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Experimental Study of a Tanker Ship Squat in Shallow Water

Mohammadreza Fathi Kazerooni[a], Mohammad Saeed Seif[a*]

[a]Center of Excellence in Hydrodynamics & Dynamics of Marine Vehicles, Sharif University of Technology,Tehran, Iran

*Corresponding author: seif@sharif.edu

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Graphical abstract

Abstract

One of the phenomena restricting the tanker navigation in shallow waters is reduction of under keel clearance in the terms of sinkage and dynamic trim that is called squatting. According to the complexity of flow around ship hull, one of the best methods to predict the ship squat is experimental approach based on model tests in the towing tank. In this study model tests for tanker ship model had been held in the towing tank and squat of the model are measured and analyzed. Based on experimental results suitable formulae for prediction of these types of ship squat in fairways are obtained.

Keywords: Ship; squat; shallow fairway; model test; towing tank

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1.0 INTRODUCTION

Ship squat is defined as variations in ship vertical position. This is usually simultaneous with sinkage and dynamic trim change. Hence, in this condition bow and stern sinks in water and the amount of sinkage is different for aft and fore. Ship squat is a common phenomenon that occurs in shallow waters. As a ship moves in water, the fluid surrounding the body flows into the direction of sides and bottom of the vessel and the flow pattern around the hull changes. Any changes in flow pattern will cause changes in pressure distribution compared to hydrostatic pressure. Asymmetric distribution of pressure causes the ship trimming by fore or aft and draught variations. For the ships with common speeds usually vessel sinks in the water and changes of draught is negligible (Milward, 1966). Combination of this vertical motions and trim angle variation in calm water is called ship squat (Barras, 2000). Therefore, even in deep waters ships squat. But the amount of squat is usually negligible in deep water compared to shallow water (Milward, 1966).

Increment of ship size in 1960 decade has caused the under ship clearance a limiting factor for navigation in shallow waters and approach channels. In the shallow water condition, ship squat is distinctly function of water depth too. In shallow waters the under keel clearance is so important and pressure drop is more than deep water case. Hence, the vessel sinks in water until buoyancy force equals the hydrodynamic pressure forces. Comparing to deep water, squat amount is much more proportional to water depths than the hull form and ship speed in shallow waterways.

Ship squat has been known for a long time. But accidents occur for ships due to the ship squat even in recent years. As an example sinkage of passenger ship Herald of Free Enterprise in Zeebruge harbor, Belgium, 1987 lead to the death of 200 passengers (Barras, 2000). Other example is grounding of QE2, 1992, by financial loss evaluated 20 million pounds. The cause of the accident is the flooding of tanks in bow due to the damage made by extreme squat and draught increment in ship fore (Barras, 2000). A more recent report of grounding due to the ship squat is Iran Noor tanker in Ningbo, China 2004. All of these cases insist on the need for precise guidelines of predicting ship squat in shallow waters.

In the technical literature various methods are described for squat prediction. Rule of thumb predicting methods, experimental data gathered from model tests, full scale trials and theoretical and semi-theoretical methods are such methods.

Constantine 1961 has considered the problem of pressure change around ship hull navigating in shallow channel (Gourlay, 2008). Slender body theory has been applied to evaluate ship squat recently and have been developed to dredged channels and canals. The results have been summarized in a formula based on Fourier transform that gives an approximate solution for channels of arbitrary cross section (Varyani, 2006).

The sailors and ship masters have been familiar with the phenomena that ship motion trim in shallow water could result to increment of ship resistance and vessel fuel consumption. For ships with symmetric bow and stern (typical older hull forms) the trim angle effect in squat is small (Milward, 1966).

