안전항해 관점에서의 항만설계 제요소의 분석 및 기존 항만설계 기준들에 대한 비교

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Analysis on the Factors influencing Port Design and Comparison of the current Port Design Criteria in terms of Safe Navigation

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요 약

항만 설계에 영향을 미치는 네가지 중요요인인 선박요인, 인간요인, 환경요인 및 항로표지요인들이 실제 항만 및 수로의 설계에 미치는 구체적인 영향들을 각 요인별로 분석하였다. 아울러 항만 및 수로 설계요소인 수심, 항로의 폭, 항로의 배치, 선회수역의 크기 및 부두의 배치 문제에 대한 분석을 기하였다. 그리고, 항만 및 수로의 설계 문제에 관한 최근의 연구결과들과 각국의 설계 Guideline들을 수집하여 특히, 항로의 폭, 항로의 배치 그리고 선회수역의 크기에 대해 그 내용을 비교하고 분석하였다. 이들 연구 결과들과 항만 설계

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기준들은 연구 방법과 설계 기준을 마련한 기구들에 따라 그 내용의 차이가 있음이 확인되었다. 따라서 이들 기준들은 항만 설계를 위한 1차 계획 수립시에만 활용되고 세부적인 설계는 1차 설계 후 항만 설계 시뮬레이션 기법을 통한 검정을 거쳐야만 안전한 항만의 설계 및 개발이 이루어질 수 있다는 것이 확인되었다.

1. Introduction

One of the problems caused by current changes in the shipping industry is that new types of ships are being built, which are, for example, significantly larger(VLCCs) or faster(container ships) than the ships that established ports have been designed to cater for. The advent of these new types of ships, and the economic advantage of accommodating oversized vessels in existing ports and navigational waterways has focused the attention of the ship operators, port authorities and government agencies on the need for improvements in the safety of navigation in port waterways. When designing a port or a channel, safety and efficiency should receive primary consideration before the project is optimised with respect to cost. Safety of the project will depend on the size and manoeuvrability of the vessels using the waterway, dimensions and alignment of the waterway, availability and efficiency of aids to navigation, environmental effects of winds, currents and waves, and experience and judgement of the pilots.

In this respect, a comprehensive literature survey has been carried out to determine the factors which influence port and waterway design in terms of the safe operation of a ship. From the literature survey, parameters influencing port and channel design such as ship factors, human factors, environmental factors and aids to navigation factors are outlined and analyzed. In addition, port and channel design elements such as depth, width of channels, alignment of channels, the size of manoeuvring area and jetty alignment which can be assessed quantitatively were also discussed and analyzed.

The studies carried out over recent years and recommendations made on port design and channel alignment were compared and discussed, with particular reference to the width of channels, alignment of channels and the size of manoeuvring area. Recommendations on port and waterway design made by different maritime organizations throughout the world such as Permanent International Association of Navigational Congress(PIANC), Canadian marine engineers, Japanese civil engineers and U. S. Army Corps of Engineers were collected, compared and analyzed.

2. Factors Influencing Port Design and Channel Alignment

Vessel differs greatly in behavior in relation to their environments, which are physical parameters like winds, currents and waves. Vessel behavior in relation to acting forces does not only refer to the hydrodynamic aspects, such as forces on the hull, but to the ability of the vessel to manoeuvre, including consideration of its hull, rudder, and propeller characteristics as well as special features such as thrusters.

Schuffel[1] points out that the ship operators' skill is considered to be the most critical factor with regard to the safety of the ship, in particular when accurate control of position and orientation is needed. It is reported that about 75% of shipping accidents occurs during coastal and teminal navigation and these are primarily due to human error.[2],[3] The ship operators' skill, therefore, is deemed to be of considerable importance with respect to the safety of the ship, especially in the restricted manoeuvring condition.

The ship handling abilities of ship operators depend upon their knowledge and experience, which includes the ability of correct interpretation of information obtained from the aids to navigation. The availability and accuracy of aids to navigation, therefore, are important factors which influence the safety of the ship, particularly in restricted areas.

Therefore, in summary, the optimum port design and channel layout depends on local environmental conditions, the type of vessels to be accommodated, human factors and the condition of aids to navigation.

2. 1 Ship Factors

As concern for the safety of ship operation in a port has increased due to the huge economic and environmental consequences of potential accidents of those ships of rapidly escalating size, operated or proposed for operation in a harbour and navigational waterways, ship's size and their manoeuvrability have become the most critical factors affecting port design criteria. In the meantime, studies of statistics of collisions and groundings have indicated that about one third of the total accidents could be attributed to a lack of manoeuvrability and could possibly have been avoided with improved ship response characteristics.[4] The knowledge of the manoeuvring characteristics of ships that are scheduled to use newly designed harbours, therefore, plays a key role in the design of the harbour. The degree of stability of a ship is shown in the steering characteristics curve of figure 1. The slope of this curve at the origin indicates the stability, in which negative slope is stable, positive slope is unstable and infinite slope is marginally stable. The slope depends not only upon the hull configuration but also on the type of the rudder.

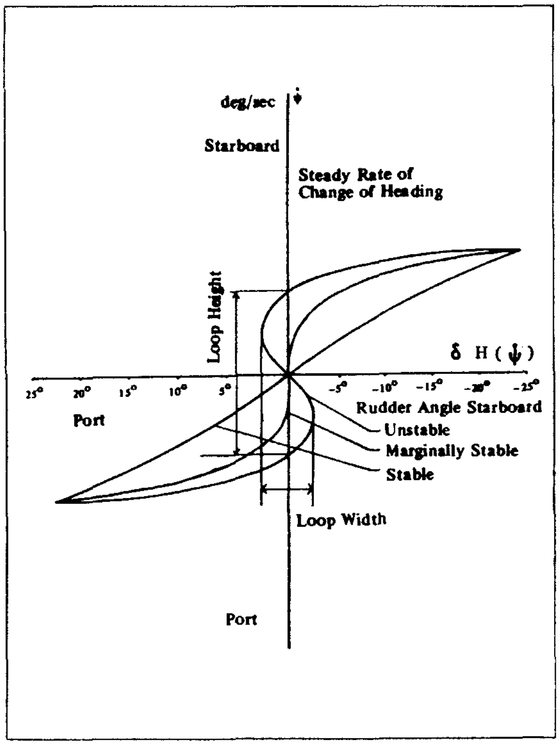

Figure 1. Steering Characteristics, r−δ Curves for Stable, Marginally Stable and Unstable Vessels. (Source : Reference [4])

Movement of unassisted vessels generally is controlled by the action of propellers and rudders located near the stern of the vessel. The controllability of the vessel also depends on the speed of the vessel, and availability of bow thrusters or tug assistance. Manoeuvring a vessel at low speeds in restricted channels tends to be more difficult as the size of the vessel increases. At high speeds, the control of a vessel can also be difficult in restricted channels because of the limited space and time available for manoeuvring and the effects of bank suction and squat on steering.

