TRANSNAV
http://www.transnav.eu
the International Journal
on Marine Navigation
and Safety of Sea Transportation
Volume 11
Number 3
September 2017

DOI: 10.12716/1001.11.03.01

Study on Manoeuvring Criteria for Safety Assessment in Shallow Water

S. Nakamura
Japan Marine Science Inc., Kawasaki, Japan

ABSTRACT: The necessity of verifying manoeuvring mathematical models in shallow water for studying the safety of ships using a ship-handling simulator is pointed out in this report. Several instances of verification of mathematical models in shallow water are introduced here based on measurements of motion conditions of full-scale ships and shallow water tank tests of models. Results of safety assessment tests of five manoeuvring phases are given using the verified manoeuvring mathematical models to discuss manoeuvring criteria in shallow water. Objective manoeuvring criteria for safety assessment in shallow water are proposed based on subjective judgement related to control margin assessed by more than 3,200 masters and pilots for over 325 simulation tests and by analysis of the study results of 15 full-scale ships.

1 INTRODUCTION

It is well known that a ship manoeuvring in shallow water generally has a larger tactical diameter and increased added mass compared to manoeuvring in deep water. Tactical diameter tests, Z-tests, etc., in deep water are conducted by the shipyard during the ship's construction; therefore, the manoeuvring performance and test results of such ships in deep water are available. On the other hand, manoeuvring performance tests of full-scale ships are difficult to carry out in shallow water, and performance is usually estimated. Although the need for manoeuvring performance criteria in shallow water has been discussed, such criteria have not been formulated as international criteria. In recent years, ship-handling simulators are being extensively used to study the number of tugs and total horsepower required to prepare for and determine critical wind speed when a ship enters port for the first time or when port facilities are being newly constructed. Ship manoeuvring mathematical models to be prepared for such studies are generally based on trial results in deep water and the particulars submitted by the shipyard. However, although the studies must focus on manoeuvring within the port and almost entirely in shallow water, manoeuvring mathematical models available are mostly those that consider general shallow water effects estimated from trial results in deep water given by the manufacturers of ship-handling simulators. While it is well known that the study of safety during manoeuvring within port using ship-handling simulators is highly significant, the author has pointed out the importance of the following two topics:

- Manoeuvring mathematical models in shallow water are generally estimated by manufacturers of simulator, the accuracy of which is not verified in most cases.
- During the study of manoeuvring safety in port, objective criteria for safety assessment are not always clear.

The following items related to the two topics mentioned above are discussed in this study:

- Free-running tank tests (turning tests, Z-tests) were conducted in shallow water on models of single-screw and twin-screw LNG carriers. Reproducibility of manoeuvring mathematical models in shallow water was verified and adjusted.
- Motion conditions while manoeuvring in shallow water within port of several LNG carriers recently commissioned were measured on board. Reproducibility of manoeuvring mathematical models in shallow water were verified and adjusted.
- The author conducted safety assessment tests with full-mission type ship-handling simulator using manoeuvring mathematical model in shallow water on several LNG carriers the reproducibility of which was already verified. The test cases amounted to 325.
- Objective manoeuvring criteria in shallow water were determined from the response to subjective judgement related to control margin by many ship operators (masters, pilots, etc.) witnessing the manoeuvring simulation tests and motion conditions for each of the following five phases: course-keeping phase, course-altering phase, speed-reducing phase, lateral-shifting phase, and standstill-turning phase. The results of one simulation test case have been witnessed and assessed by an average of 10 ship operators (masters, pilots, etc.). Accordingly, the number of persons who have assessed the 325 tests exceeds 3.200 persons.
- Subjective judgements were acquired related to control margin from masters and pilots who boarded 15 LNG carriers that entered/departed port after measuring motion conditions for each of the following five phases while berthing/sailing in shallow water: course-keeping phase, course-altering phase, speed-reducing phase, lateral-shifting phase, and standstill-turning phase.
- Based on the manoeuvring simulation tests in shallow water using models for which reproducibility had been verified, and based on the study results of the 15 full-scale ships, the objective manoeuvring criteria below were formulated as acceptable motion conditions. Results under comparatively calm weather conditions included many from the study results of full-scale ships; however, findings showed that most of the simulator tests were conducted under sea and weather conditions at acceptable limits of control margin.

