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Judging a ship by its anchor: Bronze age stone weight anchors as indicators of ship size

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A R T I C L E I N F O

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A B S T R A C T

Three scale models of a one-hole stone anchor found at the Uluburun shipwreck site were tested in the sea, with their dragging force history being monitored and recorded. It was found that on a sandy seabed the measured holding power of an anchor is about 37 % of its dry weight, and about 49 % of its dry weight on a rocky seabed. The results were applied to the *Ma'agan Mikhael II* replica ship, and the forces acting on the ship, in different sea conditions, were compared to the holding power of the anchor. Wind velocity of 31.1 knots (16 m/s) and a current velocity of 2.9 knots (1.5 m/s), were chosen as representing extreme sea conditions. The forces acting on an anchored *Ma'agan Mikhael II* ship under these conditions were calculated and extrapolated for ships of different dimensions, but with the same structure and proportions as the *Ma'agan Mikhael II* using the replica scaling relations. These were compared to the holding power of the anchor, and the results can create a model that estimates the maximum size of the ship (as represented by its cargo capacity) by the mass (weight) of the anchor. This model estimates the size of a ship using a single one-hole stone anchor.

1. Introduction

Ancient anchors, and especially stone anchors, have been the focus of maritime archaeology since Moll published the first article on the subject (Moll, 1927). Frost's pioneering work formed the basis for classification and typology of stone anchors (Frost, 1963; 1970). Her work led to extensive study, which has mainly focused on their typology and origin (e.g. Kapitän, 1984; Haldane, 1990).

The typology of stone anchors is based on anchors found scattered on the seabed, at anchorages, shipwreck sites, and in secondary use. One-hole stone anchors are considered to be the earliest type, dating to the Bronze Age (3300–1200 BCE). The anchor was attached with a rope passing through the hole, and relied on its weight to hold the ship in place. The weight of these anchors ranges from about 20 kg to about 250 kg. Later versions had additional holes, through which wooden stakes were inserted to create additional drag on the seabed. This variant, a type of composite anchor, is more efficient than the one-hole type (Curryer, 1999, pp. 17-19; Frost, 1963, pp. 7–10; Kapitän, 1984, pp. 33–35; Wachsmann, 1998, p. 255).

Stone anchors found in terrestrial archaeological sites in secondary or symbolic use can be dated and linked to a society, although there is still disagreement among scholars regarding this association (Frost, 1963, pp. 34–36; Galili et al., 1994, pp. 93–94; Haldane, 1990, p. 19). As for the use of stone anchors on ancient ships, almost a century of research has passed, and many questions still remain. This study was aimed to shed light on the holding power of one-hole stone anchors and the size of the ships that used them. The research presented here integrates experimental archaeology in the form of dragging force experiments to calculate holding power, suggesting a model for estimating the size of a ship based on the mass of the anchor.

2. Methodology

2.1. Anchor models

A set of three replica models of the Uluburun ship anchor KW 4589 at different scale factors, was manufactured (with the kind permission of Professor Cemal Pulak). The original anchor was trapezoidal in shape, with maximum height 82.7 cm, maximum width 63 cm, maximum thickness 23 cm, and a mass of 171 kg (Pulak, 2018, personal communication). It was made of sandstone which originated from the Carmel coast, locally called *kurkar* (Goren, 2013, pp. 58–59).

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Emphasis was given to the selection of the stone used to manufacture the models, its origin and its physical characteristics. Different samples of *kurkar* from the northern coast of Israel were examined (Fig. 1a). The sample with density and texture closest to that of the Uluburun anchor was chosen. The calculated density of the Uluburun anchor is 1530± 120 kg/m^3 (based on the dimensions taken from the drawing supplied by Professor Pulak), and the measured density of the stone used for the anchor models is 1720± 50 kg/m^3. The three models were machine-cut to general shape and then chiselled to the final form and surface roughness, geometrically similar to the original (Fig. 1b). Their sizes were chosen to allow for the difference in the density of the stone. The mass of the smallest anchor is 32 kg (linear scale factor of 0.57), the medium anchor is 73 kg (scale factor of 0.75), and the large anchor is 124 kg (scale factor of 0.90) (Fig. 2).