However the ship squat is not precise phenomena and the difficulties of flow analysis around ship hull mathematically clarify the need for experimental approaches. Hence, empirical formulae have always been in attention to predict the ship squat. Model tests have been held all around the world and among these efforts, the results obtained by Eryuzhu & Hausser 1978, Eryuzhu *et al.* 1994 and Barras 1979 are remarkable. Recently an experimental method based on measurement on full scale ships have been developed for predicting the under keel clearance during waterway entry. The measurements have been done in shallow water and sinkage and dynamic trim recorded. Recommendations for correction of moving trim to include the under keel clearance have been made (Harting, 2009). Merchant ship squat in Australian ports and Charleston beach have been recorded experimentally and this method is used on board the ships entering navigation channels (Ankudinov, 2000). Initial vessel trim is influential to ship squat and this effect is studied experimentally by measurement on full scale ships (Harting, 2009). Ship squat is an influential factor to predict ship maneuvering in shallow waters. Changes in maneuvering hydrodynamic derivatives due to ship squat are considerable (Ankudinov, 1996).

Analyzing the time history of ship sinkage and trim angle in shallow water shows that ship squat is an unsteady phenomena in nature and the dynamic changes of the parameters should be considered (Dufflied, 1997).

As it is expected accurate squat prediction of a ship needs large amount of calculations. Therefore it is not possible to use a precise method in operational cases and decision about accuracy of methods depends on the applications.

In recent years computational fluid dynamics methods have been used to predict ship squat. Ship sinkage and trim can be calculated numerically by non-structured networks (Yang *et al*. 2000).

In the present study, model tests are carried out in Sharif University of Technology towing tank and the results have been used to find out squat behavior. The results can be expanded to full scale by taking into account possible scale effects. Scale effects in model tests for resistance test and longitudinal forces are well known. But there have been a little research for the studying of scale effects in vertical and transverse forces. But it is expected that scale effect is small in the vertical motion case (Brix, 1994).

The series of systematic tests are held in laboratory for a tanker. The results have been compared with the data published by Milward 1996 and Norrbin 1986. The compatibility of results emphasize that the data obtained can be used for squat prediction of vessels in Iranian harbor vicinity.

■2.0 INFLUENCING FACTORS

Important factors affecting ship squat are forward speed, block coefficient, hull form, deadrise angle and water depth. The most important factor in ship squat is forward speed. Squat is approximately proportional to square speed. As an example if the ship speed halves, squat would decrease to 25% of initial amount.
Ship squat is proportional to block coefficient directly and the ratio of squat to ship draught is higher in the ships with large block coefficients. Therefor tanker ships are expected to have more squat than the passenger ferries or other slender hulls (Dufflied, 1997).

High deadrise angle of the hull form can decrease the ship squat. Ships with no deadrise angle in the parallel middle body such as tankers are affected with squat greatly.

Ship squat is a function of hull form and body lines too. If the vessel has flat surfaces especially in the bottom, these flat surfaces would be influenced by pressure drops and squat can be increased. This means that tanker ships and barge shape vessels are critical from squat point of view.

Decrement in water depth in a given speed would result into more ship squat. In order to determine the water depth the parameter UKC, under keel clearance can be defined as (Guema *et al.* 2009):

$$UKC = \frac{h-T}{T} \tag{1}$$

Figure 1 illustrates the parameters used in this definition.

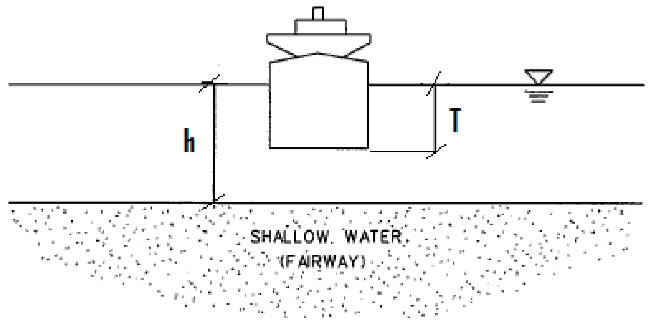

Figure 1 Definition of ship draught and water depth in shallow fairway

Another prominent factor in squat evaluation is blockage factor. Blockage factor is defined as the ratio of ship wetted cross section to channel wetted cross section as shown in Figure 2.

$$S = \frac{b \times T}{B \times H} \tag{2}$$

In the formula above b is the ship breadth, T ship draught, B channel beam and H is waterdepth.

If the ship navigates in fairway with no lateral restriction the equivalent channel breadth is used that varies 8.25 of ship breadth in ultra large tankers to 9.5 times ship breadth in general cargoes to 11.75 of ship breadth in containerships (Barras, 2000). This beam is the significant breadth of the waterway that the flow around ship is affected by lateral boundaries.

