# Ship Squat Related Parameters Measurements On Board Training Ship Mircea

Petru Sergiu Șerban[1]

[1]"Mircea cel Bătrân" Naval Academy
Fulgerului 1, 900218 Constanța, Romania
*E-mail: sergiu.serban@anmb.ro*

**Abstract.** *During July – August 2015 sailing ship "Mircea" conducted an international training voyage departing from Constanța, Romania with stopovers in four ports. On this occasion there had been conducted a series of measurements on vessel's draft, water depth below keel and ship's speed when entering and leaving the ports because these areas showed, more or less, the characteristics of restrictive areas that could favor the emergence of squat phenomenon. This paper presents experimental conditions, equipments and methods used on board to determine parameters needed in ship squat calculations. After results interpretation there were identified several conclusions regarding the measurement methods used.*

**Key words:** ship squat, sailing ship, draft, camcorder, depth under keel.

## 1. Introduction

In the last decade it was observed a continuous increase of the main dimensions of certain ships, especially for container carriers, RO-RO vessels and LNG carriers. In opposition, the dimensions of access channels, rivers, canals and harbors where these vessels operate do not increase at the same rate [1].

Therefore, restricted waters impose significant effects on ship navigation. In these situations the ship has to navigate close to the shore and other manmade structures because of limited navigable width. The shallow water and proximity of the sides of the channel affect the ship navigating through the restricted waters. With the presence of a side bank in the vicinity of the hull, the flow is greatly complicated. Additional hydrodynamic forces and moments act on the hull, thus changing the ship's maneuverability. These effects cause errors in maneuvering which can lead to grounding or collision [2].

A phenomenon that occurs on vessels in these areas is ship squat, which may be defined as the sinkage and/or trimming of the ship due to pressure changes along the ship length in shallow waters. Ship to ship interaction or ship to shore is also related to this phenomenon. The trim change can be explained by hydrodynamic interactions between the ship and the bottom due to speed and pressure distribution change. Large and fuller ships such as tankers and bulk carriers should pay extra attention when navigating in restricted waters. The squat effect is directly related to ship dimensions, its speed and water depth [3].

Ship squat phenomenon has been the subject of studies in many ways for a long time. In general, most researches rely on empirical formulas, experimental tools or numerical (Computational Fluid Dynamics) techniques, among which the first two types are more widely used [4].

Scientific research on ship squat was started by *Constantine* (1960), which studied the phenomenon for subcritical, critical and supercritical speeds. In subcritical domain, *Tuck* (1966) demonstrated that in open water conditions of constant depth, the sinkage and trimming of the vessel varies linearly with depth Froude number. This theory was developed by others, such as *Beck* (1975) for dredged channels, *Naghdi* and *Rubin* (1984), *Cong* and *Hsiung* (1991), *Jiang* and *Henn* (2003) or *Gourlay* (2008) [5].

Current researches on this phenomenon are limited to experiments on scale models for an accurate mathematical expression of ship squat. The literature presents various formulas of ship squat, the most commonly used being those of *Barrass* (2004), *Millward* (1992), *Norrbin* (1986), *Hooft* (1974) and *Romisch* (1989) [6].

The aim of the paper is to present experimental conditions, equipments and methods used on board NS "Mircea" to determine parameters needed in ship squat calculations. In summer of 2015 Romanian Naval Academy sailing ship "Mircea" conducted an international training voyage with four ports of call. On this occasion there had been conducted a series of measurements on vessel's draft, water depth below keel and ship's speed when entering and leaving the ports because these areas showed, more or less, the characteristics of restrictive areas that could favor the emergence of squat phenomenon.

| **Nomenclature** | |
|---|---|
| $h$ [m] | water depth |
| $T$ [m] | ship draft |
| $Fr_h$ [dimensionless] | Froude number (water depth dependant) |
| $C_B$ [dimensionless] | block coefficient |
| $A_C$ [m$^2$] | canal cross section area |
| $A_M$ [m$^2$] | area of midship section |
| $S$ [dimensionless] | blockage factor ($A_M/A_C$) |
| $V_K$ [knots] | forward speed of the vessel |
| $S_{max}$ [m] | maximum ship squat |
| $h_{uk}$ [m] | water depth under keel |
| $t$ [s] | moment of time |
| | |
| *Subscripts* | |
| b | bow |
| s | stern |

## 2. Ship squat

The shallow water effect manifests itself typically in the increasing of inertia and damping hydrodynamic forces of the hull, changes in the propeller and rudder operation parameters and their interaction with the vessel's hull. Besides, propulsion in shallow water gives rise to forces acting in a vertical plane and bringing about considerable changes in the vessel's stability and trim. Shallow water also causes significant changes in the vessel's roll/pitch parameters [7].