Acceptable motion conditions

- Course-keeping phase: Drift angle under 8 degrees in main engine slow ahead condition
- Course-altering phase: Turn rate greater than 8 degrees/min. in the main engine slow ahead condition
- Lateral-shifting phase: Lateral (shift) speed greater than 20 cm/sec. at start
- Speed-reducing phase: Greater than 0.2 kts/min.
- Standstill-turning phase: Turn rate greater than 10 degrees/min.

2 MATHEMATICAL MODEL IN SHALLOW WATER

2.1 *Tank tests in shallow water*

The general practice for ship manoeuvring mathematical model in the ship-handling simulator is to tune the dynamic performance based on the results of deep water trials. Turning tests of full-scale ships are difficult to conduct in shallow water, and manufacturers of simulators generally estimate the manoeuvring performance in shallow water. However, in most cases, the ship-handling simulator operations side may not be able to confirm adequately the accuracy. In a project aimed at improving the accuracy of the ship manoeuvring mathematical model of simulators in shallow water in which the author participated as one of the main members, free-running tests were conducted in shallow water on two kinds of LNG carriers (with models of 3-m overall length) with varying aft shapes: Ship A (single-screw) with Lpp: 275 m, B: 49 m and L/B: 5.6; and Ship B (twin-screw) with Lpp: 293 m, B: 49 m and L/B: 6.0. A part of the tank tests results is shown in Table 1 and Table 2.

Comparing Ships A and B, the L/B of ship B is slightly larger, and the aft shape is different because of the single-screw and twin-screw configurations of the two ships. Because of these differences, at the same initial speed of 5 knots and a water depth to draft ratio (H/d) of 1.2, the tactical diameter of Ship B was comparatively much larger, and the overshoot angle in the Z-test was smaller.

The tests confirmed that shallow water effect was not consistent, and the difference was large, depending on the hull shape. Care is necessary when setting the manoeuvring performance under shallow water effects during safety assessment while manoeuvring the ship within port using the ship-handling simulator.

Table 1. Tank test (Tactical diameter)
Tactical dia. /Lpp
Starboard 35degrees
Ship A; Lpp:275m, B:49m, draft:11.6m, Single screw
Ship B; Lpp:293m, B:49m, draft:11.5m, Twin screw

Tactical dia. /Lpp	H/d=1.2 5kts	H/d=1.5 5kts	H/d=∞ 19kts**
Ship A / Single-screw	4.4	3.5	3.0
Ship B / Twin-screw	7.0*	4.5	3.6

* Due to constraints in the width of testing tank used for the tests, some assumptions have been included.
** Speed is 19 knots at H/d=∞

Table 2. Tank test (Z-test results)
1st Overshoot Angle
Starboard 10 degree
Ship A; Lpp:275m, B:49m, draft:11.6m, Single screw
Ship B; Lpp:293m, B:49m, draft:11.5m, Twin screw

1st Overshoot Angle (Degree)	H/d=1.2 5kts	H/d=1.5 5kts	H/d=∞ 19kts**
Ship A / Single-screw	2.9	4.3	6.3
Ship B / Twin-screw	1.2	4.6	6.3

** Speed is 19 knots at H/d=∞

Fig. 1 shows the results of turning tests (deep water and shallow water with initial speed of 7 knots for both cases) by simulator of Ship B (twin-screw), based on the results of the above tank tests.

