Effect of Cross Water Currents on Ships: The State of Art Review

Gamal H. Elsaeed

Professor, Civil Engineering Department, Faculty of Engineering, Shobra, Banha University, Egypt.

A R T I C L E I N F O	A B S T R A C T
	A representative design ship was chosen for studying the effect of cross water currents on navigational ships based on statistical analysis of the available data for ship units along the River Nile, Egypt. A geometrical wooden ship model of a design representative prototype was tested in a rectangular flume at the Hydraulics Research Institute (HRI). The aim of this study is to provide operational traffic safety for passing ships along the River Nile, Egypt and to accomplish suitable designs of outfall structures, the proper design of guide pier downstream barrage components, or to verify the safe navigable path through bends.

INTRODUCTION

Acting cross currents on inland navigation units can cause or contribute to deflect ship bow which may lead to shifting or rotating the ship. These cross currents can be encountered at river crossings, stream bends, the intake and outlet structures of water plants, the inlet of branched canals and in the approach zones to navigation locks. The effect of such currents leads to increased travel time and power required for moving towards the upstream direction and possibly accident hazards in the case of empty barges. The stability of inland navigation units would be particularly dependent on the developed flow field at the outlet zone of cross water currents, which is due to the lateral hydrodynamic forces on the ship. Therefore, understanding the effect of prevailing lateral hydrodynamic forces would undoubtedly help in postponing ship steering and manoeuvrability while approaching the field of cross water currents.

Problem Description:

The ship bow is deflected for a moment while entering the cross current influenced zone as the hydrodynamic forces and the resultant moments are affecting the ship. Rotation then takes place and increases according to further ship entry into the cross current influenced zone. Furthermore, a ship is transversely displaced when the cross currents are regularly concentrated on the ship's centre of gravity. Thus, the ship rotates in the opposite direction with reduced transverse movement when leaving the cross currents influenced zone, as shown in Figure (1). This deviation may reach two times the ship's width and/or rotation in the vertical ship axis, (Ross, G., 1984). As a result to this shift in the ship's course, collision hazards may take place to other nearby passing ships. Therefore, the maximum allowable cross current velocity is defined as that velocity for which the navigational ship doesn't go out from its permitted manoeuvring lane.

Manoeuvring Lane Design Approaches and Methods:

The first approach was empirically developed by McAleer, *et al*. (1963) for the design of one -and two- way navigational waterways. The approach was developed on the assumption that navigation is easiest in a straight channel and the waterway should be made up of several segments of linked straight lines by such circle arcs. In the case of one - or two- way traffic waterways, as shown in Figures (2, 3), considering that the design ship width (the beam) is limited to 100 feet, two left and right bank clearances of 150% of the beam width for each are recommended while a maneuverable lane of 180% of the beam is kept for the moving ships. Moreover, in case of two-way traffic, ship clearance of about 100% of the design ship beam is between the two maneuverable lanes along the waterway channel.

•   The second approach to develop such criterion to design such safe inland navigation waterways has been published by Wicker, C.F., (1965 and 1971). The channel width in this approach was empirically formed as a multiple of the design ship width by considering some outer effects such as the yawing forces and ship

Corresponding Author: Gamal H. Elsaeed, Professor, Civil Engineering Department, Faculty of Engineering, Shobra, Banha University, Egypt.
E-mail: sadco@sadcoegypt.com