Squat is the decrease of under keel clearance caused by the movement of the submerged ship's body through water. Compared with the static position, the hull goes deeper into the water and trims for a few degrees.

A moving vessel pushes the water in front of her bow, which must flow back under and at the sides of the ship to replace the volume of water displaced by the ship's hull. In shallow and/or narrow waters the water particles' velocity of flow increases (Fig. 1) which results in a pressure drop, according to Bernoulli's Law. The pressure drop under the ship causes a vertical sinking of the ship's hull and depending on the vessel's block coefficient it will trim forward, aft or will sink deeper on even keel. The amount of all vertical sinking and trim is called ship squat [8].

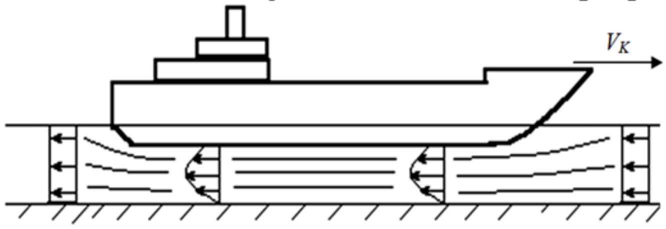


Fig. 1. Distribution of speeds between ship bottom and seabed where $V_K$ is ship speed in knots.

The effect of reduced underwater clearance manifests itself most noticeably by the ratio of water depth $h$ to vessel's draft $T$, $h/T$ is less than 2. The degree of the shallow water effect depends on the vessel's relative speed through the depth Froude number. For Froude number, $Fr_h$, of more than 0.3, the effect of the hydrodynamic forces and squat is significant. The shallow water effect, change of trim and stability and other related phenomena increase dramatically after Froude number $Fr_h$ of 0.8 and reach the maximum at Froude number around 1.0 which corresponds to the "critical" speed [9].

Squat formulas have been developed for estimating maximum ship squat for vessels operating in restricted and open water conditions with satisfactory results. Some have been measured on ships and some on ship models. *Barrass*'s formula [3] is among the most simple and easy to use for all channel configurations. Based upon his research from 1979, 1981 and 2004, the maximum squat formula (Eq. 1) is empirical and it is determined by the block coefficient $C_B$, blockage factor $S$, defined as the ration between mid-ship cross-section area ($A_M$) and canal's cross section area ($A_C$), and ship speed in knots $V_K$:

$$S_{\max} = \frac{C_B \cdot S^{0.81} \cdot V_K^{2.08}}{20}. \quad (1)$$

The main factor is ship speed $V_K$. In this context, $V_K$ is the ship's speed relative to water; therefore, the effect of current/tide must be taken into account.

The value of the block coefficient $C_B$ determines if the maximum squat occurs at bow or stern. Full-form ships produce squat at bow if $C_B$ is greater than 0.7. Fine-form ships with $C_B$ less than 0.7 produce squat at stern. Ships with $C_B$ near 0.7 produce a mean bodily sinkage equal to maximum squat with no trimming effects [10].

## 3. Training ship "Mircea"

Built between 1938 – 1939 at "Blohm und Wöss" shipyard in Hamburg, Germany, "Mircea" is the fourth ship in a series of five of the same type built at the same site, being sister with "Eagle" – USA, "Gorch Foch I" – Germany, "Gorch Foch II" – Germany, "Sagres" – Portugal.

"Mircea" (Fig. 2) is a training class A sailing ship, bark type, having three masts, 44 meters high and 23 sails with a total sail area of 1750 $m^2$. It has the possibility of mechanical propulsion using a controllable pitch propeller driven by the engine. Its sailing vessel body shape is made entirely of metal with massive metal keel. The ship is fitted with solid ballast and the side frames numbering starts from stern to bow with an inter-frame distance of 600 mm for the entire ship's length. The main characteristics are presented in Table 1.