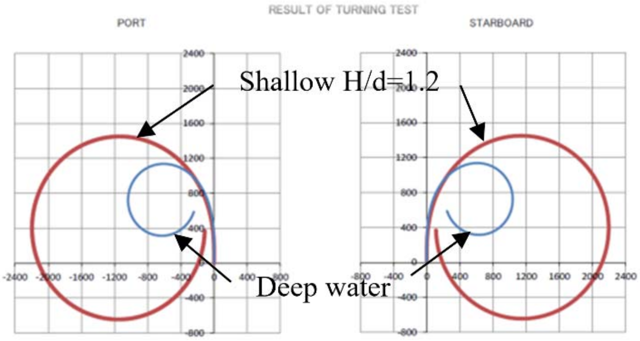

Figure 1. Results of turning tests (deep water and shallow water with initial speed of 7 knots for both cases) by simulator of Ship B; Lpp:293m, B:49m, draft:11.5m, Twin screw.

2.2 *Verification of manoeuvring mathematical model in shallow water by onboard studies*

The author and study team members boarded several ships in operation from 2007 to 2016 fifteen times, and measured ship motions during berthing/sailing manoeuvres in shallow water conditions. Signals such as ship's position and heading were acquired by GPS from the AIS plug of the ships, and the steering conditions, main engine rpm, usage conditions of tug and thruster were also recorded in time series for motion measurements.

Similar manoeuvring during measurements was performed in the ship-handling simulator. The reproducibility of the ship manoeuvring mathematical model was verified in shallow water conditions by comparing ship motion conditions.

Fig. 2 shows the track chart (wind: WNW 5.3 m/s; tidal current: ENE 0.1 knot) in the course-altering phase while berthing in Japan on December 15, 2014, from the results of fifteen measurements. (Ship particulars: LOA: 288 m, LPP: 275 m, Molded breadth: 49 m, MOSS-shape cargo tank capacity: 155,000 m^3, draft: 11.8 m)

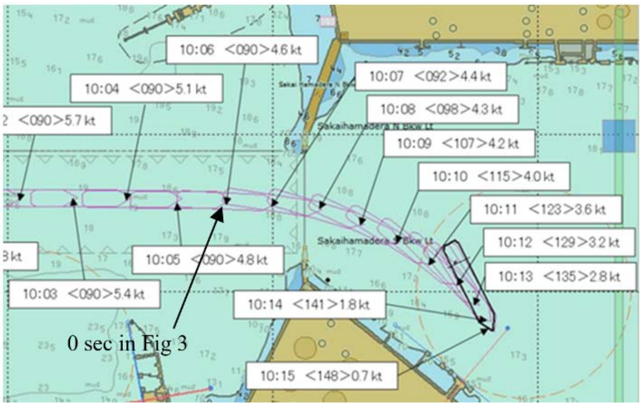

Figure 2. Track chart (wind: WNW 5.3 m/s; tidal current: ENE 0.1 knot, H/d=1.5) in the course-altering phase while berthing on December 15, 2014).

Fig. 3 shows the changed conditions in time series of turn rate for the same status. The changed conditions in time series of the turn rate when the same manoeuvres of the studied full-scale ship were implemented on the ship-handling simulator under the same phase, are superimposed in Fig. 3.

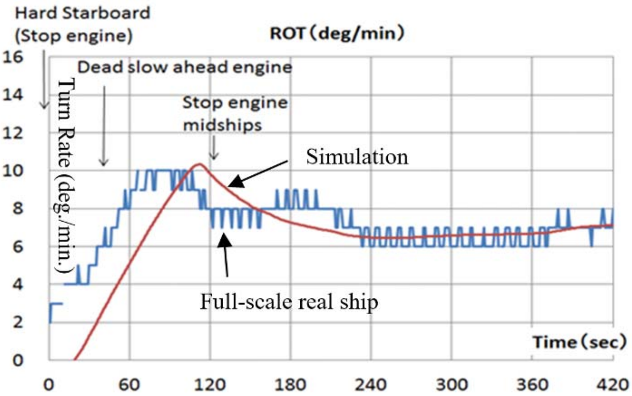

Figure 3. Status of development of turn rate in the course-altering phase of full-scale ship (berthing on December 15, 2014) and simulation (Wind: WNW 5.3 m/s; tidal current: ENE0.1 knots, H/d=1.5).