The influence of the rudder which should be taken into consideration with the ship's configuration is the propeller-rudder-hull interactions. The rudder effectiveness, for example, depends on the size and location of the rudder, number of rudders, and type, location and number of propellers, the hull configuration of the ship and details of stern profile, and clearance between the top of the rudder and stern overhang, etc.. Handling characteristics of vessels with twin screws and a single rudder are generally poor compared with vessels that have twin screws with rudders of large area located directly in the streamline of each propeller.[6] Rudder effectiveness is also affected by the ship's speed. In the process of entering a harbour and slowing down to berth, a ship experiences a substantial variation in rudder effectiveness and controllability. In the presence of winds and currents during the ship's deceleration phase by using reversed engine power, the rudder effectiveness is degraded significantly.

The manoeuvrability is also influenced by the configuration of the water area such as shallow water and banks. In general, when the depth/draught ratio becomes less than about 1.5, there is a rapid increase in the deep water hydrodynamic coefficients, the general tendency of which is an increase of the values with decreasing underkeel clearance. Generally, shallow water has a more significant effect on the added mass than on the added moment of inertia.[4]

Another influence on the ship's manoeuvrability caused by waterway configuration is the bank effect. A ship navigating parallel to a single vertical bank, infinitely long, encounters a suction force pulling it towards the bank together with a bow-out moment. To counteract these forces and moments, the mariner must apply helm towards the bank. For a channel, the effect from each bank is superimposed and is inversely proportional to the distance from each bank. However, in reality such conditions rarely exist and the actual effect depends upon a) the speed of the ship, b) the length of the bank relative to the ship length, c) the heading of the ship relative to the bank direction, d) the height of the bank relative to the water height, e) the slope of the bank, f) asymmetry in opposite bank heights, lengths, and so on, in the channel.

Considering the fact that the manoeuvrability of a ship required to negotiate waterway is one of the most important factors to be considered in the design of a port and waterway, Atkins[7] conducted an experiment on what the actual effect of a reduction in manoeuvrability would have on safe navigation of a ship in restricted waterways. The result shows that the pilot was not able to compensate for the reduced manoeuvrability. Transit in the channel with less manoeuvrable ships resulted in greater variability in track position in the straight legs and turns. Since there is clear indication that with less manoeuvrable ships, the pilot requires more channel width for safe navigation, ship factors governing the manoeuvrability must be considered as one of the most important elements in the design of a port and waterway.

2. 2 Human Factors

The safety of the ship manoeuvre is dependent not only on the inherent characteristics of the ship itself, but also on the skill and experience of the ship operator. It has been often pointed out that human factors, that of ship operators, involving their training and judgement ; their attitude ; reaction and possible errors along with delays in the communication, especially during approach to the pier, meeting and passing of ships in the channel, are important elements which affect directly the safety of the ship in manoeuvre.[8][9][10] However, it is extremely difficult to discern how many groundings and collisions in real life can be attributed to human error or misjudgement and how many have been due to the inherent controllability of the ship. The groundings may have been originated by the pilot not changing course in time, not recognising the presence of currents or winds, or by the ship's low controllability.

As the pilot's judgement is related to his experience and skill, based on outside information, piloted controllability also depends upon the effectiveness, accuracy and reliability of various information which is obtainable from navigational aids and aids to navigation that are available to the pilot.

In the report on Human Error in Merchant Marine Safety[3], 14 factors were listed which are either major or potential causes of accidents at sea. These factors indicate that, primarily, individual and task variables do so to a lesser extent. The "top five" factors are ; inattention, ambiguous master-pilot relationship, bad bridge design, poor operational procedures and poor physical fitness. It was only a few years ago that it became obvious that the manoeuvrability of ships could be limited by human aspects. Before that time it was thought that, by training, human capability could ever be increased to handle ships in any difficult situation. Some obvious limitations of human ship operators are as follows[11]

1) One is not able to anticipate over very long time intervals. (an electronic navigation aid like a course or position predictor can be of help)

2) One is not able to detect a very small change in position. (an electronic navigation aid like a rate of turn indicator can be of help)

3) One is not able to determine how much rudder angle is needed to correct the position of the ship, because one is not able to discern to which degree a change in ship's position has been caused by a rudder angle or by other influences such as winds, currents or disturbances of compass or other electronic position indicators.

2.3 Environmental Factors-Winds, Waves, and Currents

Environmental influences such as winds, waves and currents in open-type channels and manoeuvring areas, which force ships to proceed in the yawed position in order to maintain their course and thus making vessel paths considerably wider than they would be in calm waters or in the restricted channels are considered to be one of the most important factors affecting the port and waterway design criteria.[6][10] Among these three environmental factors, wind effect was found to be the most significant one in a questionnaire by the National Maritime Institute (NMI), where 42 British pilots out of 49 admitted that in their knowledge, wind had been a prime cause of accidents.[4]

In order to maintain a steady course in the presence of strong wind, the ship must take up a yawed position heading away from course and apply a certain of helm, depending upon the ship's configuration and the intensity and direction of wind. The more the rudder is required to maintain this steady yawed condition, the less it is available to make turns and changes in course, in which case the ship's safety is severely reduced. As winds increases, however, the ship will reach a limit where the rudder is unable to maintain this steady yawed position even with maximum rudder angle. In addition, if the ship is attempting to make a turn with wind present, the rudder may not be able to counteract the wind influence and, consequently, the ship could become uncontrollable.

These wind effects depend upon the ship's configuration, the ratio of the wind speed to the ship speed and the relative wind speed. Winds from the beam and aft of beam present the most serious effects to the ship's manoeuvrability, especially when the wind speed exceeds about 10 times the ship's speed.[4] The force and moment acting on the ship's body depend upon the ship's lateral area above the water surface and its distribution, and the relative wind speed and directions. In the case of a large oil tanker which has most of its superstructure in the stern area, the ship tends to weathercock into the wind. For a LNG carrier and a container ship, the area of which is more uniformly distributed along the ship's length, when the wind is coming from the bow, the ship's bow is pushed away by the wind, while the ship's stern is pushed away by the wind from the stern. This tendency is illustrated in figure 2. The difference of these moment distributions caused by wind significantly affects the ship's controllability and the ship's safety as well.