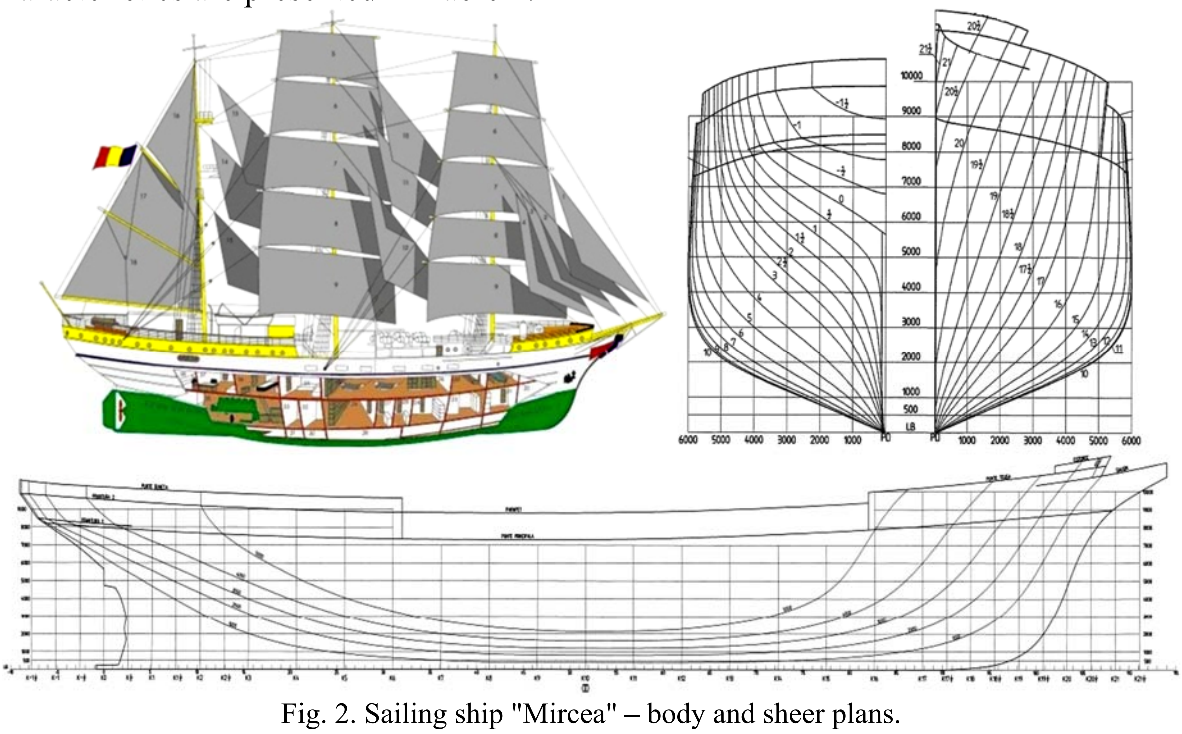

Fig. 2. Sailing ship "Mircea" – body and sheer plans.

Between 1st July and 10th August 2015, Romanian Naval Academy "Mircea cel Bătrân" training ship conducted an international training voyage, departing from port of Constanța, Romania and stopovers in the ports of Civitavecchia (Italy), Barcelona (Spain), Marseille (France) and Bar (Montenegro).

*Table 1*

**Sailing ship "Mircea" characteristics**

| Dimensions | Unit |
|---|---|
| Length over all | 81.6 m |
| Maximum body length | 73.6 m |
| Length between perpendiculars | 62.0 m |
| Beam | 12.0 m |
| Moulded depth | 7.3 m |
| Moulded draft | 5.35 m |
| Block coefficient | 0.486 |
| Gross tonnage | 1312 t |
| Displacement | 1840 dwt |
| Propulsion | 1100 hp MAK diesel engine |
| Speed | 9.5 knots |
| Endurance | 21 days |
| Range | 4000 Nm |

## 4. Measurement methods used

Within port waters, during the entrance maneuver until quay mooring maneuver and during the departure maneuver from harbor, there were performed measurements of closely related parameters to the phenomenon of squat: vessel draft, depth under keel and speed.