Although the effectiveness of rudder was slightly delayed with the main engine stopped in the simulation model at conditions of H/d=1.5, water depth approximately. 17.5 m, advance speed of 4.6 knots, rudder hard to starboard at 10:06 hours when course alteration started, the startup conditions of turn rate, maximum turn rate, etc., were reproduced to good accuracy. Full-scale ship data are indicated in pulse form because the heading measured from AIS data are integer values, and the turn rate is also an integer value.

3 SAFETY ASSESSMENT TEST USING FULL-MISSION TYPE SHIP-HANDLING SIMULATOR

The manoeuvring mathematical model with which reproducibility of manoeuvring performance in shallow water was verified in the previous section, was used and several tests were conducted to verify port/harbour implementation plan, and wind speed criteria that become limits for safe operation, number of tugs, horsepower, etc. An overview of the safety assessment tests conducted for LNG carriers shown in Table 3 is discussed here. These are safety assessment tests conducted with the purpose of formulating operational criteria for receiving ships or constructing berths. The berths were 16 in all: 15 within Japan, and 1 in Australia. The tests conducted over the past five years were considered for judgment; however, combining berthing and sailing, the number of tests finally reached 325. Since studies aiming to determine operational limits were many, the number of cases implemented for wind speeds between 10 m/s and 15 m/s were numerous, including some cases with a maximum wind speed of 20 m/s. Tests were conducted in shallow water with tidal current between 0 to 0.5 knots, and ratio of water depth to draft (H/d) between 1.2 to 1.5.

Manoeuvring during tests using full-mission type ship-handling simulator was the responsibility of the pilot routinely performing berthing/sailing operations at the berth. The master witnessed the manoeuvring test, and together with the pilot in charge of manoeuvring, subjective judgements including control margin for each manoeuvring phase were obtained through questionnaire surveys. On an average, about 10 masters witnessed one test. The total judgements for the verification tests were based on assessments from over 3200 persons for each manoeuvring phase.

Table 3. Ships for which test were conducted by full-mission type ship-handling simulator

Tank Cap.[1]	Tank Type	Loa	Lpp	B[2]	Draft Load	Draft Ballst[3]	Axis[4]
147K[5]	Moss	289m	277m 4	9m	11.8m	9.4m	1
154K	Moss	288m	277m	43m	11.5m	9.4m	1
155K	CCM[6]	288m	275m	49m	11.6m	9.5m	1
177K	Moss	300m	287m	52m	11.5m	9.5m	1
170K	Mem[7]	291m	279m	45m	11.5m	9.7m	1
180K	CCM	298m	293m	49m	11.5m	9.8m	2
217K	Mem	315m	302m	50m	12.0m	9.5m	2
266K	Mem	345m	332m	54m	12.0m	9.6m	2

[1]Cap: Capacity [2]B: Breadth [3]Ballst: Ballast
[4]Axis: Number of Propellers [5]K: Thousand
[6]CCM: Continuous Covered Moss
[7]Mem: Membrane

Fig. 4 shows the full-mission type ship-handling simulator used in the tests. Fig. 6 is the computer-graphics generated image of a typical ship subjected to tests.

