sep-18	16:26:28	Subaerial/Submerged Scenario	Saltation	3.606 ± 1.3	1 ± 0.15
N	28-Sep-18	16:28:29	Subaerial/Submerged Scenario	Sliding	3.5 ± 2.5	1.15 ± 0.15
K	28-Sep-18	16:32:30	Subaerial/Submerged Scenario	Sliding	4 ± 2.25	1.15 ± 0.15
L	28-Sep-18	16:51:17	Subaerial/Submerged Scenario	Saltation	4 ± 2.25	1.15 ± 0.15
D	28-Sep-18	16:51:17	Subaerial/Submerged Scenario	Sliding	4 ± 2.25	1 ± 0.15
B4	28-Sep-18	18:16:18	Subaerial/Submerged Scenario	Sliding	2.525 ± 1.3	0.8 ± 0.15

one although the actual volume would be controlled by roughened faces due to prolonged weathering and wave stress. Boulders that deviate from the cuboid shape, characterized by the actual volume and projected areas being less than the hypothesized boulder size, showed a decrease in the flow velocity in the revised formulas ([Fig. 10](#) Middle); even though few boulders showed an increment in the flow velocity ([Fig. 10](#) Right). The volume and projected areas of the boulders are the competing parameters that control the transport potential of the boulder itself. The volume, thus, the weight, is a key factor in resisting the motion of the boulder by increasing the friction force and weight moment. On the other hand, the projected areas influence in generating drag and lift forces to the boulder. The drag and lift forces affect the sliding and saltation of the boulder, respectively, while the moments of drag and lift forces enhance the overturning movements. Therefore, the boulders having a greater reduction due to their weight compared to the reduction due to the drag and lift after the revised

formulas, showed a reduction in the flow velocity. These boulders were mostly surface-rippled (Fig. 10 Middle). However, the boulders having a greater reduction owing to drag and lift compared to the reduction in their weight after the revised formulas showed an increment in the flow velocity (Fig. 10 Right). These boulders were found to be platy (flatness index > 1) with broken edges.

6.2. Modelling incipient transport mode

The minimum flow velocities calculated with the incipient motion formulas, after revising the projected areas and volumes for the boulders displaced along the coasts of the Maddalena Peninsula (south-eastern Sicily) during the impact of Medicane Zorbas, were compared with those reported by Scicchitano et al. (2020) through the analysis of a video showing the boulder displacements. Observations confirmed that when the flow velocity increased, the boulders were transported by saltation, rather than overturning. Although the formulas predicted the same scenario, the flow velocities are not compatible. As shown in Fig. 11, for most of the cases, the boulder needs a smaller velocity to initiate the transport in overturning and saltation compared to the velocity calculated using the formulas. This resulted in a mismatch between the predicted and observed transport mode. Considering that the coefficient of lift controls both overturning and saltation. The higher the lift force on the boulder, the greater the overturning and saltation. This suggests that a 0.178 lift coefficient was probably not sufficient for this study.

Fig. 12 shows the best fitting of the predicted transport mode to the observed transport with a 0.7 lift coefficient. The increase in the lift coefficient slightly lowered the minimum velocity needed to transport the boulders, due to sliding. This was because the increased lift force decreased the effective weight of the boulders. This resulted in less friction being applied to the boulders. It is also evident that the predicted flow velocity range for both sliding and overturning of the boulders was narrowed and lowered by the increased lift force; in the same way, the minimum flow velocities needed to saltate the boulders are modified. Overall, the increase of the lift coefficient, and thus, the lift force/moment, lowered the minimum flow velocity to transport the boulders in each transport mode.