2.2. *Ma'agan Mikhael II*

To estimate the relation between the weight of an anchor and the size of the ship, the replica ship *Ma'agan Mikhael II* was selected as a reference. This is a sailing replica of the 400 BCE Ma'agan Mikhael shipwreck, discovered in 1985, some 70 m from the shoreline of Kibbutz Ma'agan Mikhael, which is located about 30 km south of Haifa on the Mediterranean coast of Israel. The shipwreck site was excavated in 1988 and 1989 by the Leon Recanati Institute for Maritime Studies at the University of Haifa, with the late Dr. Elisha Linder as project head, and Jay Rosloff of Texas A&M University leading the excavation team. The surviving timbers, which occupied a space 11.15 m long, 3.11 m wide and 1.5 m deep, comprised a considerable fraction of the original hull. The ship was built shell-first with the planks first connected edge-to-edge by mortise-and-tenon joints to form the shell, and then the frames were fastened to the installed planking by double-clenched copper nails. Because of the significance of the archaeological find, the remains were completely excavated, retrieved from the seabed, and after conservation, the ship was reassembled, and is now on display at the Hecht Museum at the University of Haifa. Based on its reconstruction, the ship could carry a cargo of 15.9 tons (Ben Zeev et al., 2009, pp. 1-4, 70; Kahanov, 2011, pp. 162-163).

A full-size sailing replica of the original ship took more than two years to build (2014–2016), using the techniques and materials of the ancient shipwrights. The replica project, headed by the late Professor Yaacov Kahanov of the Leon Recanati Institute for Maritime Studies, was aimed at discovering the practical secrets of the construction of the ancient ship, to understand its sailing abilities and behaviour at sea, and to learn about life on board (Ben Zeev et al., 2009, 1; Cvikel and Hillman, 2021, 112–113; Kahanov, 2011, 169). The final dimensions of the *Ma'agan Mikhael II* are 16.6 m overall length, with a beam of 4.3 m over frames. The ship is rigged with a mast carrying a single square sail (Cvikel and Hillman, 2021, p. 120).

There is a time gap between the Bronze Age, when one-hole stone anchors were first used, and the date of the Ma'agan Mikhael ship. Despite this gap, the *Ma'agan Mikhael II* was chosen as a reference model for this research because it is the earliest dated ship that is both based on archaeological findings and iconography from the period, and has real sailing capability. The availability of the ship for this study enabled us to take measurements of the hull and calculate the volume of the ship. Furthermore, taking into consideration that ship sizes and construction techniques had changed through this period, a margin of error was included in the calculations. An assessment of the various surface areas of the *Ma'agan Mikhael II* was based on drawings used in the design of the replica (Ben Zeev, 2018, personal communication; Helfman, 2018, personal communication), measurements made on the actual ship, and comparison to photographs of the ship. The draught of the ship, for estimating the area above and below the water surface, was set at 1.3 m, which was the actual draught during the *Ma'agan Mikhael II*'s sail from Israel to Cyprus in November 2018 (Palzur, 2018, personal communication).

2.3. Holding power tests

A total of 90 holding power tests were conducted in order to compare the performance of the anchor on different types of seabed strata and with different angles of the rope. Three series of experiments were planned to separate the different variables: dry and damp sand out of the water; sandy and rocky seabed underwater; angle of the rope – parallel to the ground and at about 30°. The tests were performed by controlled dragging of each of the anchors while measuring the force needed to move it at a constant velocity. The test set-up is described in Miller et al. 2018.

In the plots of the force meter records four stages are evident (Fig. 3): (A) The beginning of dragging process and the tightening of the rope; (B) The movement of the anchor and the force required to move it (in Fig. 3 it is relatively constant); (C) The end of dragging and loosening the rope; and (D) The average force needed to keep the anchor moving.

Only a small part of the recorded signals is 'flat' like that in Fig. 3. What can be defined, in most of the signals, is the force required to begin the movement of the anchor (point B in Fig. 3). Once it began to move, most of the times the measured force changed with time, sometimes significantly. In the present study we are concerned only with the force required to begin the anchor movement, since it is also the beginning of the ship's movement, i.e., the anchor's holding power.