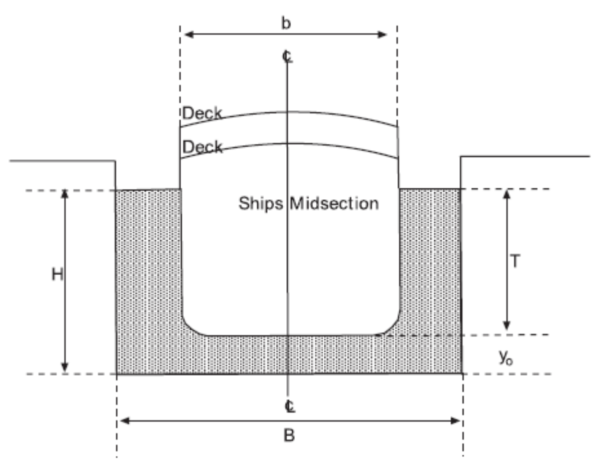

Figure 2 Ship in channel at static equilibrium

For evaluation of shallow water effects, it is so common to define a Froude number according water depth as follow:

$$F_{nh} = \frac{V}{\sqrt{gh}} \tag{3}$$

■3.0 OVERVIEW OF METHODS TO PREDICT SHIP SQUAT

The disasters occurred to ships navigating in shallow water emphasize the importance of squat prediction and dominant need for guidelines. In different references various methods are suggested for squat evaluation (Milward, 1996). Rule of thumb methods, experimental data obtained from model tests and full scale measurements, theoretical and semi theoretical methods are suggested. As mentioned previously squat evaluation for a ship demands complex calculations. Therefore it is impossible to present a simple method. Finally decision on the validation of the methods depends on the accuracy level needed in applications. The simplest rule of thumb is M930 rule. This rule just informs people that squat may occur and implies without any details that squat depends on ship speed. Either the relation of squat and forward speed is not debated in this rule. Furthermore the effects of hull form and water depth is not included and there is no suggestion of how to calculate the squat in speeds more than ten knots.

Ortlepp 1978 has presented a method of squat evaluation based on Archimedes principal in deep waters. He has emphasized that squat is more in shallow waters than deep water. His results show that squat is intensely a function of water depth and depending on water depth the amount of squat is 2 to 7 times of squat in deep water for a given speed. As it is seen further than this fact that squat is more than shallow water Ortlepp method is not applicable yet. The Ortlepp's results in deep water is gathered from experiments with trim gauges installed on a particular vessel, Irving Glen. However trim indicators used in past show the draught increment due to elevation of surface waves too. Therefore such results are not reliable so much.

Admiralty Manual of Navigation 1987 represents three methods to predict the ship squat.

Squat= 10 % of ship draught (4)

Squat= 0.3 m for each 5 knots forward speed (5)

$$squat\ (m) = \frac{V^2}{100}, knots \tag{6}$$

This guideline suggests evaluating ship squat by three methods and using the one which exceeds. It is totally obvious that the methods are not so accurate and no application limit is mentioned for them. These methods are suitable for just urgent cases where the ship motion characteristics and waterway topologies are not well known. For emergency applications the most suitable method is one represented by Barras 2000 in which an additional factor is considered for ship hull form geometry. In Barras formula the ship squat S is given as below:

$$S = 2c_B \frac{V^2}{100} \quad \text{, for channels} \tag{7}$$

$$S = c_B \frac{V^2}{100} \quad \text{, for shallow fairway} \tag{8}$$

In these formulae squat is obtained in meters if the forward speed is in knots. There are so many experimental methods for predicting ship squat in literature. Majority of these methods are based on experimental measurements on ship models in towing tanks. Several of these model tests are handled in Sharif University of Technology Towing Tank and the results are in good agreement to published data. In most cases the results can be expanded to full scale. The scale effects of longitudinal forces in resistance and propulsion model tests are well known but the research in the field of scale effects in vertical motions are so scarce. However it seems that scale effects for the vertical motions are negligible.