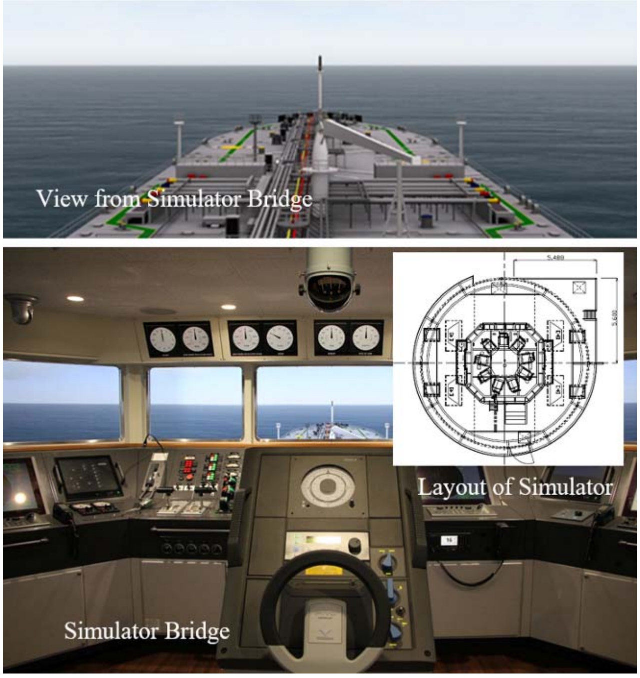

Figure 4. JMS full-mission type ship-handling simulator (360°-screen with visibility in the downward direction) used in the tests.

Figure 5. Computer graphics-generated image of LNG carrier used in the manoeuvring simulation tests (217K Membrane)

Berthing and sailing tests included manoeuvring for approach; the five phases shown in Table 4 were considered as the manoeuvring phases for the survey questionnaire to be responded to by the masters present and the ship operators.

A five-stage judgement was made with the assessment divided into five judgement categories shown in Table 5 for each of the five manoeuvring phases for which the questionnaire survey was given to the pilots performing and the masters witnessing the manoeuvres.

Table 4. Manoeuvring phases

Berthing Manoeuvre	Sailing Manoeuvre
Course-keeping phase	Lateral shifting phase
Course-altering phase	Standstill turning phase re
Speed-reducing phase	Course change phase
Standstill turning phase	Course-keeping phase
Lateral shifting phase	

Table 5 Control Margin level of subjective judgement on manoeuvring sensed by the ship operators and the persons witnessing the manoeuvres

Assessment category	Control Margin level of subjective judgement	
5	Adequate margin remains	Acceptable
4	Margin exists	margin level
3	Allowable margin level	
2	Margin does not exist	Unacceptable
1	No margin	margin level

4 OBJECTIVE MANOEUVRING CRITERIA OF SAFETY ASESSMENT IN SHALLOW WATER

Motion conditions of manoeuvring phases from the simulation test results introduced in the previous section and the responses of subjective judgement from ship operators were analyzed. Not only simulation test results, but also interviews with pilots and masters were conducted during the 15 on-board studies introduced in "Sec. 2.2 Verification of manoeuvring mathematical model in shallow water by boarding and studying ships" were also analyzed.