controllability. The approach was developed for one- and two-way traffic. In this approach, the proposed arrangement for one- and two-way traffic was defined as shown in Figures (2, 3) respectively. This approach revealed that the first step for the design of waterway width is determining the required width of the maneuvering lane. This was defined - as shown in Figures (2, 3) as the channel within which the ship may easily maneuver without encroaching on the safe bank clearance or without approaching another ship too closely. Therefore, considering the width of each part of the channel element, the total inland waterway channel width can be worked out.
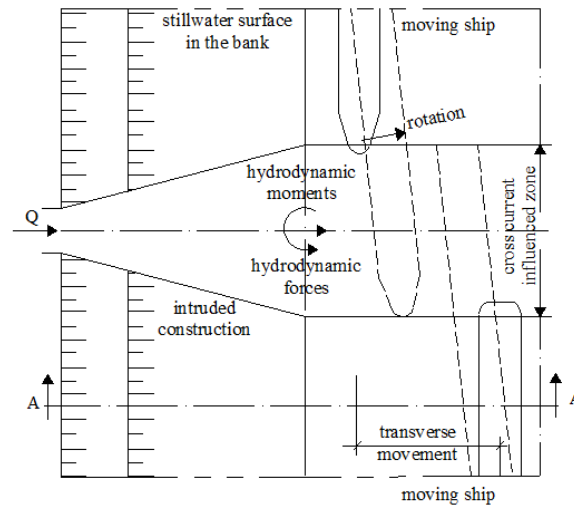

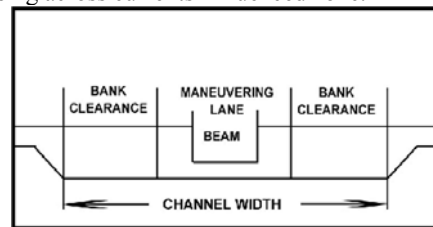**Fig. 1:** Ship movement while passing across currents influenced zone.

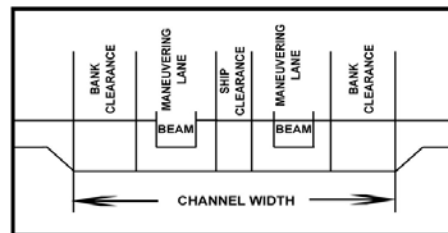**Fig. 2:** One – way traffic waterway channel.

Fig. 3: Two – way traffic waterway channel.

It can be seen from Figure (2) that the total channel width in the case of one-way traffic consists of two parts denoted as [A] and [B]. While in the case of two-way traffic, as shown in Figure (3), the waterway channel consists of three parts, which are noted as [A], [B], and [C] respectively. The principal part [A] is the width of the maneuvering lane, which was worked out by Wicker, C.F., (1965 and 1971) and is as follows:

[A] = 1.8 B_s in the case where no yawing forces are applicable,

[A] = 2.0 B_s in the case of poor controllability,

[A] = 3.0 B_s in the case where strong yawing forces are present at the port entrance,

while [B] is the bank clearance located at the two sides of the navigation channel and should be not less than 1.5 B_s for strong wind and flow currents, and the parameter [C] is the ship clearance between the maneuvering lanes in the case of two-way traffic or the distance between the inner boundaries of the maneuvering lanes, and can be equivalent to 1.0 B_s.

- The third approach, which was produced by PIANC & IAPH (1997), is based on development of two main

equations to calculate the waterway width in either of the single or two-way channels as a multiple of the beam of the design ship. The navigational channel width elements in a straight reach are shown in Figures (2, 3), which can be evaluated for a one-way channel by Eq. (1), while for a two-way navigation channel, Eq. (2) was introduced.

$$Wo = W_{BM} + \sum_{i=l}^{n} W_i + W_{Br} + W_{Bg} \qquad \text{Eq. (1)}$$

$$W_T = 2W_{BM} + 2\sum_{i=l}^{n} W_i + W_{Br} + W_{Bg} + \Sigma W_p \qquad \text{Eq. (2)}$$

Where:
– **Wo** and **W_T** are the final bottom width of the designed navigation channel for one- and two-way respectively.
– **W_{BM}** is required channel width for maneuvering of the designed ship to sail safely in very favorable environmental and operational conditions.
– **W_i** are additional channel widths due to ship speed and wave
– **W_{Br}** and WBg are the bank clearance on the "red" and "green" sides of the navigation channel
– **W_p** is the passing distance comprising the sum of a separation distance based on ship speed and an additional distance based on traffic density.

The additional values for channel width (**W_i**) depend on vessel speed, cross current, longitudinal current, and cross wind characteristics. While the basic maneuvering width (**W_{BM}**) can be worked out as a multiple of the design ship beam (B_s) as given in Table (1). Also (**W_p**) values for passing distance in the case of two-way traffic are shown in Table (2). In addition, values of each of (**W_{Br}** and **W_{Bg}**) are given in Table (3).