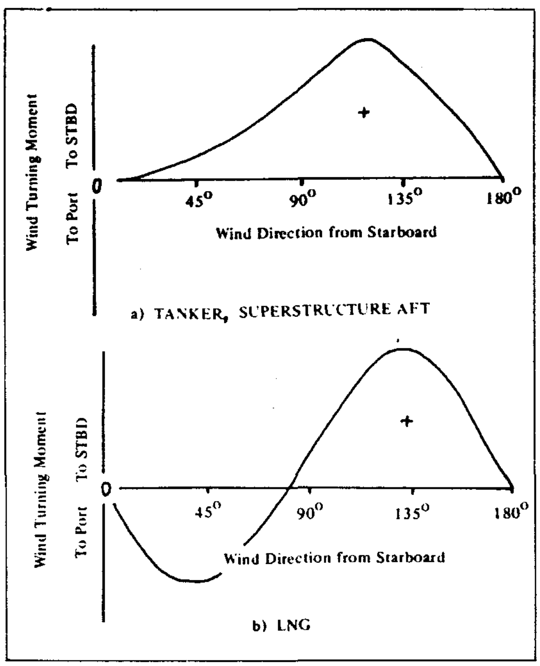

Figure 2. Comparison of General Wind Moment Distribution Between Large Tanker and LNG (Source : Reference [4])

Cross currents and wind produce navigating difficulties for vessels at low speeds and require special consideration in establishing the width of manoeuvring lanes.[12] Abrupt changes in current velocity and/or direction and formation of eddies at or in the vicinity of harbour entrance are also hazardous to navigation, and accordingly the channel should be designed to keep them down to a minimum. Typically, the most severe effect evolves from a strong following current when the ship's ground speed is high while the water speed is low, impairing manoeuvrability.[7] However, moderate currents, normally either ahead or following, do not have such a significant effect on the channel width requirement.[12]

The combination of wind and current also degrades performance in turns. Excessive windage can contribute to difficulties in turning depending on the topsides and superstructure configuration. In case where environmental conditions degrade turn performance, the channel or turning basin in the harbour should be widened appropriately. An appreciable decrease or increase of water level may also be caused by winds and waves which, in the case of decrease, could be very dangerous, particularly in entrance channels.

The effect of environmental conditions on the ship is extended to the influence on the pilot. That is, while the ship proceeds along the channel with a specific drift angle to maintain the ship's course equivalent to the channel direction, due to the presence of high drift angles, the pilot's perception of his position and therefore the accuracy of corrective orders is degraded.[7] A drift angle increases the "swept width" of the ship's path, thus occupying a wider portion of the channel (figure 3). The effect of the degradation of the pilot's control process is to increase the crosstrack variability. The net effect of environmental factors is thus a reduction in safety, placing the extreme points of the ship closer to the channel edge and increasing the crosstrack variability of those points.

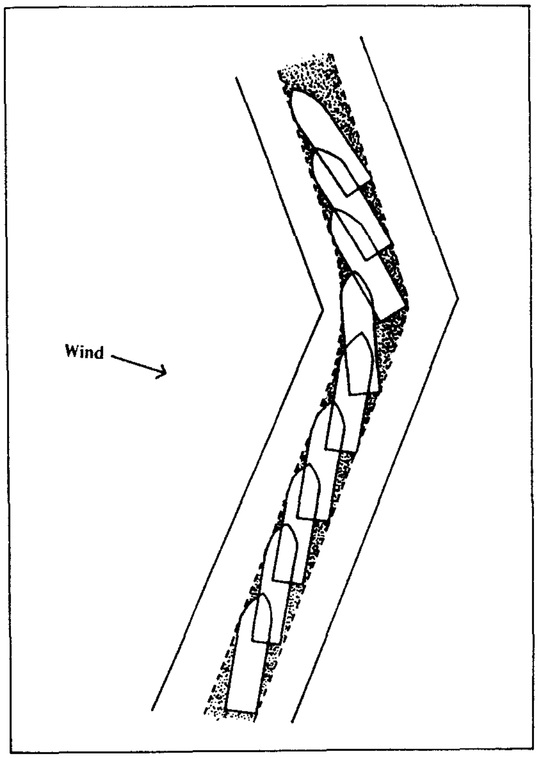

Figure 3. Swept Path in Channel Bend
(Source : Depicted by the Authors)

2. 4 Aids to Navigation Factors

The result of the experiment conducted by Atkins[7] shows that, in a comparison of the ship transits in the channel, with and without midleg buoys, the additional buoys clearly caused the mean track line to shift toward the centre of the channel away from the edges and reduced the variance between transits. One of the findings of the research on the lighting effectiveness of buoy for nighttime piloting, carried out by Smith et al. [13], is that quick flashing buoys are more effective for a ship's turn than slower flashing buoys are. This is illustrated in figure 4. These results clearly indicate that the ability of a vessel to stay within certain limits of a manoeuvring area, whether a channel or a turning basin, depends upon the availability and alignment of aids to navigation and the arrangement accuracy and reliability of those aids as well. They are of course closely connected to the human factors which react to the information collected from aids to navigation. It is, therefore, conceivable that by providing the navigator with better information through more, or enhanced, aids to navigation, a new channel could be made narrower while maintaining an adequate safety level.

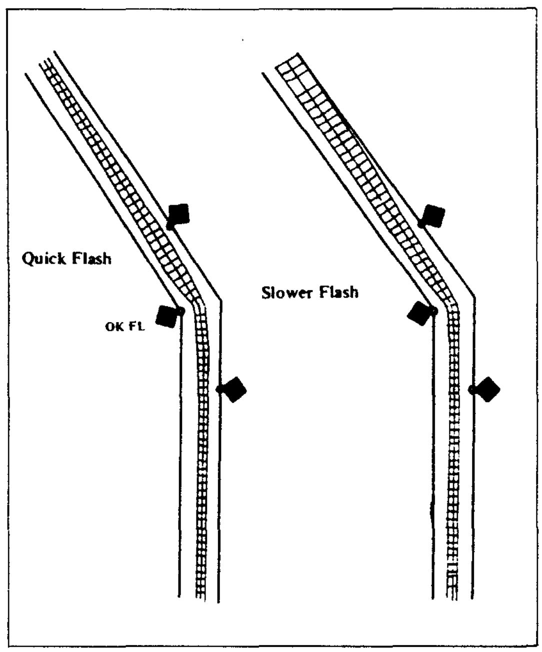

Figure 4. Effect of Characteristics of Turnpoint Buoy (Source : Reference [13])

Vessel navigational aids, such as radar, gyrocompass, depth finder and speed log, provide navigators with part of the information needed and the remainder is provided by channel and leading marks or other aids to navigation placed on the waterway. Aids to navigation which affect the port design criteria can, therefore, be categorized into shore based aids to navigation and navigational aids on board.

Since better accuracy in channel navigation increase the possibility of reducing the dimensions of channels and manoeuvring areas within a fixed safety margin, especially where unfavourable hydrographic and or environmental conditions influence the ship's path, aids to navigation which help pilots determine the correct position of the ship should not be neglected in the design of a port and waterway.

3. Elements of Port and Channel Design

Among the various elements of port and channel design which should be assessed quantitatively, the five key elements of depth ; width of channels; alignment of channels ; the size and arrangement of manoeuvring area and jetty alignment are analysed and discussed in this section.