■4.0 MOTION REGIMES IN SHALLOW WATER

Ship motion regimes in shallow water up to channel Froude number of 0.85 is called sub critical region. Most ships navigate in shallow water with sub critical speeds. According to experimental results ship resistance increases magnificently with channel Froude numbers and reaches a peak in approximately 0.85. Hence, in this region the ship resistance in shallow water is much more than deep water resistance. Therefore if the engine power remains constant, the vessel would experience speed loss in shallow water. As a result to maintain the speed in sub critical shallow water more engine power is needed. Further the diagrams of trim by fore and sinkage with respect to depth Froude number are increasing in this region. The ship trims more and sinks in the water till it reaches an obvious peak. According to technical literature this peak occurs approximately in channel Froude number of 0.85 to 0.9 (Milward 1996).

The flow regime around ship hull moving in shallow water by channel Froude numbers more than 0.85 is called super critical region. The vessel hydrodynamic behavior in this region is reverse to sub critical flow regime. In this region the resistance ratio (resistance in shallow water / resistance in deep water) is less than unity. Hence, the ship resistance in super critical regime is nearly less than deep water. The trim angle persists to an approximately steady amount and the ship bows up. However the sinkage would be negative in this region. The vessel lifts up and the draught decreases. The super critical region is not so much in interest because most ships enter the shallow water in sub critical regime. Majority of squat studies have been held in sub critical regime.

■5.0 EXPERIMENTAL EQUIPMENT SPECIFICATIONS

5.1 Shallow Water Towing Tank

The main dimensions of the towing tank depend on the dimensions of the ship model that would be used. Therefore the dimensions of the towing tanks around the world that could be used for shallow water tests and approach channels modeling are so varying. Figure 3 shows an illustration of the shallow water towing tank. The shallow water towing tanks are not accessible within the country. So some facilities have been added to the towing tank in the Sharif University of Technology to ease the perform of shallow water tests.

The material used in the fabrication of the artificial bottom is so influential in test results. It is essential that the roughness of bottom that has been used be a correct scale of natural fairway in the harbor vicinity. The basis of the similarity here has been considered Reynolds number similarity which characteristic length is the bottom roughness. Usually the computed roughness is so small that the relevant material is so hard to access in the commercial resources. The flow generated by ship motion in shallow water is really turbulent. Hence, sufficient roughness should be considered in shallow water modeling to satisfy the turbulent boundary layer restriction.

All the measurements held in the towing tank is done for steady state condition. Therefore it is essential that all the parameters in the towing tank tests reaches a steady amount and persisted for an adequate time interval. Also it is not necessary to install the artificial bottom among all the tank length but it is obvious that the length of the artificial bottom should be as enough for all the parameters to reach the steady state condition in shallow water. As an example in the Sharif University of Technology towing tank with 25 m length, all the test parameters reaches steady amount in a 10 m artificial bottom. Figure 6 shows the artificial bottom and bank installed in the towing tank.

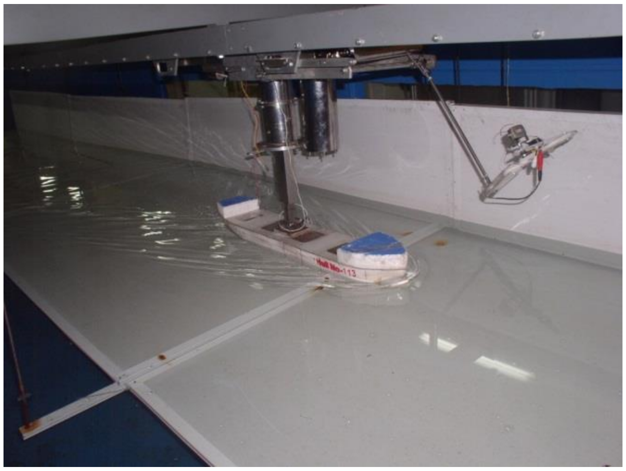

Figure 3 Artificial bottom installed in the towing tank

5.2 Ship Model Selection

Model used to perform tests depends on various parameters. Studying the ship squat in the vicinity of harbors consists of two separated problems. The first is to study the squat characteristic of a certain ship in harbors and the other one is study on squat of ships in general in order to obtain criteria for ship squatting in Iranian harbors. For the first problem the ship model is well defined but in the second one it is necessary to obtain methods to select the ship models in such a way to cover vast ship types entering the Iranian harbors. This method conclude to a database that can be used for prediction of ship squat. So the selection of ship model is so important. In this research a wide study of ships entering Iranian harbors have been done. Simply the ships can be divided into two categories based on their length and tonnage.