Table 1: Basic Maneuvering Lane.

Ship Maneuverability	Good	Moderate	Poor
Basic Maneuvering Lane, W_{BM}	$1.3B_s$	$1.5B_s$	$1.8B_s$

Table 2: Passing Distance for Two-Way Traffic.

Width for passing distance, Wp	Outer Channel exposed to open water	Inner Channel protected water
Vessel speed (knots)		
- fast > 12	$2.0 B_s$	-
- moderate >8-12	$1.6 B_s$	$1.4 B_s$
- slow 5 – 8	$1.2 B_s$	$1.0 B_s$
Encounter traffic density		
- light	0.0	0.0
- moderate	$0.2 B_s$	$0.2 B_s$
- heavy	$0.5 B_s$	$0.4 B_s$

Table 3: Additional Width for Bank Clearance.

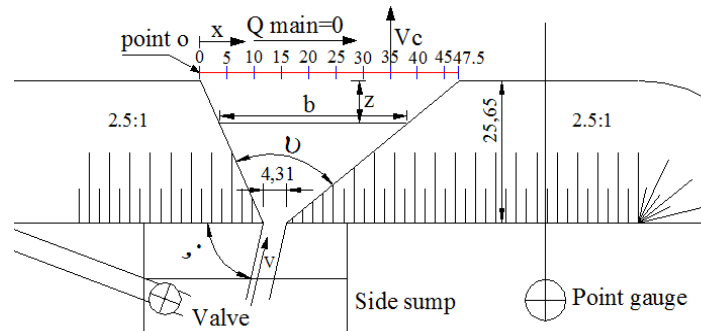| Width for bank clearance (w_{Br} or w_{Bg})	Vessel Speed	Outer Channel exposed to open water	Inner Channel protected water
Sloping channel edges and shoals	Fast	$0.7 B_s$	-
	Moderate	$0.5 B_s$	$0.5 B_s$
	Slow	$0.3 B_s$	$0.3 B_s$
Steep and hard embankments, structures:	Fast	1.3	-
	Moderate	$1.0 B_s$	$1.0 B_s$
	Slow	$0.5 B_s$	$0.5 B_s$

Developed Formulas Concerning the Effect of Cross Currents:

The first formulae was developed by (Ross, 1984), the next by (Bakowies, 1987) followed by (Pulina, 1993) and the last one, considered a state-of-the-art approach, shall be described below briefly to determine the maximum allowed cross current velocity which takes the characteristics of the ships mainly into consideration, such as the length (L), the width (B), the draught (ta), the weight (m), and the velocity of the ship (Vs). In addition, the outlet conditions such as the induced velocity by the outlet (V), the outer angle of the water exit (α), the inner angle of the outlet between its two sides (θ) and the water depth (h) are shown in Figure (4).

Pulina Formulae:

$$Vc\max. = 0.81 \cdot \frac{Vs}{L} \cdot \left[\frac{Zq \cdot mg}{0.6 \cdot z^{0.5} \cdot t_a \cdot b \cdot Cz \cdot \frac{\rho}{2}} \right]^{0.5}$$

b   = Width of the intruded construction at the location of the stillwater surface at the bank.
mg   = Entire accelerating mass of ship.
t_a = Draught of ship.
Vc max. = The maximum allowed cross current velocity at the outlet of the intruded construction.
Z   = Distance between outlet of the intruded construction and the location of the stillwater surface at the bank.
Vs   = Speed of the ship.
Zq   = Transverse movement of ship.
Cz   = Resistance parameter of ship right-angled to longitudinal axis
L   = Length of the ship.
ρ   = Density of water.

Fig. 4: Intruded construction beside navigable waterway.