Fig. 1. A. samples of *Kurkar* stones with different porosity, from the northern coast of Israel (A. Efremov); and b. Chiselling the stone anchor models (M. Bram).

Fig. 2. The three anchor models with main dimensions (N. Lavie).

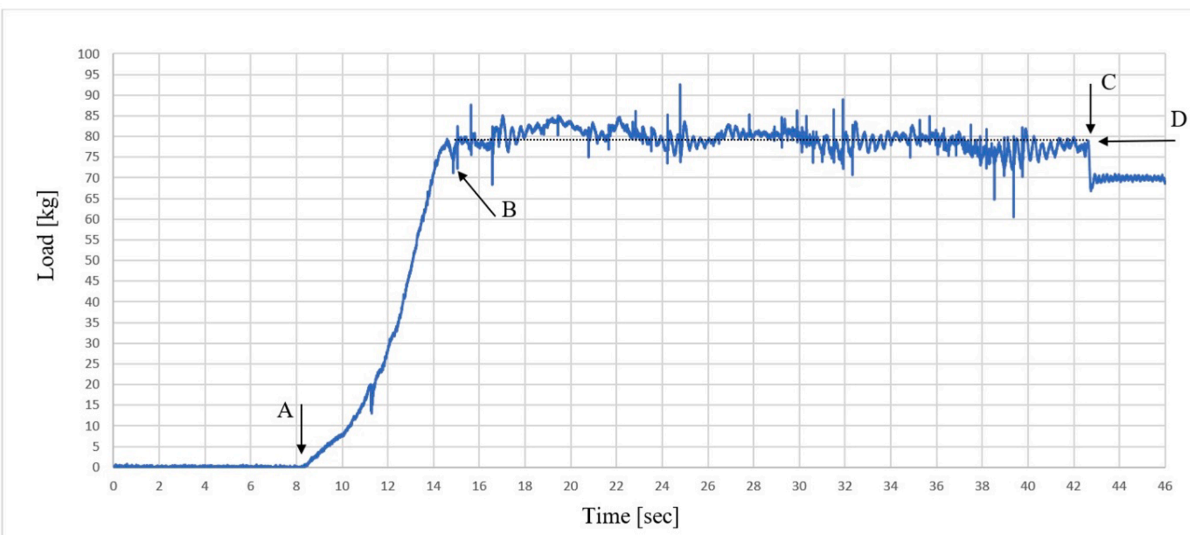

Fig. 3. Force meter results.

2.4. The forces acting on an anchored ship

In order to formulate the relationship between an anchor mass and the size of its ship, the forces that produce a static load on an anchored ship were examined assuming steady wind and current. Waves, which generate dynamic loads, have a multitude of characteristics and variables that are difficult to quantify. For this reason, even modern anchoring design considers only the static load operating on an anchored ship (Clark, 2009, p. 4).

The environmental conditions of sea level, wind directions, and temperature in the Mediterranean Sea in ancient times, combined with evaporation, rainfall and changes in water density, led to the assumption that the winds and currents in 3300 years ago were similar to present-day conditions. Hence, for research purposes, the present-day conditions of winds, currents and tides were used to draw conclusions about ancient times (Mantzourani and Theodorou, 1989, p. 44; McGrail, 2001, p. 89).

Winds in the Mediterranean in the accepted sailing season are generally Beaufort 1–4, and do not exceed Beaufort 7 (Bar-Yosef Mayer et al., 2015, pp. 420-423; Mediterranean Pilot, 1988, pp. 19, 29–32, 34–35). Winds of Beaufort 7 and up are defined as storms, during which sailing is not recommended. The surface currents in the Mediterranean Sea are determined by the flows from the Atlantic Ocean, the Black Sea and the large river estuaries. They are also influenced by winds, tides and temperature differences (thermohaline). The velocity of the surface currents which characterize much of the Mediterranean, ranges from 0.1 to 0.5 knots (Bar-Yosef Mayer et al., 2015, p. 418; Mediterranean Pilot, 1988, pp. 20-21). In narrow flow areas, the coastal configuration causes the current to accelerate. The most powerful currents are measured in the Straits of Gibraltar, the Bosphorus, and the Dardanelles where their velocity, which is influenced by tides and river water flow into the Black Sea can attain 4 knots (McGrail, 2001, pp. 91-92). In general, tidal currents in most other areas of the Mediterranean have a lesser impact than the surface currents (Bar-Yosef Mayer et al., 2015, p. 418; McGrail, 2001, p. 92; Mediterranean Pilot, 1988, pp. 20-21).