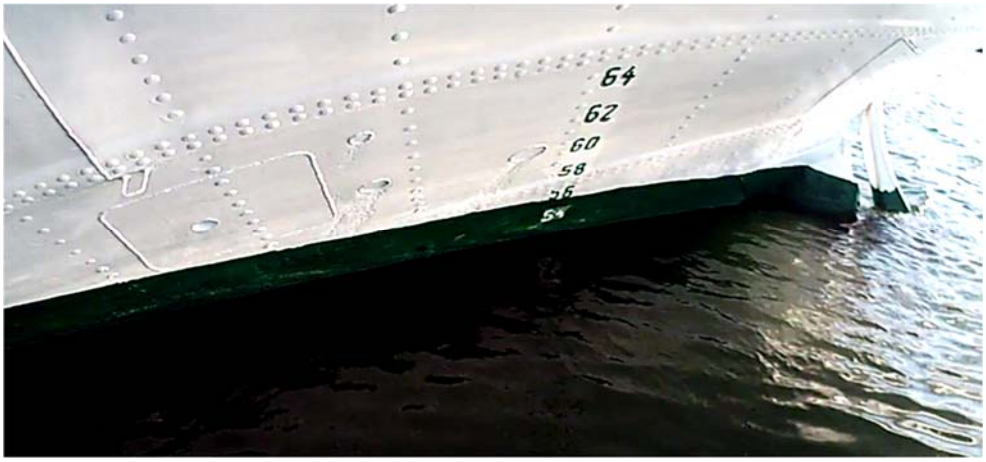


Fig. 3. Stern draft mark on board "Mircea".

On board, the ship's draft is determined by a direct reading of draft marks located at bow and stern on the hull (Fig. 3). Typically, drafts' reading is done before the ship leaves the quayside by direct observation from the shore. When the ship is underway, bow draft is readable on board from forecastle deck, but stern draft cannot be read because the draft scale is not visible from the poop deck. To eliminate this problem and record stern draft variation, the author used a HD Midland XTC 200 720p camcorder mounted on a wooden extending rod, 4 m in length (Fig. 4), fixed to the deck railing.

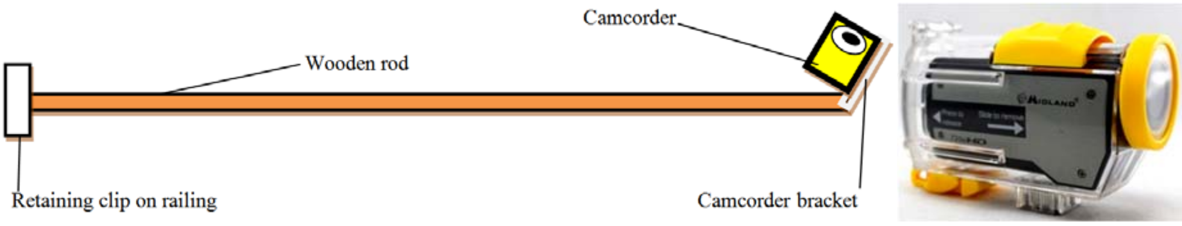


Fig. 4. HD Midland XTC 720p camcorder.

At the same time there were recorded data of depth under keel from Sperry ES 5000 echo sounder fitted on board the ship. It accurately measures depth in shallow or deep waters, having four operating scales ranging from 10 m to 2000 m and displays a seabed depth graph on a LCD display (Fig. 5). For continuous depth recording, the echo sounder enables printing the graph on paper. Thus, the author extracted depth from graphics for different moments in time, which were correlated with the draft recorded on the camcorder.


Fig. 5. Sperry ES 5000 echo sounder.

Vessel's position, course and speed were retrieved electronically from the electronic charts system, which receives this information from GPS.

## 5. Results

For squat, critical speed or depth Froude number calculations, water depth $h$ is necessary and can be obtained by adding the measured under keel depth $h_{uk}$ with average draft $T$. Knowing the bow and stern drafts ($T_b$, $T_s$), the following formula (Eq. 2) was used for water depth:

$$h = h_{uk} + \frac{(T_b + T_s)}{2}. \quad (2)$$

After collecting speed and water depth data from each port and studying draft videos there had been obtained information synchronized in time which are presented in the following figures.

At the entrance, the initial moment $t$ for data gathering was considered, in each case, when the vessel doubled the entry lighthouse of the port and the end of the measurements was considered when the ship speed was 3 knots (1.54 m/s). Reversely, the beginning of measurements was considered when the ship speed exceeded 3 knots and the end when the ship left harbor. Data extraction was done at 30 seconds intervals. The speed of 3 knots was chosen as the lower limit for readings start/stop because below this speed, the ship moves too slowly and the phenomenon of squat would not occur or would be imperceptible.

## 5.1. Port of Civitavecchia, Italy

In accordance with the ITTC (International Towing Tank Conference) recommendations, a ship is in shallow waters if the ratio between the water depth *h* and mean draft of the ship *T* satisfies the condition $1.2 < h/T < 1.5$.