3. 1 Depth

Depth of channels and manoeuvring areas should be enough to allow safe transit and manoeuvring of ships, but their dimension should be reasonable to avoid the excessive cost of dredging. The depth of water is one of the dimensions having a great bearing on the controllability of ships, their safety and cost of waterways and harbour maintenance. Limited channel depths can affect ship manoeuvrability because of the turbulent flow pattern produced. No precise information is available on the effect of shallow water on steering but it is generally recognized that vessels become harder to control and require large rudder angles unless speed is considerably reduced. Also, vessels operating in shallow water will require greater power and more fuel consumption than when operating in deep water and could cause movement of loose bottom material, leaving it piled up in the way of the next vessel.[6]

The depth required is usually based on the draught of the loaded design vessel plus squat, sinkage in fresh water, effect of trim and wave action, and safety and efficiency clearance, as shown in figures 5 and 6. Additional depth might be required because of the location of vessel sea water intake and to provide for advance maintenance and dredging tolerance (figure 6).

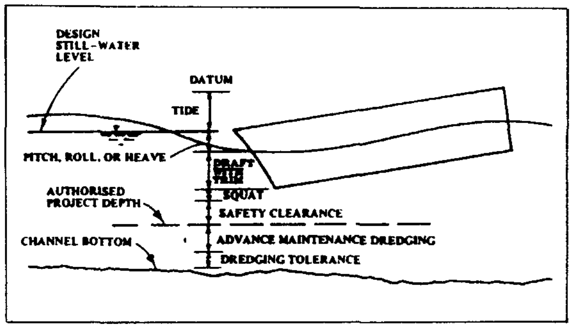

Figure 5. Depth for Entrance Channel with Wave Effects(Source : Reference [6])

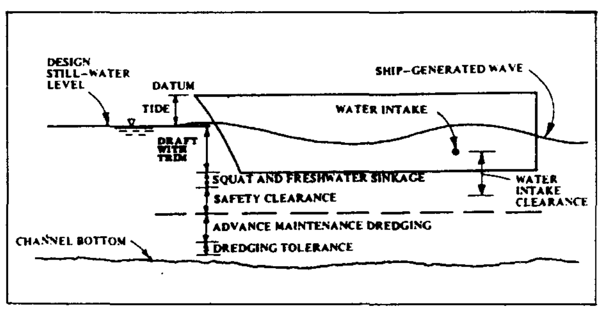

Figure 6. Depth for Interior Protected Channel (Source : Reference [6])

Squat is the downward displacement of a vessel moving along a waterway which presents side or bottom restrictions.[14] This displacement is measured as the approach of the vessel's bottom towards the sea bed. It depends on several factors including the speed of the vessel, characteristics of the channel and vessel and interaction with other ships. Sinkage in fresh water results from the decrease in the density of the water when the vessel passes from sea water to fresh water. Advance maintenance consists of dredging deeper than the channel design depth to provide for the accumulation and storage of sediment. Justification for advance maintenance is based on the reliability of the channel depth and economy of less frequent dredging. Genrally, the depths of waterways and manoeuvring areas are determined by the following[10][15] ;

1) Deepest draught of the largest ship to be received into a port.

2) Sinkage resulting from squat and/or bottom clearance.

3) Ship motions caused by swell and waves in the case of unprotected area.

As the normal manoeuvring characteristics of ships are modified by the depth of water, it is desirable, from the viewpoint of controllability of large ships, to have an adequate overdepth for good performance with minimum power consumption and effectiveness of rudder. But the difficulty is that the water depth must be at a minimum to reduce the cost of dredging and maintenance, and therefore there should be an adequate compromise between them to determine the optimum water depth.

3. 2 Width of Channels

Width of channels should be designed so as to allow the largest and least manoeuvrable ship which is expected to use the channel to transit safely and efficiently. Channel widths must allow for the width of the manoeuvring lane, clearance between vessels when passing, and bank clearances particularly in restricted channels, as shown in figure 7. Additional clearances will be required in channel entrance and in channel bends. The manoeuvring lane is the portion of the channel width within which the vessel might deviate without encroaching on the safe bank clearance or on the path of another vessel to the extent that it would create dangerous interference between the vessels. To avoid interference and danger of collision, a ship clearance lane must be provided between manoeuvring lanes for channels designed for two-way traffic. Bank clearance is the horizontal distance between the edge of the adjacent manoeuvring lane and the bottom of the side slope. Bank clearance is required to reduce or eliminate the effect of bank suction on the controllability of the vessel and the danger of colliding with the bank or grounding.

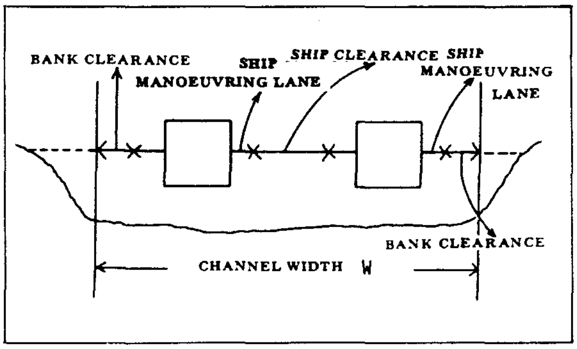

Figure 7. Representation of Channel Width (Sources : References [6], [16])

The channel width is usually measured at the toe of the side slopes or at the design depth as shown in figure 7. In general, the width of channel is a function of the following parameters [15] ;

1) The beam, speed and manoeuvrability of the design vessel

2) Whether the vessel is to pass another vessel

3) The channel depth

4) The channel alignment and whether the channel is in a restricted or wide waterway

5) The stability of channel banks

6) The winds, waves, currents and cross currents in the channel

7) Shipboard navigational aids and shoreside aids to navigation

Navigation in entrance channels is often affected adversely by strong and variable tidal currents, waves, winds, rough seas, fog and other difficulties.[6] Safe navigation will generally require an entrance channel much wider than that of the inner channel since control under such conditions will tend to be difficult for ships. When the channel end is affected by cross currents and a vessel enters into a calm water area, the width needs to be changed to take into account the conditions to which the vessel is subjected, the bow being no longer subjected to the action of the current, while the stern is still affected (figure 8). The harbour entrance must be wide enough to give access to vessels but at the same time narrow enough to limit the entrance of wave energy. The width of the entrance is often a compromise between navigational requirements and the degree of protection desirable in the harbour. The navigational requirements are related to the size of the ship to use, the density of traffic, the number of entrances, the water depth and the heights, directions and frequencies of winds, waves and currents.[15]

3.3 Alignment of Channels

A channel should be aligned to provide safe navigation without being subject to difficult manoeuvres and strong cross currents. In order to minimise initial and maintenance dredging work, the alignment of a navigation channel is usually designed to follow the course of the deeper channel in a river or estuary.