According to above discussion finally it had been decided to use a model of tanker ship as described in Table1.

Table 1 Tanker & model specifications

	Tanker	Model Tanker
Length (m)	176	1
Breadth(m)	31	0.17
Draught(m)	9	0.05
Displacement	41523 tons	7 kg
F_n	0.06-0.27	

Figure 4 shows the model that has been used.

Figure 4 Tanker model

6.0 EXPERIMENTAL RESULTS AND VALIDATION

There are so many experimental methods for predicting ship squat in literature. Majority of these methods are based on experimental measurements on ship models in towing tanks. Several of these model tests are handled in Sharif University of Technology Towing Tank and the results are in good agreement to published data. In most cases the results can be expanded to full scale

To evaluate the squat of ships entering Iranian harbors model tests in Marine Engineering Laboratory are conducted and the results are compared to experimental formulae based on model tests. To obtain the lower limit of ship squat comparison to Norrbin 1987 formula is so suitable:

$$S = 0.01888 c_B \frac{B}{L}\frac{T}{h} V^2 \tag{9}$$

In this formula S is maximum ship squat predicted by Norrbin relation, C_B the block coefficient of the hull form, B ship breadth in meters, L ship length in meters, T ship draught in meters, h water depth in meters and V is ship speed relative to flow velocity in Kmph.

In order to predict the higher limit for ship squat, the formula presented by Milward is applicable. This formula can be used until the end of the sub critical flow regime in shallow water. This formula can be used until the channel Froude number of 0.4 sub critical region.

$$S = \frac{[(\frac{12.22 c_B B}{L}) - 0.46] {F_{nh}}^2}{1 - 0.9 F_{nh}} L \tag{10}$$

In the following diagrams the results obtained from model tests in different speeds and water depths are compared to Norrbin and Milward formulae. It is clear that the Norrbin formula is in lower level of value compared to model tests. So it can be concluded that Norrbin formula gives a lower limit for ship squat. Also the scale effects of the models are prominent and some of the differences may be due to the scale effects.