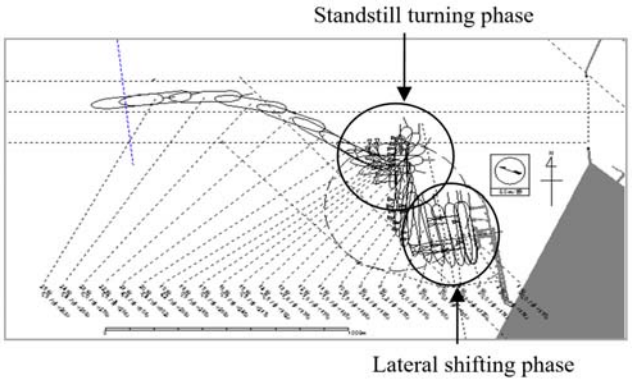

Figure 6. Example of sailing manoeuvre track chart

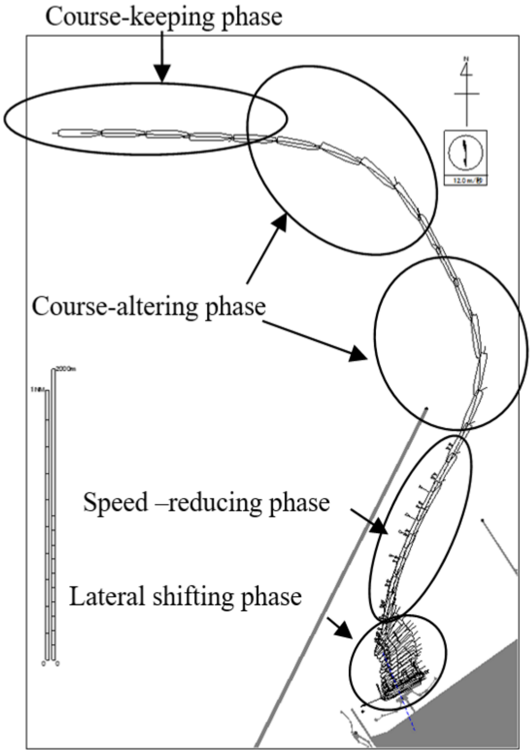

Figure 7. Example of berthing manoeuvre track chart

The criteria analyzed here are based mainly on the test results of LNG carriers of overall length of 300 m approximately; however, the results may be applied to other ship types of almost equivalent class.

Fig. 6 and Fig. 7 show the manoeuvring phases and typical track charts according to the ship-handling simulator test.

4.1 *Course-keeping phase*

Drift angle, lateral (shift) speed, deviation from planned course may be considered as motion conditions expressing the course-keeping phase, while main engine rpm, ship speed and rudder angle may be considered as control variables. Since it has been reported that the ease/difficulty of manoeuvre felt by the ship operator has a high correlation with the drift angle, the drift angle in the slow ahead condition (about 8 knots speed through the water) is considered the typical phase for course-keeping manoeuvre.

Fig. 8 shows the relationship between drift angle in the course-keeping phase and the subjective judgment of the ship operators for LNG carrier. The subjective judgment has been plotted in the figure as the average value of about 10 assessors for each test. (■ represent the results of interview related to the degree of margin in on-board studies of full-scale ships)

As clarified in the tank test results (Table 2) in Section 2, LNG ships show the trend of improved course-keeping ability in shallow water. Generally, the wind-receiving area and wind effects are large in LNG carriers; however, although the course-keeping manoeuvring tests shown in Fig. 8 include many cases of wind speed exceeding 10 m/sec, there were only a few assessed cases in which the control margin was small.

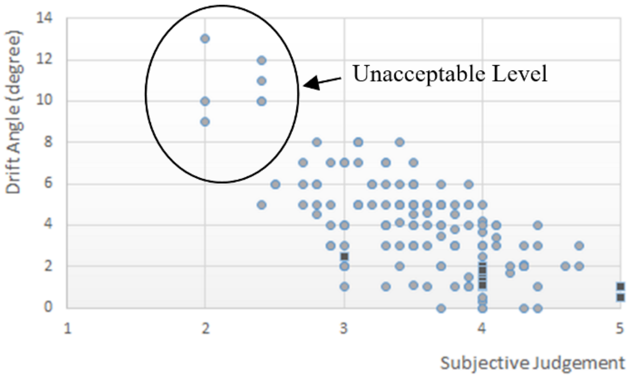

Figure 8. Relationship between drift angle in the course-keeping phase and the subjective judgment of the ship operators for LNG carrier

From these results, it can be observed that the average value of subjective judgement is 2 (margin is small) when the drift angle exceeds 8 degrees. The criterion for manoeuvrability in shallow water may therefore be considered as acceptable within a drift angle of 8 degrees in the slow ahead condition of the main engine.

4.2 *Course-altering phase*

Turn rate and deviation from planned course may be considered as motion conditions expressing the course-altering phase, while main engine rpm, ship speed and rudder angle may be considered as control variables. Among these variables, the ship operator can sense the rudder effect only from the turn rate. Fig. 9 shows the relationship between turn rate in the course-altering phase and the subjective judgment of the ship operators for LNG carrier.