7. Discussion

7.1. Sensitivity of minimum flow velocity and incipient transport mode to coefficients of drag, lift, static friction, and seawater density

Accurate estimation of input parameters in the incipient motion formulas is pertinent for the prediction of reliable results. Drag, lift, and friction are key to generating the matrix of forces and moments for a boulder to be set in motion. Thus, the coefficients of C_d , C_b , and μ_s play a major role in accurately modelling those forces and moments in the formulas. In addition, seawater density partly controls the transport of the boulders. Fig. 13a shows the sensitivity of flow velocity and transport mode to the coefficient of drag. When the coefficient of drag increased, the minimum flow velocity to transport the boulders, due to sliding, decreased. The increased drag effect provided a greater possibility for platy boulders (B2 and K) to transport, due to sliding. The increased drag effect also reduced the minimum flow velocity to transport, particularly, cubic/cuboid boulders (N and D), due to overturning. The minimum velocity to saltate the boulders was not affected by the coefficient of drag. The effect of the lift was drastic on the transport modes of overturning and saltation (Fig. 13b). This generated a significant reduction in the computed flow velocity required to initiate boulder movement by saltation. This allowed the boulders to saltate at significantly lower flow velocities. The increment in the lift coefficient also decreased the range of flow velocity to transport the boulders, due to overturning, compared to that of sliding. However, it did not significantly affect the

minimum velocity to transport the boulder, by sliding. When the coefficient of static friction increased, the minimum velocity to transport the boulders, by sliding, increased (Fig. 13c). This had an inverse effect compared to the cases of the drag and lift coefficients (Fig. 13a-b). The increment in friction force stabilized the boulders against the motion, while it narrowed the opportunities for sliding, and compelled them to transport due to rolling. As shown in Fig. 13c, the transport modes of overturning and saltation were independent of the friction between the boulder and the bed. Furthermore, seawater density affected the overall transport potential of the boulders. As shown in Fig. 13d, the increase in sediment concentration from zero to 20% determined the decrease in the minimum velocity for sliding, overturning, and saltation. The density effect was greater for saltation and overturning compared to sliding. The sensitivity analysis confirmed that the effect of the lift coefficient, with the selected range from 0.1 to 1, was more significant for the minimum flow velocity compared to that of the coefficients of drag and static friction, and the density of the seawater.

7.2. Limitations of the concept and going forward

Since the first application of basic physics and hydrodynamics to model the incipient motion of boulders by high-energy marine events (Nott, 2004, 2003b), several attempts have been made to upgrade the theory of the incipient motion formulas (Nandasena, 2020). Boulder morphometry is restricted in the formulas as the theory has been developed for cuboid boulders, even though, the formulas have commonly been applied to non-cuboid boulders (Benner et al., 2010; Costa et al., 2011; Hansom et al., 2008; Noormets et al., 2004). In these cases, the formulas provide a greater volume and projected area compared to the actual figures. The proposed study also confirmed the possibility that the formulas may actually overestimate the results (the minimum flow velocity) when applied to non-cuboid boulders. In the last ten years, the increased use of photogrammetric (Biolchi et al., 2019a, 2019b; Cox et al., 2018; Gienko and Terry, 2014; Scicchitano et al., 2020) and TLS (Mastroruzzi and Pignatelli, 2012; Pignatelli et al., 2010b, 2009; Scicchitano et al., 2012) techniques to accurately reconstruct the actual shape of the boulders, have allowed us to obtain the actual projected areas and volumes in the formulas. Through 3D polygonal models, it is possible to assess the dimensional features of the projected areas and volumes. Assessment of the dimensional features has been affected by a degree of uncertainty as a result of both the rough surface of the boulders, as well as instrumental errors. Boulders characterized by high rough surfaces are conditioned by an overestimation of dimensional features. However, boulders characterized by smooth surfaces have a match better with real dimensional features. In this study, the actual projected areas and volume of 23 boulders, described in previous studies, along the coasts of Sicily and Apulia, were inserted into the formulas using the virtual coefficients of drag, lift, and volume of the boulders. The accurate magnitudes of force and moment of drag and lift are pertinent for the formulas to predict reliable results. Although the formulation of these forces and moments is widely accepted, their magnitudes are challenged by the constant coefficients of drag and lift. These coefficients vary with flow-object interactions (Blott and Pye, 2008; Hoerner, 1965; Malavasi and Guadagnini, 2007; Watanabe et al., 2019).