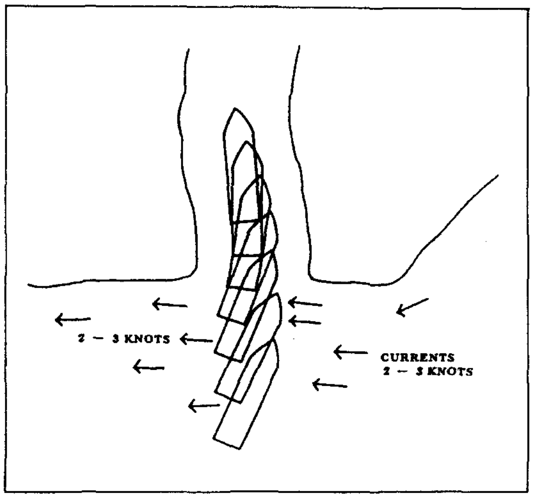

Figure 8. Ship Manoeuvring at Channel End Affected by Cross Currents (Source : Depicted by the Authors)

Since ships deviate more from their courses in bends than in straight sections, the ideal channel is free from curves. But this is rarely obtained in rivers and harbour areas where topography and layout often requires a direction change in the channel. Although bends in the alignment should be minimised as much as possible, a channel alignment comprising straight reaches with small curves between reaches would permit leading marks to be erected on the extensions and provide better channel location and pilot control. Since the swept path of a vessel making a turn is wider than that in a straight reach, a wide manoeuvring lane would be required in bends.

The width of the path would depend on a number of factors including the amount of turn, speed and manoeuvrability of the vessel, length and beam of the vessel, and the effect of waves and current. Accordingly, in addition to minimising bends, the channel should be aligned to minimise the channel width in order to avoid excessive cost of construction and maintenance, taking into account such factors as ship characteristics, environments, aids to navigation and ship operators' human capabilities.

3. 4 Manoeuvring Area

After a vessel comes into a harbour and before a vessel starts the actual berthing and mooring procedure, it usually stops or moves very slowly in the water area which is called "manoeuvring area". The manoeuvring area consists of ; 1) the necessary water area to allow vessels to reduce speed, and 2) the necessary swinging area. These water areas are, generally, protected from currents and waves. The manoeuvring area necessary to reduce the vessel's speed includes ; 1) a speed decreasing area in which the vessel's speed decreases to about three to two knots and where berthings or moorings are prepared, and 2) a stopping area where the speed reduces to zero, the vessels coming alongside with the aids of tugs.[15]

The manoeuvring area is a function of the length and manoeuvrability of the ship to use the water area. Environmental factors such as winds and currents should be considered, in addition to the pilot's human factors, when determining the size and configurations of the turning basin.

3. 5 Jetty Alignment

The jetty should be aligned to ease the ship's berthing and unberthing. Therefore, ship's characteristics such as length and draught including manoeuvrability and controllability, the use of tugs, strength and direction of the predominant winds and currents should be fully taken into account. The length of the jetty is primarily determined by the length of the ship utilizing it and the number of berths.

3. 6 The System which determines Port and Channel Design

As discussed in previous sections, factors which influence port design and channel layout could be divided into four groups which are; ship inherent factors ; environmental factors ; human factors and aids to navigation factors. When the designing factors are considered to be the input of the system, the output could be the adjustable design elements such as depth of the waterway, width of the channel, alignment of the channel, size of the turning basin and jetty alignment. This system can be drawn as figurs 9.

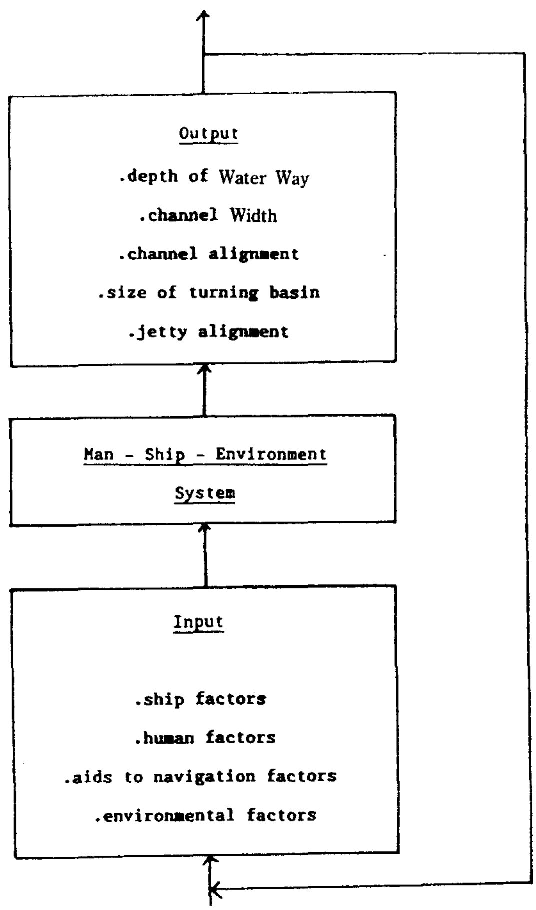

Figure 9. Port and Channel Design Determination System (Source : From discussions in section 3)

Since the inputs of the system should be taken into consideration simultaneously when designing a port or a channel, as shown in figure 9, and the presence of the human element within the ship control system requires manoeuvring experiments for the port design to be done on a real time scale, the work to optimise the design of the port and channel should be conducted in a dynamic manner, in which all the input parameters are considered at the same time. A dynamic ship simulation, in which human pilots are involved, is, therefore, thought to be one of the most practicable and useful methodology to deal with the port and waterway design work.

4. Current Research Results and Comparison of the Recommendations on Port Design and Channel Layout

Although many research papers related to the subjects of the port design and waterway dimensions have been published, there had not been any established international recommendations on these subjects until Working Group 2 of the 2nd International oil Tankers Commission (IOTC) of PIANC dealt with optimal dimensions and layouts of approaches (channels and manoeuvring areas) for large tankers in 1973.[17] The following Working Group 4 of the International Commission for the Reception of Large Ships (ICORELS), which was organised within PIANC in 1978, set up recommendations on the optimal layout and dimensions for the adjustment to large ship of maritime fairways in shallow seas, sea straits and maritime waterways in 1980.[11]

Four years before Working Group 2 of the 2nd IOTC made recommendations, in 1969, Canadian marine engineers published a standard on port design, in which they tried to provide a standard or norm, by which port design requirements could be measured or assessed. Further recommendations made by Japanese civil engineers[18], known as the General Guidelines on the Port Construction, revised in 1983 since the legislation of the Technical Standards on Port Facilities in Japan in 1978, contains new technology on port engineering. As concern for the safety of ship operation in narrow waterways and harbour areas has been increasing among those working for port operation and construction in Japan, it was tried in the Technical Standards on Port Facilities and the revised General Guide Line to introduce some general recommendations on the port design and channel alignment.