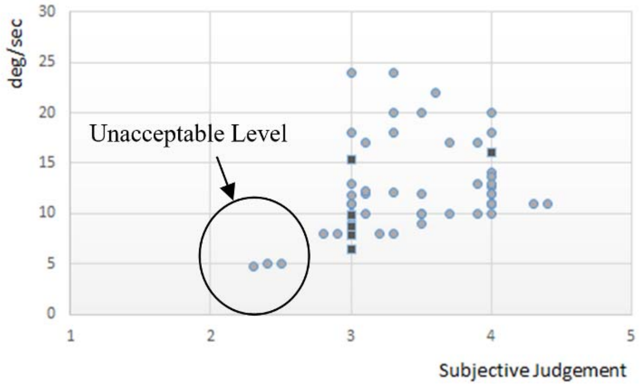

Figure 9. Relationship between turn rate in the course-altering phase and the subjective judgment of the ship operators for LNG carrier

The subjective judgment has been plotted in the figure as the average value of about 10 assessors for each test. At a turn rate of 5 degrees/minute, the average value of subjective judgement is less than 2.5 (small control margin). However, at the turn rate of 8 degrees/minute, the average value of subjective judgement is greater than 3 (acceptable margin level). The course-altering phase mentioned here refers to course-altering manoeuvre using main engine and rudder only of one's own ship.

4.3 *Lateral-shifting phase*

The lateral shift speed during sailing using tugboat, etc., is taken as the index of lateral shift manoeuvre. For manoeuvring with the control target of lateral shift speed as 10 m/sec. or less at the final stage of berthing, it is difficult to make this lateral shift speed the index of control margin. The method of unberthing to express control margin as the index of lateral shift speed is appropriate. Fig. 10 shows the relationship between maximum lateral shift speed and the subjective judgement value of control margin in the lateral-shift phase during unberthing. Fig. 11 shows the relationship between the lateral shift speed and the subjective judgement value three minutes after the start of the lateral shift. Ship operators who perform sailing manoeuvres slowly are many, and so are ship operators who feel that it may be allowed even if the lateral shift speed does not increase after three minutes have elapsed. Finally, if the lateral shift speed reaches 20 cm/sec., the state when the allowable control level is sensed can be understood. In other words, to ensure control margin against external forces such as wind and tidal current, provision of tugs or thrusters may be necessary if the lateral shift speed increases above 20 cm/sec.

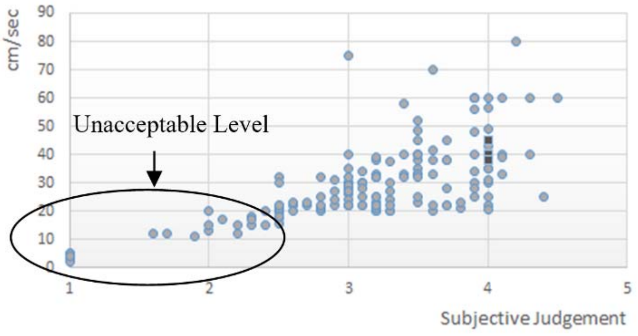

Figure 10. Relationship between maximum lateral shift speed and the subjective judgement value of control margin

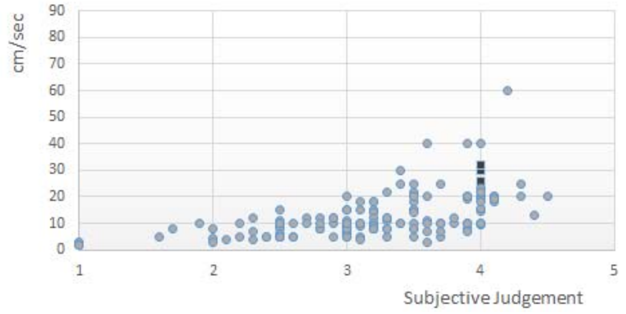

Figure 11. Relationship between the lateral shift speed and the subjective judgement value of control margin three minutes after the start of the lateral shift

4.4 *Speed-reducing phase*

Fig. 12 shows the relationship between speed reduction (knots/min.) during reduced speed manoeuvring and subjective value of control margin.

It can be observed that if the speed can be reduced by more than 0.2 knots/min., the ship operator can sense the acceptable margin level. For these tests, the main engine of the ship and tugs were used as the speed-reducing means.