A direct and complete study to estimate these coefficients has never been conducted, whereas, proxies have been referred from indirect studies. In their comprehensive study, Rovere et al. (2017) considered two boulders weighting 13 and 33 tons. Nott's approach applied to these boulders revealed that the lift coefficient should be between 2.006 and 2.775 to transport the boulders from a cliff-edge setting. However, in the proposed study, the lift coefficient is about 0.7, which is a result of the best fit between the predicted transport modes and the observed transport modes of the submerged/sub-aerial boulders of south-eastern Sicily. This suggests that the contribution of the lift force

is greater for cliff-edge boulders compared to other boulder settings (Watanabe et al., 2019).

In their studies, Noormets et al. (2004) modelled the effect of flow over a boulder by different wave types and Hansom et al. (2008) discussed the spatial variation of hydrodynamic force on a boulder. Such studies are worth in assessing the flow regime over the boulder thus hydrodynamic force to the boulder. The applicability of their concepts needs to be validated by field data and to be tested for other types of boulders. In this study, the centre of pressure (i.e. acting point) of drag, lift, and reduced-gravity forces were restricted to the geometric middle of the corresponding area and volume, because suggesting the exact location of the point of action of those forces under a turbulent, sediment-mixed, non-uniform flow impacting the boulder, is not an easy task (Terry and Malik, 2020). The resistance against the motion of boulders due to the roughness of the bed could be dependent on the nature of the contact between the boulder and the bed. For isolated, detached, unsupported boulders, the bed resistance can be modelled by static friction. A simple field test, such as that of measuring the force to move a boulder on the same site, would allow the estimation of the static friction coefficient (Milella et al., 2018; Nandasena et al., 2013). However, the macro roughness by protrusions of the bed could completely restrict the incipient transport due to sliding, and force it to overturn at the protrusion. Modelling such irregular roughness is inherently difficult. However, careful field observations would help to determine a meaningful and realistic interval that can be used in the theoretical considerations (Weiss and Diplas, 2015).

This may not be realistic if high-turbulent flows shoal and break over fine sediment beds. Terry and Malik (2020) had suggested that to obtain better results, the effect of sediment concentration in seawater needed to be included in the formulas. They reported that the minimum flow velocities required for boulder transport decreased as sediment concentrations increased. While our study also confirmed a reduction in the minimum flow velocity, it was found that the effect was greater for saltation and overturning compared to sliding when the concentration of sediments increased. Needless to say, this is under the assumption that both water and sand impact the boulder at the same speed.

In their experiment, Bressan et al. (2018) observed that boulders moved when only partially submerged by the flow, and emphasized the need to consider the flow variability induced by turbulence. However, the contribution of inertia and impact forces to the incipient motion is not clearly understood, and such forces are considered ephemeral during the transport process (Cox et al., 2020; Kennedy et al., 2017). Advanced numerical modelling confirmed that the effect of the impact force on the incipient motion was significant to simulate the observed incipient velocity of the boulders (Nandasena and Tanaka, 2013). Moreover, in their simple experimental study, Lodhi et al. (2020) reported that inclusion of the hydrodynamic impact force reduced the overestimation of the minimum flow velocity by almost 45% if compared with the measured velocity.

7.3. Storm waves and tsunami boulders

The attribution of storm vs tsunami boulders is often focused on different features, like the mass of the largest boulders or other megaclastic rocks (Dewey and Ryan, 2017; Hall et al., 2010; Williams and Hall, 2004), the inland distribution (Dewey et al., 2021; Mastronuzzi and Pignatelli, 2012), the geomorphological and sedimentological features of the deposits (Goff et al., 2018, 2012; Noormets et al., 2004, 2002), the mechanism of transport (Kennedy et al., 2017; Nandasena et al., 2011a; Nott, 2003b; Paris et al., 2010b; Terry and Malik, 2020). All these features have widely discussed in order to discriminate between storm and tsunami deposits (Cox et al., 2020).

Several studies based on the analysis of the meteo-marine features and hydrodynamic models were used to attribute coastal boulders to tsunami or storms, for example in the Balearic Islands (Roig-Munar et

al., 2019, 2018), in Cyprus (Evelpidou et al., 2020; Whelan and Kelletat, 2002), in Chile (Abad et al., 2020; Spiske and Bahlburg, 2011), along the Caribbean coasts (Engel and May, 2012; Morton et al., 2008; Scheffers and Kelletat, 2006; Spiske et al., 2008), in Indonesia (Paris et al., 2010b), in Iran (Shah-hosseini et al., 2011), in Japan (Goto et al., 2010a).