An anchored ship is subject to the combined influences of wind and current. The combination of the forces operating on the ship affects the required holding power and thus the mass of the stone anchor. The combined force of wind and current is the highest when they operate in the same direction, and therefore it is the most relevant for calculation. It is also assumed that ships carried anchors which could be handled in extreme sea conditions. Ancient mariners, as today's sailors, were required to be prepared for emergencies, and equipped their ship to anchor under the most challenging sea conditions. Extreme conditions for calculation were assumed to be: sea conditions corresponding to a wind velocity of 16 m/s (31.1 knots, Beaufort 7) and a current velocity of 1.5 m/s (2.9 knots), in the same direction as the wind.

2.5. *Basic steady state flow physics*

The evaluation of the forces acting on an anchored ship uses the equation of steady state hydrodynamic flow physics: i.e. calculation of the force a flowing fluid exerts on a body it encounters. That is: the forces exerted by wind and current on the hull of the ship, above and under water respectively.

Expression (1) is used to calculate the force in Newtons [N].

$$F = \frac{1}{2}\rho^{*}V^{2*}A^{*}Cd \quad (1)$$

where F – force [N]. ρ– density of fluid [kg/m^3] (air – 1.3 kg/m^3, sea water – 1040 kg/m^3). V – relative velocity between the fluid and the body [m/s]. A – frontal area presented to the flow by the part of the body totally immersed in the fluid [m^2]. Cd – drag coefficient.

The drag coefficient (Cd) is a dimensionless number which represents the influence of the body shape (not the size) on the force exerted on it by the flow. The drag coefficient was measured for a variety of shapes and proportions, both for air and for water flows, around them. These values have been used extensively in aircraft and watercraft designs and are listed in many tables (Grée, 1981, pp. 66-67; Ogg, 1977, pp. 12-13).

Expression (1) is correct for bodies totally immersed in fluid. In such cases the drag coefficient gives the correct values for cases like aircraft or submarines. Surface ships, which ply the interface between water and air invest their energy not only in moving over that interface, but also in wave-making. Hence, their drag coefficient is not constant, but actually depends on the velocity of the ship. The drag coefficient used for the calculations in the current study is the value of the coefficient at the 'cruising speed' of the ship, as derived from data collected during the voyage to Cyprus of the *Ma'agan Mikhael II*, which was in the range of 3–5 knots (Palzur and Gal, 2021, personal communication).

For the evaluation of the drag coefficient in this study known Cd values for various bodies and structures were considered and adapted to the hull shape of the *Ma'agan Mikhael II*. The Cd of the underwater section of the hull was based on previous calculations as part of the design of the sailing replica (Ben Zeev et al., 2009, pp. 52-63). The Cd of the hull above water was estimated based on the sailing speed at different wind velocities (conditions of constant wind velocity and sailing speed) (Palzur, 2019, personal communication). Furthermore, as the real value is likely to be somewhat different from the estimated one, and each body considered here is somewhat different in its form from the reference in Table 1, a margin of error was determined for the Cd for each structure (Table 1).

For the mast, open sail and rigging, the total area presented to the flow is about 50 m^2 with a drag coefficient of about 1. When the ship is anchored, the sail is furled into a rather small presented area (not much more than 1 m^2, including the mast and other components), with an unknown, but significant, drag coefficient (over 1, due to turbulence around them). Therefore, it was decided to remain with the 50 m^2 but with a rather small drag coefficient of 0.04 (actually, the equivalent of 2 m^2 area and a drag coefficient of 1). As can be seen in Table 1, the force acting on the mast, sail and rigging is estimated to be approximately equal to the combined forces acting on the hull. Additionally, the centre of the air pressure on these components is about 3.5–4 m above the ship's centre of gravity, thus creating rotation on the various axes in addition to the drift.