At the entrance to the port of Civitavecchia there were measured depth under keel obtained from the echo sounder, stern draft obtained from video recordings and bow draft from direct observations. Mean draft was calculated with value of 5.35 m, because bow draft was consistently 5.3 m and stern draft varied between 5.35 m and 5.4 m according to analyzed records. Thus, every 30 seconds, there were calculated water depth *h* (Fig. 6) and the ratio *h/T*. It was noted that this ratio values ranged between 2.68 and 4.27, so it was not within the limits necessary to meet the shallow water condition presented above. The situation was similar at the departure maneuver.

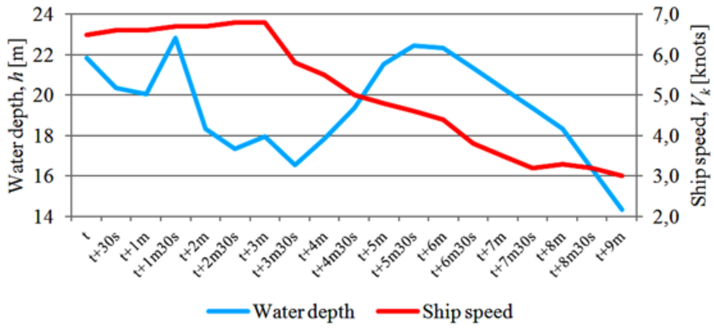


Fig. 6. Civitavecchia - entrance maneuver. Water depth and ship speed.

Total distance traveled when entering port was 1358 m with a maximum speed of 6.8 knots (Fig. 6) and when departing, 1649 m with a maximum speed of 6.9 knots (3.55 m/s).

## 5.2. Port of Barcelona, Spain

When entering Barcelona there were made the same measurements as previous. Mean draft was calculated to 5.325 m as the bow draft was consistently 5.3 m and stern draft varied between 5.3 and 5.35 m. Thus, at each moment of time, there were calculated water depth *h* (Fig. 7) and the ratio *h/T* with values ranging between 2.31 and 4.66, which was not within the limits necessary to meet shallow water condition.

If a ship is in open water conditions, there is an artificial boundary port and starboard, parallel to her centreline, beyond which there are no changes in ship speed, ship resistance or in ship squat. This artificial boundary is known as a "width of influence" whose value depends on the type of ship and the block coefficient. Inside this width of influence when moving ahead, the ship will experience a loss of speed, a decrease in propeller revolutions and also increased squat [3].

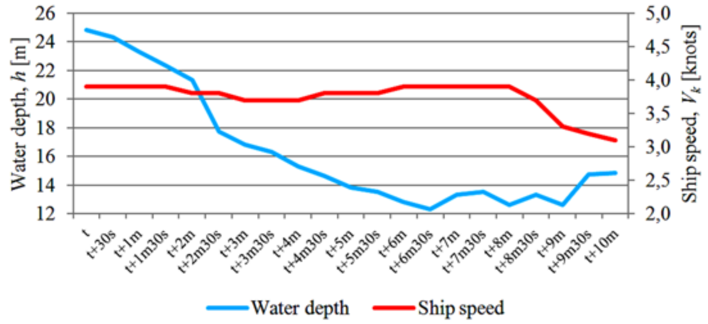


Fig. 7. Barcelona - entrance maneuver. Water depth and ship speed.

For this case, the width of influence was calculated to a value of 216.42 m. Although the vessel moves to the center of the fairway, the width of influence boundaries were violated sometimes by the breakwaters or piers from the harbor, but due to the average low speed of only 3.74 knots, the ship motion was not influenced by the presence of obstacles and squat did not occur. On departure the situation was similar, but *h/T* values ranged between 1.96 and 3.12, but still not sufficient to satisfy shallow water condition.

Total distance traveled when entering port was 1148 m with a maximum speed of 3.9 knots (Fig. 7) and when departing, 1501 m with a maximum speed of 6 knots.

## 5.3. Port of Marseille, France

On entering Marseille there have been made the same measurements as previous. Mean draft was calculated to 5.3 m as the bow and stern draft were consistently 5.3 m. Even so, the ratio *h/T* had values ranging between 2.34 and 2.91 when entering harbor and 2.23 to 4.31 when departing.