Results achieved in this work showed that the incipient motion formulas could not be useful tool for the discrimination between tsunami and storm boulders, because the formulas can only predict the minimum flow velocity to initiate the transport of the boulder. The derivation of the formulas only considers the flow depth and flow velocity when the flow hits the boulder. Analysis of flow-boulder interaction for the subsequent transport and deposition could help with the determinations of the wave type. Forward numerical modelling (Imamura et al., 2008; Nandasena and Tanaka, 2013), modern field data, and large-scale experimental investigations could offer insights in to the ongoing debate of storm vs tsunami boulders (Cox et al., 2020). A joint approach that considers geomorphological imprints and numerical models to assess mechanism of boulder transport could be useful for the discrimination between storm and tsunami boulders (Etienne and Paris, 2010; Goto et al., 2010b; Hall et al., 2010, 2006; Morton et al., 2008; Williams and Hall, 2004).

8. Conclusions

The deterministic and theoretical approach followed in the proposed study, allowed us to describe the incipient motion of coastal boulders during the occurrence of high-energy events, storms and Medicanes. These high-energy events determine the impact of multiple waves on coastal boulders with subsequent transportation and deposition. The initial flow-boulder interaction could be described through the incipient motion formulas developed in this work, whereby the virtual parameters and actual dimensional features of the boulders were assessed by means of modern survey techniques. The results of incipient motion formulas applied to the boulders surveyed along the coasts of Sicily and Apulia showed that:

- the flow-boulder interaction is strictly conditioned by the projected areas of the boulders and their actual volumes;
- the boulder shape influences the movement, i.e., the movement of cubic/cuboid boulders can be described with incipient motion formulas;

Although incipient motion formulas showed in this work can be applied in several study cases, further analyses are required to assess their application also for tsunami boulders.

The boulder movements are strictly conditioned by the drag, lift, and friction forces; in addition, seawater density partially affects the transport potential of the boulders. Each of these parameters influences the minimum flow velocity required to trigger the boulder movement under specific conditions (sliding, overturning, saltation), as follows:

- The contribution of the drag coefficient, i.e., when the drag coefficient increased, the minimum flow velocity to transport the boulders, due to sliding, decreased, while it did not affect the saltation condition;
- The contribution of the lift coefficient: when the lift coefficient increased, the minimum flow velocity to saltate and overturn the boulders decreased exponentially, even though it did not significantly affect the minimum velocity to transport the boulder under a sliding condition;
- The contribution of static friction, i.e., when the static friction coefficient increased, the minimum velocity to transport the boulders, due to sliding, increased;

- The contribution of the seawater density, i.e., the minimum flow velocities decreased with the increase of sediment concentration. Moreover, the density effect was greater for saltation and overturning compared to sliding

Among these parameters, the lift coefficient seems to be the most influential because even small changes in its values (between 0.1 and 1) can determine significant changes in the minimum flow velocity.

Finally, the application of incipient motion formulas in combination with the drag (1.5) and calibrated lift (0.7) coefficients showed a good agreement with the flow observed through videos recorded during Medicane Zorbas in south-eastern Sicily. The application of incipient motion formulas could be improved with large-scale experimental investigations so as to obtain an empirical form.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CrediT authorship contribution statement

N.A.K.Nandasena: Conceptualization, Formal Analysis, Methodology, Supervision, Validation, Writing-original draft; **Giovanni Scicchitano:** Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing-review & editing; **Giovanni Scardino:** Data curation, Formal analysis, Methodology, Software, Writing-original draft; **Maurilio Milella:** Formal analysis, Visualization, Writing-review & editing; **Arcangelo Piscitelli:** Data curation, Investigation; **Giuseppe Mastronuzzi:** Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing-review & editing.

Data availability

Datasets related to boulder data were obtained by field surveys performed through Terrestrial Laser Scanner techniques and drone.

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Appendix A. Supplementary data

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