Little is known about the structure of ships of the Bronze Age, and therefore it was assumed that the ships would have similar construction and similar proportions, however with different dimensions, i.e., they are supposed to be geometrically similar to the *Ma'agan Mikhael II*, and that the ship's cargo capacity would be reduced or enlarged as the cube of the linear dimensions with the size of the ship. Actually, the cargo capacity of a ship is the definition of its size (NB: 1 ton is defined as volume – 100 cubic feet, not weight) (Kemp, 1975, p. 876) (The 'ton' calculated below is weight in metric tonnes of 1000 kg).

Table 1
Area, drag coefficient, margin of error and force for each section of the *Ma'agan Mikhael II*.

Section of ship	Frontal area of the body [m^2]	Drag coefficient	Margin of error	Force [N]
Hull above water	4.9	0.70	±0.10	250
Hull under water	2.1	0.10	±0.02	330
Mast, sail and rigging	50	0.04	±0.02	570

3. Results

3.1. *Anchor holding power*

The dragging force of the anchor replicas under water was measured and recorded in each of the tests. The force at the initial movement was identified and its average for sandy and rocky seabed was calculated for each size of anchor. The results, presented in Table 2 and Fig. 4, indicate that there is a linear relationship between the anchor mass and the force required for its initial movement. These linear relationships indicate that the anchor's holding power on a sandy seabed is about 37 % of its dry mass, and on a rocky seabed is about 49 % of its dry mass.

(The term 'Rocky Seabed' used here refers to a relatively flat, homogeneous, rocky surface.)

The holding power of the anchor is the maximum force that the ship exerts on the anchor before it begins to move (Fig. 4). It is the combination of the wind pressure on the part of the ship above the surface and the current pressure on the part below the surface. As described above, these forces can be estimated using Expression (1), together with the dimensions of the relevant sections of the ship.

3.2. *Scaling*

The *Ma'agan Mikhael II*, which is the reference ship for this study, has an estimated load capacity of 16 tons (Ben Zeev et al., 2009, pp. 1-4, 70; Kahanov, 2011, pp. 162-163). Here, the load capacity was chosen as the independent parameter, the rest of the parameters being derived from it with a 'scaling parameter' – λ (=W_λ/W_0), where W_λ is the load capacity of the ship in question and W_0 – the load capacity of the reference ship.

Table 2
Average force needed to begin anchor movement under water.

Surface type	Anchor mass [kg]	Average force [kgf]	Average force [N]	±	Number of entries
Sand	32	14	137	3	4
	73	26.9	264	4	10
	124	46.6	457	8.5	7
Rock	32	14.7	144	3	9
	73	36.8	361	8	8

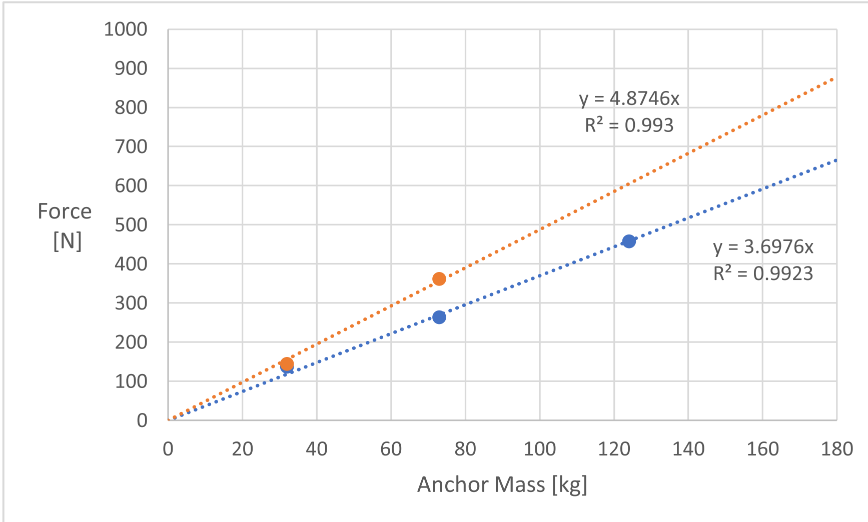

Fig. 4. The relationship between the anchor mass and the average force required for moving the anchor underwater on sandy (blue marks) and rocky (orange marks) seabeds.