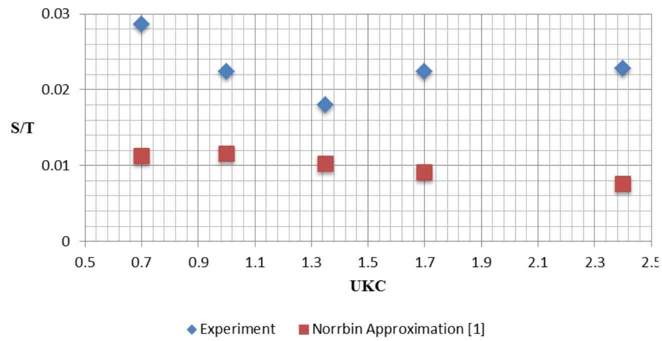

Figure 5 Tanker squat, Froude number 0.064

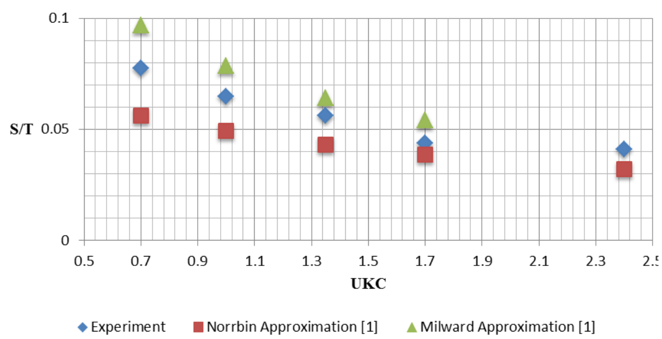

Figure 6 Tanker squat Froude number 0.128

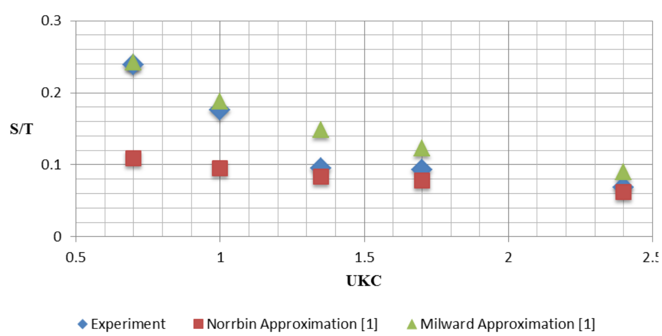

Figure 7 Tanker squat Froude number 0.176

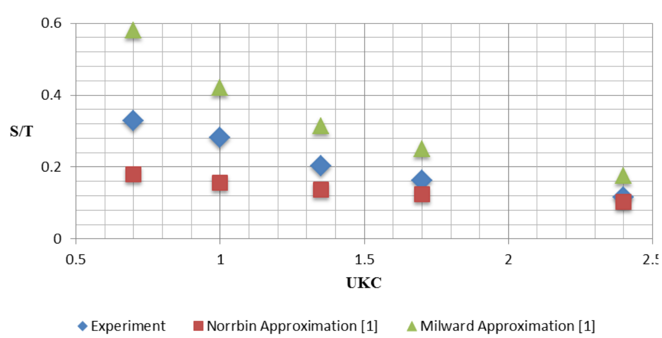

Figure 8 Tanker squat Froude number 0.223

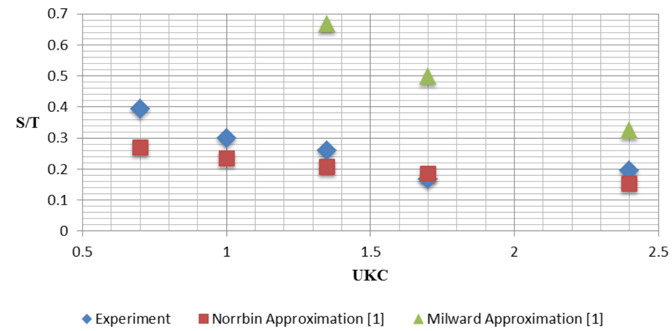

Figure 9 Tanker squat Froude number 0.271

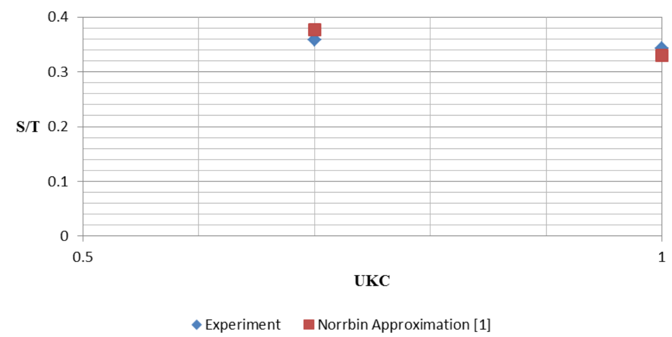

Figure 10 Tanker squat Froude number 0.319

Figures 5-10 show the experimental results. The results shown in Figure 5 are far away Milward approximation. This is mainly due to scale effect. In this tests the towing speed of the model is so small that the turbulent flow around the ship hull is not simulated correctly. It should be mentioned that no turbulence simulator is used during the tests. In higher speeds the flow around the ship model is completely turbulent.

Results presented in Figure 8 shows that the Norrbin's criteria is not accurate in higher forward speeds. In this occasions the model tests results should be used directly. Furthermore in all diagrams one could see that the model test results are far behind the Norrbin's formula for lower UKC values. In these extreme cases the flow blockage is more and the flow speed outside of the boundary layer increases significantly. Therefore the pressure drops are more obvious and the model sinkage increases.