    The entire accelerating mass of the ship in this equation yields from the addition of the mass of the ship and the supplementary hydrodynamic mass.
$mg = m \cdot (1 + m_w/m)$, where:

$$m_w = 2.2 \cdot m \cdot \frac{1.9^{t_a/h}}{(B/t_a)^{0.84}} \quad \text{For} \ t_a/h < 0.47 \quad \& \quad m_w = 0.814 \cdot m \cdot \frac{16^{t_a/h}}{(B/t_a)^{0.84}} \quad \text{For} \ t_a/h > 0.47$$

h   = Depth of water.
m   = Mass of ship.
m_w = Supplementary hydrodynamic mass.
B   = Width of ship.

    Additionally the resistance parameter of the ship right-angled to its longitudinal axis yields from the following function:

$$Cz = \left(17.6 \cdot \frac{3.2}{V_s} - 13.4 \right) \cdot (0.16)^{h/t_a} \geq 0.3$$

    Furthermore, the effecting transverse velocity component on the passing ship just downstream the lock chamber was comprehensively treated by Novak (1996). Different detailed design methods and techniques for filling and emptying several types of inland navigation locks were presented. In order to ensure safe and speedy entry or leaving each of the lock chambers and the navigable river, a particular plan for such an approach transition zone between the lock and the waterway was proposed as shown in Figure (5).
    The main function of the proposed approach basin is to protect the ship against the effecting cross current and even reverse flow that are usually generated downstream from a power plant or sluiceway gates of the hydraulic

structures. Also Novak (1996) assured the necessity of reducing the transverse velocity components below the maximum permissible value of about 0.35 m/s which can be considered very unfavourable for navigation and consequently may cause accidents.

In addition, mathematical investigation was carried out by Romisch (1998) in a form of generalized considerations about the effect of cross currents on inland navigation ships. The behaviour of the passing ship across homogeneous, wide-ranged fields of drift- or wind-generated currents was analytically described. In this case, the equilibrium of the passing representative ship under various effecting hydrodynamic forces was described with an expression that specifies the steady state condition. Therefore, in case of cross currents induced by water in/or outlets at the banks or inland waterways, each of the lateral shift and drift angle of the representative ship was illustrated as shown in Figure (6).
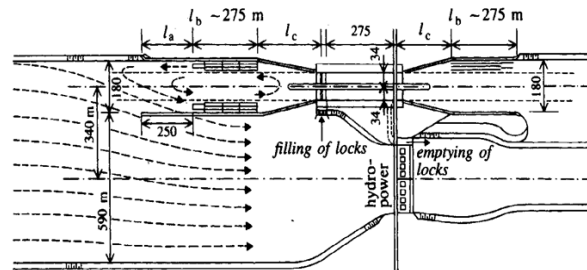

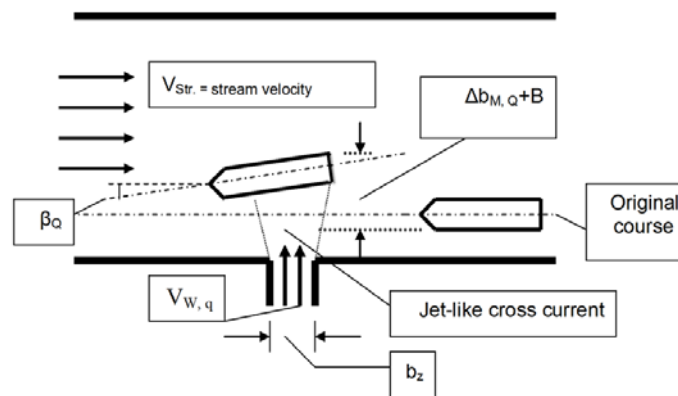**Fig. 5:** Lock with approach basin on the Danube (Novak 1996).

Fig. 6: Equilibrium condition at cross current field [Romisch, 1998].