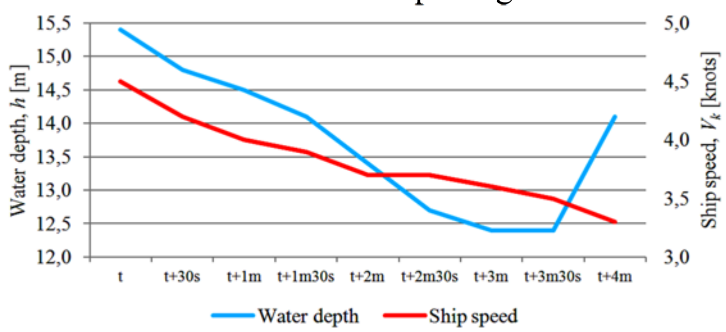


Fig. 8. Marseille - entrance maneuver. Water depth and ship speed.

In this case, the width of influence was 217 m. The width of influence starboard limit was violated on a small portion by the entry dike, but due to average low speed of 3.82 knots the ship motion was not influenced by the presence of obstacles and squat did not occur.

Total distance traveled when entering port was 475 m with a maximum speed of 4.5 knots (Fig. 8) and when departing, 591 m with a maximum speed of 5.9 knots.

## 5.4. Port of Bar, Montenegro

On entering Bar, mean draft was calculated to 5.325 m as the bow draft was consistently 5.3 m and stern draft varied between 5.3 m and 5.35 m. Thus, for every moment of time, there were calculated water depth *h* (Fig. 9) and *h/T* ratio. It was noted that ratio values ranged between 2.99 and 3.62, so it was not within the limits necessary to meet the shallow water condition. On departure, *h/T* values ranged between 2.43 and 3.14.

In this case, the width of influence was 216.41 m. The port artificial boundary of width of influence was violated on a small portion by the entry dike, but due to average low speed of 3.44 knots the ship motion was not influenced by the presence of obstacles.

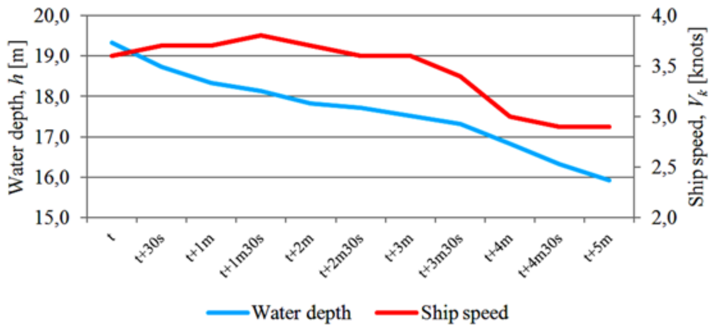


Fig. 9. Bar - entrance maneuver. Water depth and ship speed.

Total distance traveled when entering port was 531 m with a maximum speed of 3.8 knots (Fig. 9) and when departing, 703 m with a maximum speed of 4.3 knots.

## 6. Conclusions

The aim of the paper was to present experimental conditions, equipments and methods used on board NS "Mircea" to determine parameters needed in ship squat calculations. In summer of 2015 Romanian Naval Academy sailing ship "Mircea" conducted an international training voyage with four ports of call. On this occasion there had been conducted a series of measurements on vessel's draft, water depth below keel and ship's speed when entering and leaving the ports because these areas showed, more or less, the characteristics of restrictive areas that could favor the emergence of squat phenomenon.

From the taken measurements and results interpretation there were extracted the following conclusions:

- The only way on board the ship to measure draft is by direct observation of draft marks. Therefore, for the stern draft readings, which are harder to read, it was used a video camera fixed on a wooden extending rod to record draft variation and viewing it afterwards.
- Regarding measuring methods, there have been identified, on board and when compiling data, a difficulty in syncing the draft records with under keel depth graphs from echo sounder and speed obtained from the electronic charts system, because

these information come from different navigation equipments with offset internal clocks.

- Attempts to capture on record a noticeable draft change, which could be attributed to the phenomenon of squat, proved unsuccessful due to unsuitable ship characteristics, slow maneuvering speed and ports not sufficiently restrictive.

Another decisive factor of squat non-occurrence was the variable ship speed on entering and departing maneuvers. In laboratory conditions, experiments on models in towing tanks are made at constant speed over long distances and water depth and canal width are also constant. These conditions favor the squat phenomenon, but in reality full-scale measurements proved to be more difficult to reproduce.

Maximum squat determination for shallow and/or narrow waters remains an important issue for safety of navigation. Masters should know before entering such areas, where and how much the draft will increase to take actions for countering this phenomenon.

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