The higher limit of squat for large cargo ships can be calculated by Milward formula. However the squat of tanker model measured from model tests is within the two limits given by Milward and Norrbin. Hence, such formulae are applicable to ship entrance in Iranian harbors for low speeds. In higher speeds the simulation methods based on model tests and computational fluid dynamics are suggested. The results obtained from model tests in towing tank of Sharif University of Technology is very good reference in these cases.

The tanker squat calculated from Norrbin and Milward approximation is compared to model test results. In lower waterway depths Norrbin approximation is accurate and Milward approximation is precise for higher water depths.

7.0 CONCLUSION

In this study squat phenomena have been investigated experimentally. The results obtained can be used as an appropriate database for tanker ship squat prediction in shallow waters. According to the test results squat magnitude is very high for the models studied.

In the model tests it is shown that in the limiting conditions the squat of this vessel can be reached to thirty percent of ship draught. So, this is very dangerous for tanker navigation in shallow water due to grounding risks. Furthermore, in this study a well-defined method for predicting ship squat is introduced and facilities are provided in the towing tank. Different formulae have been published in navigation guidelines across the world. Most of these relations are very simple and hull form is not considered. So usually the actual ship hull form is far from the hull forms tested and squat prediction by means of such relations may not be accurate. In cargo ship operations few centimeters of draught increment may results in so considerable payload and benefit. In these cases, accurate squat simulations such as the procedure described in this paper is very beneficial.

References

[1] Admiralty Manual of Navigation. 1987. HMSO. 1.

[2] Ankudinov, V., Dagget, J. C., 1996. Squat Prediction for Ship Maneuvering Applications. Proceedings International Conference on Marine Simulation and Ship Maneuverability. Denmark, Copenhagen. 9–13

[3] Ankudinov, V., Larry, L., Dagget, J. C., 2000. Prototype Measurement of Ship Sinkage in Confined Waters. Proceedings International Conference on Marine Simulation and Ship Maneuverability, Orlando. May 8–12.

[4] Barras, C. B. 2000. *Ship Stability for Masters & Mates*. Elsevier Science

[5] Brix. H. 1994. *Maneuvering Technical Manual*. Hamburg University Press

[6] Dufflied R. J. 1997. Investigation Into Steady and Unsteady State Squat. Naval Architecture Bachelor Thesis, Australian Maritime College.

[7] Eryuzlu, N. E., Hausser, R. 1978. Experimental Investigation Into Some Aspects of Large Vessel Navigation in Restricted Waterways. Proceedings of Symposium of Aspects of Navigability of Constraint Waterways Including Harbor Entrances. 2: 1–15

[8] Gourlay, T. 2006. Flow Beneath a Ship at Small Underkeel Clearance. *Journal of Ship Research*. 50: 250–2258.

[9] Gourlay, T. 2008. Slender Body Methods for Predicting Ship Squat. *Ocean Engineering*. 35: 191–200.

[10] Gucma. L., Schoeneich, M. 2009. Monte Carlo Method of Ships Under Keel Clearance Evaluation for Safety of Ferry Approaching to Ystad Port Determination, R&RATA#. 2(13): 2.

[11] Alexander Harting, Anne Laupichler, Jorge Reinking. 2009. Considerations on the Squat of Unevenly Trimmed Ships. *Ocean Engineering*. 36: 193–201.

[12] Milward, A. 1996. Review of Prediction of Ship Squat in Shallow Waters. *Journal of Navigation*. 49: 77–88.

[13] Norrbin, N. H. 1978. Fairway Design with Respect to Ship Dynamics and Operational Requirements, Swedish State Shipbuilding Tank (SSPA) Research Report No.102, Gothenburg, Sweden.

[14] Tuck, E. O. 1966. Shallow Water Flows Past Slender Bodies. *Journal of Fluid Mechanics*. 26: 81.

[15] Varyani, K. S. 2006. Squat Effects on High Speed Craft In Restricted Waterway. *Ocean Engineering*. 33: 365–381.

[16] White, F. M. 2002. *Fluid Mechanics.* Mc Grew Hills.

[17] Yang, C., Lohner, R., Noblesse, F., Huang, T. 2000. Calculation of Ship Sinkage and Trim Using Unstructured Grid. *European Congress on Computational Methods in Applied Sciences & Engineering*. ECCOMAS 20.