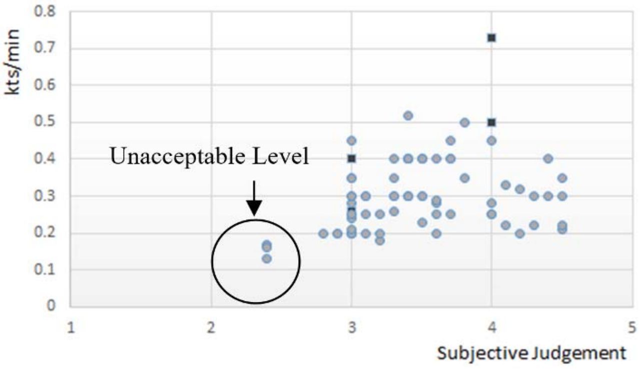

Figure 12. Relationship between the speed reduction (knots/min.) and the subjective value of control margin

4.5 *Standstill-turning phase*

Fig. 13 shows the relationship between turn rate and subjective value of control margin in the standstill turning phase using tugboat. In many of the tests standstill turning occurred after un-berthing, and although many test cases were at wind speeds below

15 m/sec., turning could be carried out within a turning area of twice the overall length in all the cases. Moreover, the turn rate was greater than 10 degrees/sec. and the subjective value of control margin was also at the acceptable level.

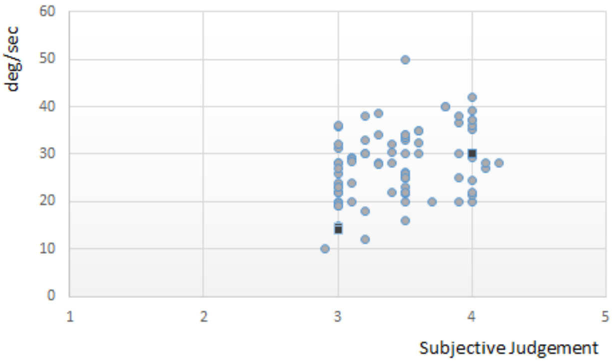

Figure 13. Relationship between turn rate and subjective value of control margin in the standstill turning phase using tugboat

5 CONCLUSIONS

Conclusions of this report are summarized below.

1 The importance of verifying manoeuvring mathematical models in shallow water was pointed out for the safety assessment of manoeuvring in port using ship-handling simulator.

2 Instances of verification of manoeuvring mathematical models after conducting tank tests were introduced for verifying the manoeuvring simulation mathematical models in shallow water. Measurements of motion conditions in shallow water with full-scale ships for fifteen times and instances of verification of mathematical models of simulator were introduced.
Differing instances of manoeuvring performance were found because of the differences in L/B and aft hull shapes even for almost the same length (Lpp) from the results of tank tests in shallow water. For twin-screw ships with the hull forms introduced earlier, it was confirmed that when H/d became 1.2, the tactical diameter increased relatively and course-keeping ability improved.

3 Safety assessment tests were carried out with full-mission type ship-handling simulator using manoeuvring mathematical model in shallow water on several LNG carriers, the reproducibility of which was already verified. The test cases amounted to 325.

4 The findings of acceptable criteria in shallow water obtained from the results of 325 cases of ship-handling simulation tests and the results of motion condition measurements of full-scale ships carried out 15 times are as given below. Assessment of ship-handling simulation tests was made from the results assessed by about 10 masters and pilots per case. Criteria have been formulated according to the perceptions of more than 3200 masters, pilots and ship operators.

Acceptable manoeuvring criteria

– Course-keeping phase:
Drift angle under 8 degrees in the main engine slow ahead condition
– Course-altering phase:
Turn rate greater than 8 degrees/min. in the main engine slow ahead condition
– Lateral-shifting phase:
Lateral shift speed greater than 20 cm/sec. at start
– Speed-reducing phase:
Greater than 0.2 knots/min.
– Standstill-turning phase:
Turn rate greater than 10 degrees/min.

ACKNOWLEFGMENTS

This research is a compilation of the findings of studies and tests continuously implemented over many years by a team consisting of large number of staff members led by the author in the company presently employed.

The author is grateful to the cooperation given by all concerned personnel.

The author would like to express his gratitude to concerned staff members and other related personnel.

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