Table 3 details the derived scaling factors of the other relevant dimensions. It is assumed that the ships considered here are similar in construction to the *Ma'agan Mikhael II*, since during the Bronze Age most ships were also built shell-first, with mortise-and-tenon joints, and even of the same or similar size and capacity (and see below – Margin of error). In addition, it is also assumed here that the average density of the load (i.e.– the weight of the cargo divided by the volume of the ship) is about the same for all the relevant ships. This allows simple geometrical scaling.

The forces acting on a ship are calculated using Expression (1) which considers the density of the fluid, the frontal area presented to the flow by the body, the relative velocity between the fluid and the body, and the drag coefficient, representing the shape of the body (not its size). Of all these parameters, only the frontal area is scaled when the problem is scaled by the load capacity of the ship. The rest of the parameters in Expression (1) are independent of the ship and the scaling.

λ is the scaling factor, $\lambda = W_\lambda/W_0$,

where W_λ is the load capacity of the ship under consideration (in tons),

W_0 is the load capacity of the *Ma'agan Mikhael II* (~16 tons).

For example, if the scaling parameter is 8 (i.e. – the ship has a load capacity 8 times that of the reference ship), then any relevant length in the ship is twice ($8^{1/3}$) that of the homologous length in the reference ship, and any area in the ship is 4 times ($8^{2/3}$) that of the homologous area in the reference ship. However, under the assumption that the ship carries a load 8 times that of the reference ship, the sail area is only 4 times as large. That is – the sail can produce only half the force per ton of load. But similarly, the hull areas presented to the wind and to the current are also only 4 times as large, meaning that the drag forces are also only 4 times as large. These forces, on the hull and on the furled sail and rigging, are the forces required to keep the mass of the whole ship moving at the same velocity, not to accelerate it to that velocity.

All the data obtained from the *Ma'agan Mikhael II* were calculated by Expression (1). As can be seen in Fig. 4 the relation between the holding power and the anchor mass is linear and the proportionality coefficients for dragging over sandy and rocky surfaces are given in it. Therefore, it is possible to estimate the holding power for similar anchors by their mass. Defining the total force on the ship under consideration F_λ and the total force on the reference ship F_0, the expression becomes:

$$F_\lambda = F_0 * \lambda^{\frac{2}{3}} \tag{2}$$

Therefore, the maximum force that an anchor of mass *m* can develop on a sandy seabed is given by Expression (3), and on a rocky seabed by Expression (4).

$$F_{\lambda,s}[N] = 3.7 * m[kg] \tag{3}$$

$$F_{\lambda,r}[N] = 4.9 * m[kg] \tag{4}$$

Hence:

$$F_{\lambda,s} = F_0 * \lambda^{\frac{2}{3}} = 3.7 * m = F_0 * \frac{W_\lambda^{2/3}}{W_0^{2/3}} \tag{5}$$

Therefore

$$W_\lambda^{2/3} = \frac{3.7 * W_0^{2/3}}{F_0} * m \tag{6}$$

$$W_\lambda = W_0 * \left(\frac{3.7 * m}{F_0}\right)^{\frac{3}{2}} \text{ for sandy seabed, and similarly} \tag{7}$$

$$W_\lambda = W_0 * \left(\frac{4.9 * m}{F_0}\right)^{3/2} \text{ for rocky seabed,} \tag{8}$$

where m is given in kg and W_0 , W_λ are given in tons.

The two reference values that are still missing are F_0 and W_o. F_0 is the total force acting on the *Ma'agan Mikhael II* under the conditions defined above, therefore it is the sum of the wind force on the section of the hull above the water, the wind force on the mast, the folded sail, the ropes, etc., and the force of the current on the section of the hull below the water line, all assumed to act in the same direction. All these forces are calculated using Expression (1), and are presented in Table 1. The result is: F_0 1150N (Table 1).