In 1983, the Engineer Manual on Hydraulic Design of Deep-draught Navigation Project, which aims to provide Guidance for the layout and design of deep-draught navigation projects, was published by U.S. Army Corps of Engineers.[6]

These recommendations made by PIANC, Canadian and Japanese civil engineers and U.S. Army Corps of Engineers dealt with the port and channel design elements such as depths, width of channels, alignment of channels, berthing area, jetty alignment and breakwater arrangement. Recommendations and current research results on the three key parameters of width of channels, alignment of channels and manoeuvring areas are compared and discussed in this section.

4. 1 Width of Channels

When making a decision on how to adapt channel and manoeuvring area widths to ship sizes and manoeuvrability, channel widths are expressed as K times the beam or length of the largest vessel navigating the channel. Although there has been a few new studies which dealt with the width of the navigational channel, the results of these studies appear to be variable. The study conducted by the probability methods based on the simulation by Maquet[19] concluded that the entry to the port Le Havre should be 10 times the beam of the largest calling ship. His additional study showed that, by eliminating certain unfavourable but highly paralysed trajectories, the width of the channel could be reduced to 8 to 9 times the ship's breadth with sufficient safety. The simulation studies conducted by the Wageningen Simulator with human pilots, using traditional aids to navigation (pairs of buoys) concluded that the minimum width of the channel should be 8 times the ship's beam.[11] Studies carried out by the company EASAMS Ltd. (maximum deviation method) concluded that,[11][15] for a ship in a channel at a speed of 10 kts, the width of the channel had to be 6 times the ship's breadth if the position of the ship's centre of gravity was known to within ± 5m, 7 times if it was known to ± 10m and 7.5 times if it was known to within ± 20m.

Meanwhile, comparing the results noted in the approaches to various ports in the various studies carried out up to 1973, the PIANC's 2nd IOTC made a few and quantitatively rough recommendations as follows[17] ;

1) Nominal width of channels should be at least five times the ship's beam even in the absence of cross currents.

2) In the case of cross currents the width of channels should be increased according to current intensity.

3) the channel radius at curves must be greater than 5 times the length of the ship. The extra width in curves was not determined.

Working Group 4 of the ICORELS of PIANC, which succeeded Working Group 2 of the 2nd IOTC, made more detailed recommendations on the optimal dimensions and layouts of approaches as follows[11] ;

1) The nominal width of a channel with one－way traffic is determined from ;

a) The maximum beam of the vessels to be received.

b) The difference (transverse component only) between the vessel's true position and the vessels position estimated by the mariner, using all kinds of information, in particular the aids to navigation.

c) The additional deviation which might occur from the moment when the deviation is first noted to the moment when the correction becomes effective.

d) The additional width needed to take into account the drifting due to cross currents is ;

$L/2 \sin\beta$

with ; L＝length of the vessel

$\tan\beta$＝(transverse component of current speed/speed of the vessel)

Cross winds should similarly be taken into account.

2) The only general recommendation which can be made at present is that the nominal width should not be smaller than 5 times the beam of the largest vessel because of the risk involved, as equipment failure (shore－based or shipborne) cannot be absolutely excluded. Under more adverse conditions, particularly in the presence of cross currents, the width should be increased accordingly.

3) On curves, the width of the channel must be greater in accordance with ;

a) The necessary extra width for the path due to the length L of the ship, thus $L^2/8R$, with R＝radius of curve

b) The supplementary reserve margin, to take into account manoeuvring difficulties especially those caused by the fact that the vessel does not respond immediately and consequently the pilot must anticipate the manoeuvre. The margin will be much more important when ;

－ the radius is short

– the angle of course change is large
– the current and wind intensity is high

The ends of zones having different widths should be joined together by straight lines ; the alteration of width should not exceed 10m for a stretch of 100m.

4) In a two way channel the passing of ships is not dangerous if the distance apart is at least twice the beam of the larger vessel, but the limited accuracy of passing manoeuvre has to be taken into account. With the present state of knowledge, the width recommended in 2 above for a one way channel should be augmented by 3–5 times the beam of the largest vessel, plus the drifting effect due to current and/or wind (length of largest vessel x SIN(maximum drift angle β)). When this provision cannot be made, simultaneous two way traffic for large vessels should not be allowed. If traffic density is high or cross traffic cannot be excluded, the risk of accidents or failures has to be taken into account, even more than in the case of a one way channel.

On the other hand, as shown in figure 10, the Canadian Port Design Manual[12] divided the width of the channel into 3 zones of ; a) manoeuvring lane, b) bank clearance, and c) clearance between vessels. In figure 10, the width of the manoeuvring lane for one–way traffic is recommended to be 1.4 times the beam of the vessel, which that for two lane and multi–lane