The final result for sandy seabed is therefore:

$$W_\lambda = 0.00292 * m^{3/2} \tag{9}$$

Table 3
Scaling the various dimensions.

Dimension	Scales as
Load	λ
Volume	λ
Area	$\lambda^{2/3}$
Length	$\lambda^{1/3}$

$$m = \left(\frac{W_\lambda}{0.00292}\right)^{\frac{2}{3}} \tag{9a}$$

And for rocky seabed:

$$W_\lambda = 0.00445 * m^{3/2} \tag{10}$$

$$m = \left(\frac{W_\lambda}{0.00445}\right)^{\frac{2}{3}} \tag{10a}$$

where m is given in [kg] and W_λ in [tons].

These two relations are plotted in Fig. 5, and as can be seen, the required anchor for sandy seabed covers the requirement for rocky seabed as well, therefore only sand anchors will be referred to in the rest of this paper.

3.3. Margin of error

Some caution is required in determining whether the construction of ancient ships was similar to that of the *Ma'agan Mikhael II*, and therefore margins of error were considered, as shown in Table 1. Implementing these gives a margin of error of about 27 % of the total calculated force (Fig. 6). This includes the possible variations of the structure, the geometry, and the deviations from the principles of geometrical scaling, of the areas of the various section of the ship under consideration. As seen in Fig. 6, the reference ship requires an anchor of 335 kg, but other, similar ships, of the same load capacity, need an anchor between 240 and 430 kg, depending on their construction and drag coefficient (Fig. 6).

4. Discussion

This paper offers a method for assessing the size of a Bronze Age ship based on its stone anchor. The calculations presented refer to the situation where a ship is anchored with only a single anchor, of the type found in the eastern Mediterranean. It is reasonable to assume that in certain cases, several anchors were used simultaneously. If a cluster of relatively light anchors is found together, it may indicate an emergency when the ship did not have a sufficiently heavy anchor, or the crew was not able to deploy the required heavy anchor, and resorted to a cluster of lighter and easier to handle ones instead. Another possibility is the unlucky event that the ship sank before the crew could deploy the anchors, but (happily for us…) it pinpoints the location of the wreck, which is what we are looking for.

The linear relationship between the holding power and the mass of the anchor (Fig. 4) means that two anchors have the same holding power as a single anchor having the same mass as both together. The advantage of using several light anchors instead of a single heavy one is in the ease of handling and the much better safety situation for both ship and crew in bad weather. A possible disadvantage is the need to handle several ropes and anchors during an emergency.

It is seen here that anchoring on sand requires heavier anchors than anchoring on flat rocks. This stems from the dragging experiments where the initial dragging force on a rocky surface was higher than that for a sandy surface, i.e. – higher apparent friction coefficient.

The total forces calculated are those required to cause only the initial movement of the anchor. If the anchor, following the initial movement, develops a greater resistance to the pull, it cannot be considered as 'a failure of the anchoring'; it only means that the calculated required anchor mass is the minimal required mass. From another point of view, it can be said that the calculated size of the ship is a built-in over-estimate, so that the actual size of the ship should be estimated as somewhat smaller than the calculated size.

Considering that a skipper always prepares for the worst, this means a heavy anchor, actually heavier than the small crew of the ship could manhandle. This further supports Frost's understanding that some kind of a derrick was vital (Frost 1963). Another possibility is the use of several lighter anchors, with its advantages and disadvantages, as discussed above.

5. Conclusions

In instrumented dragging tests of three models of one of the Uluburun anchors, with different scaled masses, it was found that the holding power of the one-hole stone anchor is about 37 % of its dry weight on a sandy seabed, and on a rocky seabed is about 49 % of its dry weight. This is the basis for the relationships developed here for estimating the size of a ship (its load capacity) by the mass of its anchor. These relations were developed, making extensive use of the basic hydrodynamic steady state flow formula, coupled with estimated drag coefficients, and assuming similarity in shape and construction of the ships.

The calculation of the forces of wind and current operating on an anchored ship was performed for rough sea conditions in the Mediterranean Sea – 16 m/s (31.1 knots) wind and 1.5 m/s (2.9 knots) surface current in the same direction as the wind. The *Ma'agan Mikhael II* was chosen as the reference ship.