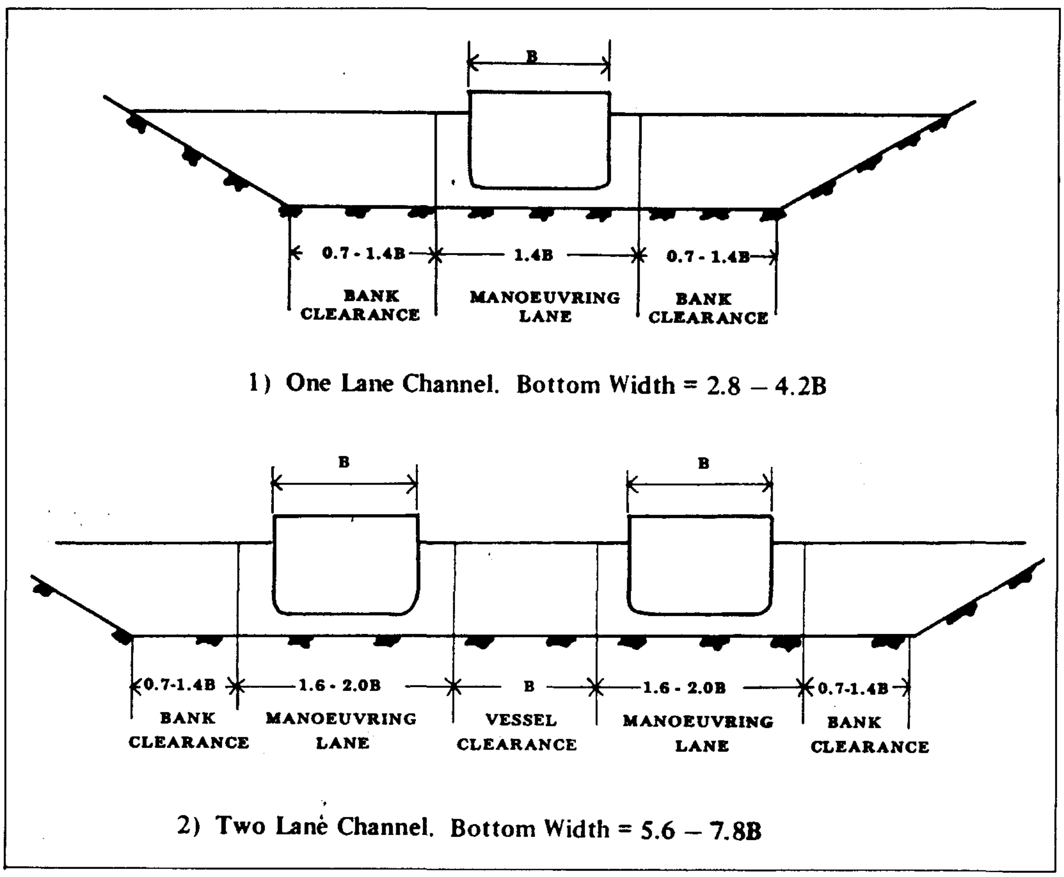

Figure 10. Channel Width Recommended by Canadian Port Design Manual (Source : Reference [12])

traffic should be 1.6–2.0 of the beam depending on the controllability of the vessel. Clearance between vessels is recommended to be equal to the beam of the largest ship. The recommended bank clearance, which depends on the controllability of the ship, speed of the ship, wind, risk of damage if the hull strikes the bank and whether the vessel is piloted or not, is 0.7 of the beam of the vessel under favourable conditions and where the vessel is piloted, and 1.4 of the beam of the vessel under unfavourable conditions, hard bank material and for an unpiloted vessel.

The U.S. guidelines established by Army Corps of Engineers[6] adopted similar concepts to the Canadian Manual in recommending the width of the channel, dividing the channel width into the manoeuvring lane, ship clearance and bank clearance. The guidelines recommend that the minimum width of a manoeuvring lane for a vessel of good manoeuvrability and under control of a skilled and diligent pilot is 160 percent of the design vessel beam, which is applicable for channels with no cross currents, cross wind, or waves that will cause the vessel to yaw. These also recommend that the manoeuvring lane width should be 200 percent of the beam under the same conditions for vessels of poor manoeuvrability. As for the clearance between ships, the guidelines recommend that the minimum width of the clearance lane is usually 80 percent of the beam of the design vessel assuming no yawing force. It is also recommended in the guidelines that in channels with no yawing forces and design vessels of good controllability, the minimum width of bank clearance should be 60 percent of the vessel beam. Where there are strong yawing forces or where the material beyond the channel edge consists of rock or other hard materials, the guidelines recommend that the width of the bank clearance might have to be increased to as much as 150 percent or more of the design vessel beam, depending on local conditions.

Meanwhile, the Japanese General Guidelines on Port Construction[18] recommend that the width of the channel should be greater than the width criteria listed in table 1, which is given in terms of ship's length.

Table 1. Width of Channels
(L ; length of the calling ship)

type	length of channel	traffic density	width of channel
two way traffic	comparatively long channel	when shipping traffic is busy	2L
		otherwise	1.5L
	otherwise	when shipping traffic is busy	1.5L
		otherwise	L
one way traffic			0.5L

(Source : Reference[18])

The work of Onodera (a Japanese researcher)[20] postulated that the required width of the Mizushima Branch seaways is determined by the following formula, on condition that no more than one 100,000 DWT class ship can pass in one way traffic with no provision for overtaking.

$$B = 1.3\ L + A$$

where, B ; required width of seaway
L ; ship's length
A ; measuring error in ship positioning

From these research results and recommendations made by different groups, it is found that there are great differences and inconsistency in the optimum dimension of the navigational channel under the present state of knowledge.

4. 2 Alignment of Channels

The design of the alignment of the approach channel is dictated by a number of factors such as the safety of navigation, the ease of manoeuvre and the harmony with other relative port facilities in addition to the cost of construction and maintenance. In terms of cost intention is mainly to achieve minimum initial and maintenance dredging activities. In most cases, the layout of a channel is more or less predetermined by geography, local conditions and circumstances. when several layouts are possible, a channel should be chosen which offers easy navigation under the most stable and clearly defined conditions.

The committee of ICORELS of PIANC pointed out that as a vessel's manoeuvrability is greatly affected by cross currents or winds, it is desirable to align the channel for the drift angle not to exceed 10－15 degrees in the channel, at least where difficult navigational situations are to be expected, taking into account the minimum speed for large vessels using the channel. It also recommends that currents be met preferably head on. The followings are the main recommendations on the channel alignment made by the ICORELS of PIANC.

1) Since course alteration are main danger point, channels with a straight layout are to be preferred. Small course changes at large intervals in compliance with the natural flow of currents are also unobjectionable if reliable aids to navigation permit a strict control of ship's movement and positions.

2) A single curve is better than a sequence of smaller curves at close intervals. However, radial steering necessitates the channel curves being well marked in such a way that position control is possible without time consuming plotting.

3) Curves should have a radius of at least 5 times the length of the largest vessel, preferably 10 times and more.

4) Intermediate straight lines between curves should have a length of at least 10 times the length of the largest vessel, If possible.

5) Narrow passages (for example, bridges) in the course of channels necessitate a well marked straight steering line of at least 5 times the length of the largest vessel on both sides.

Meanwhile, the Canadian Port Design Manual [12] recommends that curves, particularly sharp turns should be avoided. However, where they become necessary because of excessive dredging that would otherwise become inevitable, it recommends that the following minimum requirements should be applied for vessels navigating without tug assistance ;

1) Where the central angle of turn is 25° or less, the minimum radius should be at least equal to three times the length of the largest vessel.

2) For angles between 25°－35° the minimum radius should be at least equal to five times the length of the largest ship.

3) For angles in excess of 35° the minimum radius should be equal to ten times the length of the largest vessel.

4) A straight section equal to at least twice the length of the vessel should be provided between two consecutive turns.

In the meantime, the Japanese General Guidelines on Port Construction recommends that following items should be considered ;

1) Channel direction should not be at right angles to the direction of wind, waves and currents.

2) Tangent lines to the channel curve should be as parallel as possible to the channel direction.

3) The channel should be aligned to reduce the dredging required to secure necessary navigable depths for as long as possible.

4) The channel bend should be designed to

allow the vessel to make a turn in less than 30 degrees. When the turn with more than 30 degrees are needed, the channel width should be wide enough for the vessel to turn with a radius of at least 4 times the ship's length.

Meanwhile, the U.S. guidelines[6] recommend that channel curves should have a radius of at least five times the length of the longest vessel and preferably ten times or more, which coincides with the recommendation made by the ICORELS of PIANC.