The results obtained provide a tool for estimating the size of a ship and its load capacity based on the mass of a single anchor. Since the

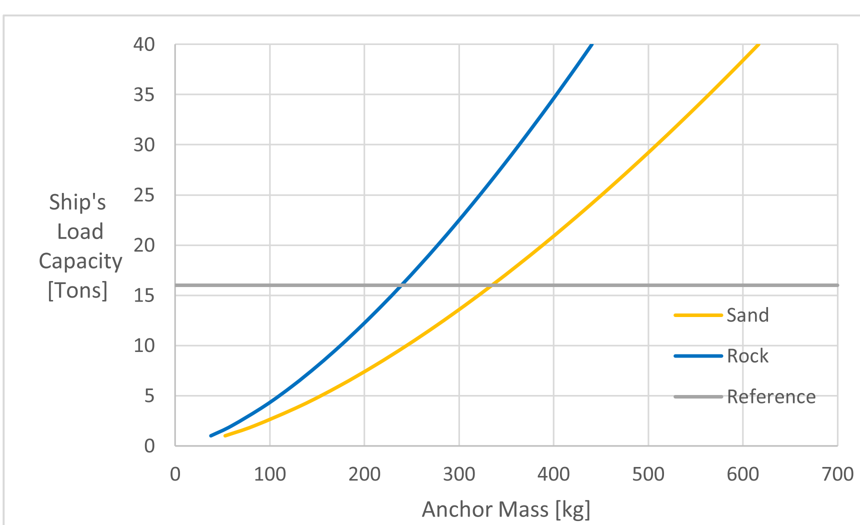

Fig. 5. The relation between the required anchor mass and the load capacity of the ship.

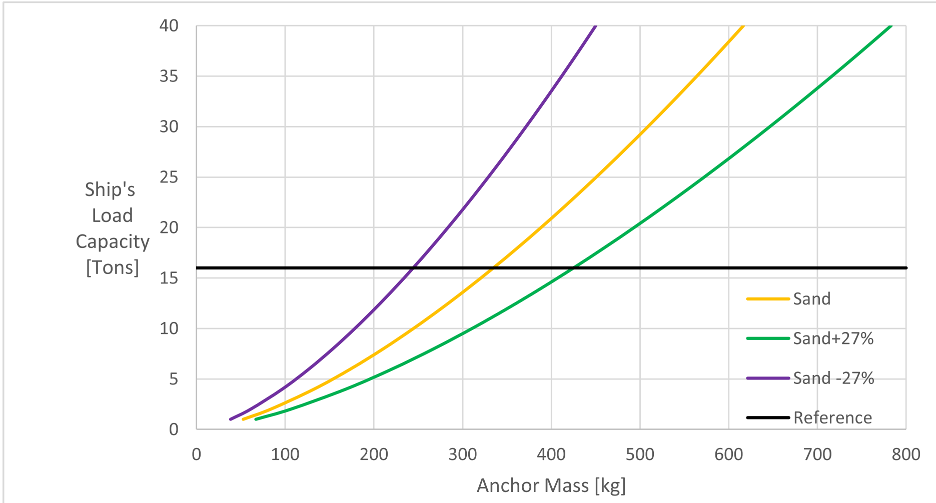

Fig. 6. The dependence of the anchor mass on the load capacity of the ship with a margin of error of 27%.

holding power seems to increase linearly with the anchor mass (Fig. 4), adding another anchor of a given mass increases the holding power accordingly.

Estimation of a ship size based on a single anchor should follow the above procedure, based on the same data, as a first step, and then increase the number of anchors being used, if deemed necessary, probably based on the distribution of the anchors on the sea-bed (whether deployed or remained in the hull).

This information is important for understanding the ships that carry the anchors, which archaeologists find scattered on the seabed, in ancient anchorage sites and in shipwreck sites. These results can be updated when additional information about the construction of the Bronze Age ships is revealed.

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.

Data availability

No data was used for the research described in the article.

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Authors' declaration

The authors declare that there is no contradiction of interests concerning this article.

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