As was discussed above, since the alignment of the channel is more or less predetermined by local geography and is largely dependent on local environmental conditions, recommendations on the layout of the channel were made relatively in general terms rather than specific.

4. 3 Manoeuvring Areas

Manoeuvring areas should be aligned to be adequate for safe manoeuvring, considering the arrangement of the breakwater, piers and the fairway. As the ship's speed in the manoeuvring area is very slow, the ship is greatly affected by currents and waves. Manoeuvring areas, therefore, should preferably be sheltered from currents and waves. If this is not possible, Working Group 4 of the ICORELS of PIANC points out that,[11] at least the water area necessary for losing way should be sheltered from significant cross currents and it is therefore recommended that the cross component and the longitudinal component coming from astern should not exceed 0.15m/s each. The length of the necessary manoeuvring area to allow vessels to reduce speed equals the stopping distance of the vessels, bearing in mind their speed in the access channel, plus a margin. The width of the manoeuvring area must take into account the drift during the stopping manoeuvre due in particular to reverse propulsion with single screw vessels.[15]

Working Group 4 of the ICORELS of PIANC made recommendations on the shape and dimensions of the water area for the movement of vessels and tugs during the turning manoeuvre under normal conditions, which are defined in figure 11, according to the length and characteristic of the vessel under consideration.

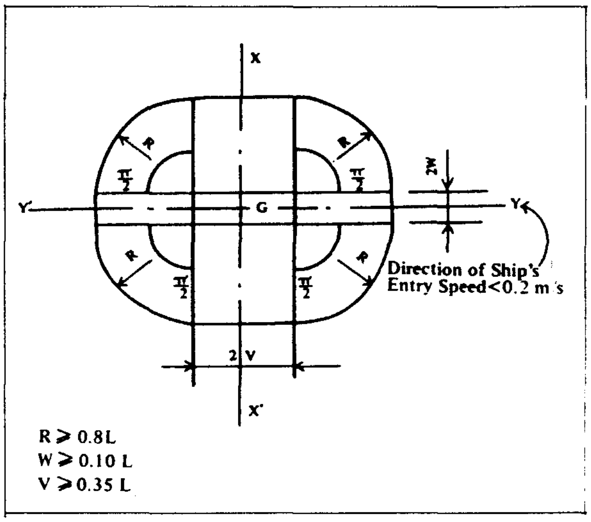

Figure 11. Dimension of Manoeuvring Area (Source : Reference [11])

In the diagram, XX' and YY' show respectively the symmetrical axes of the swinging area and V and W the components along these two axes of the maximum distance reached in comparison with G by the vessel centre, supposed to be motionless before the turning manoeuvre. In most cases, the centre G of the swinging area is situated on the theoretical course of the vessel, at the point where the vessel's speed should normally be less than 0.20m/s. In such cases, if it is possible for the vessel, with the assistance of tugs, to keep to her theoretical course and if the centre of the turning area is effectively marked, the Working Group remarks that one may deem W < 0.10L and V < 0.35L. The Working Group also points out that for all practical purposes, the area required is a turning circle with a diameter equal to twice the length of the vessel. The normal conditions mentioned above are ;

1) The vessel to be assisted by tugs adequate in number and power.

2) The current to be less than 0.10m/s and if the turning vessel is on light water line the wind to be less than 10m/s.

If the conditions in 1) are not met for any reason, the Working Group recommends that the turning axis would be determined by a circle of a diameter not less than three times the length of the vessel, to allow her to turn under her own power. If the conditions in 2) are not met, the Working Group comments that the necessary area for the movement of the vessel and tugs during the turning manoeuvre should take into account the drift of the vessel during the manoeuvre.

On the other hand, the Japanese General Guideline on port construction recommend that the area of manoeuvring to ease the ship's turning should be determined according to the standard shown in table 2. The Canadian manual and U.S. guideline did not deal with manoeuvring areas, mainly dealing with recommendations on channel design and alignment.

Table 2. Size of Turning Basin recommended by Japanese Guideline

(L ; ship's length)

type of turning	area
turning by her own power	circle of diameter 3L
turning assisted by tug boats or anchor operation	circle of diameter 2L

(Source : Reference[18]).

5. Conclusions

From the literature survey carried out to determine the factors influencing port and waterway design, it was found that the port and channel manoeuvring areas required for safe and efficient movement of vessels depend on the size and manoeuvrability of the vessels, environmental conditions such as winds, waves and currents, aids to navigation and the human's ability to control the vessel. Since these factors should be treated simultaneously when designing a port or channel, and the presence of the human element within the ship control system requires manoeuvring experiments for the port design to be done on a real time scale, a dynamic ship simulation, in which human pilots are involved, is regarded as one of the most useful method within the current state of knowledge.

Although the studies carried out over recent years have provided much new information about channel widths, alignment of channels and the size of the manoeuvring area, they do not appear to be consistent in their results. In addition, port design elements such as the width and alignment of the channel vary over a wide range, as a result of variations in local conditions and type of traffic accommodated. The recommendations made by the maritime or marine related engineering organisations over the world, therefore, do not offer decisive optimal design criteria, but provide port designers with only the minimum standards required, which can be utilised at the initial stage of the planning, and are all different. For example, recommended channel widths differ considerably according to the research group and recommending organisations, and the methodologies implemented. Table 3 shows the differences of the recommended channel widths, which were discussed in the previous section.

As shown in table 3, while Japanese General Guidelines recommend that 0.5L is the minimum width, which could be 3 to 6B according to the L/B ratio, the research carried out by J. F.

Table 3. Differences of Recommended Channel Widths

research group	recommended width	remarks
PIANC 2nd IOTC	4B	for oil tankers
Working Group 4 PIANC	5B	general recommendations
J.F.Maquet	10B(8-9B)	probability on simulation
Research by Wegeningen Simulator	8B	simulation by human pilots
EASAMS Ltd.	6-7.5B	maximum deviation method
Japanese General Guidelines	0.5L(3-6B)	guidelines
S.Onodera	1.3L+A	

(Source : From section 4)

Maquet by the simulation probability method concluded that 10B is the minimum width. Even more, the research conducted by the statistical method based on the probability of a grounding by Witt[21] postulates that the total minimum channel width can be estimated to be 12 times the beam of the ship. One more question arising here is whether such a width should be represented by the ship's beam or else by the ship's length as with the Japanese case, or even whether it should be represented by combining them or including more parameters.

Additional studies to confirm the validity of findings and to resolve their apparent inconsistency and possibly to achieve a reduction of recommended widths associated with appropriate aids to navigation and improved manoeuvrability are, therefore, seen to be necessary. In addition, it appears to be necessary to examine each port or channel development project by the ship simulation methodology, after initial design is drafted based on the recommendations given by various organisations, according to its environmental conditions and geography, and the size and manoeuvrability of the vessels to be accommodated.

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