Considering the specification of the representative ship and flow condition in each of the main waterways and the induced jet-like cross current, an expression for the maximum permissible shift that may be caused by the cross current was derived by Romisch (1998) as follows:

Romisch Formulae:

$$\frac{\Delta b_{M,Q}}{B} = 8.5 \left[2.a.\left(\frac{b_z}{L}\right).\frac{V_{w,q}}{v_s \pm v_{str}} + 0.43.\sin 60.\left(\frac{V_{w,q}}{v_s \pm v_{str}}\right) \right]$$

Where:
a   Factor depending on whether the ship is moving in the upstream direction (0.67) or moving in the downstream direction (1.00).
V_q Transverse flow velocity component at the course of the ship [m/s]
V_s Speed of the navigable unit (the ship) [m/s]
V_{str} The axial flow component velocity which is considered to be (+ ve) in the main flow direction and (– ve) in the opposite flow direction [m/s]
$\Delta b_{M,Q}$ Width of the path which the barge needs for maneuvering to compensate the effect of cross-flow velocities
B   Width of the barge

L   Length of the barge
b_z Extent of the cross flow field affecting the barge

Studies, Discussion and Analysis:

    The influence of crossing the Nederrijn and Amsterdam, Rhine canal from ship movement and river morphology aspects was shown by means of a physical modelling technique (Jansen et. al. 1979). In this case, the resulted shift in the simulated ship was monitored for various possible flow cases and river characteristics. The effect of outflow discharges from a thermal power plant and industrial drains into the River Rhine on the passing ships was investigated by (DVWK, 1984). The study was carried out with the existing prototype condition in front of an outfall structure during which the resulted ship pathway was recorded. The test showed a complete lateral ship drift of about two times the ship width and possible rotation which is due to the induced transverse momentum on the ship. The test was carried out during the real river condition with an ordinary ship speed of about 10 km/h.

    Moreover, concentration of the induced cross currents out of the rainwater collection system of Bamberg city in Germany into the main Danube canal on a moving inland ship was experimentally investigated by Tobias and Anderias (2000). To confirm the design of the constructed outlet to the navigation channel, physical modelling tests were conducted in a model flume on a scale of 1:25 during which a representative ship model was used as shown in Figure (7). The result showed that the measured cross current velocities at the outlet of the intruded construction were less than the maximum allowed cross current velocity by (Pulina, 1993). But the cross current velocities were irregularly distributed over the entire width of the intruded construction, so they redesigned the shape of the intruded construction again and documented it as the final variant of the intruded construction to get the regular distribution of the cross current velocities.
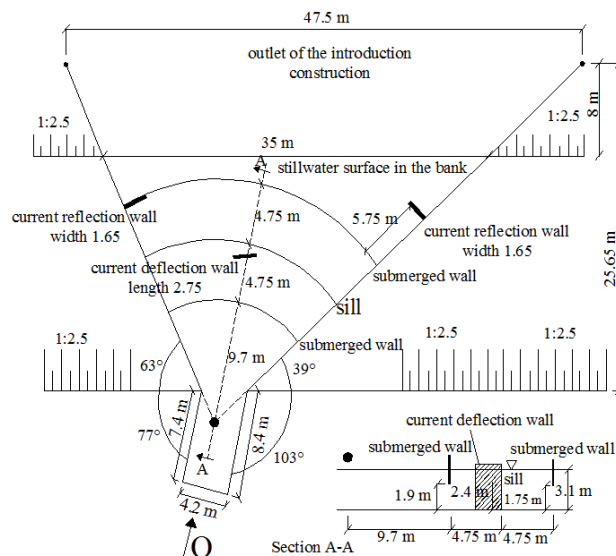
**Fig. 7:** Final variant of the introduction construction.

    The final variant of the intruded construction can be seen in Figure (7) in which two bended submerged walls as well as a sill were built-in. The first submerged wall showed a radius of 9.7 m with a distance over the bottom of 1.9 m, while the second showed a radius of 19.2 m with a distance over the bottom of 1.75 m. The sill was positioned between the two submerged walls. It had a radius of 14.45 m with a height of 2.4 m. On the other hand, two current reflection walls and a current deflection wall were used. One current reflection wall was positioned at the left side of the intruded construction at a height equivalent to the height of the front submerged wall showing a width of 1.65 m.

    More investigations to expect the ship drift due to storm water outfall through a pressurized pipe into the main Danube canal, Bamberg (Germany) at the approach to a navigation lock were carried out by Tobias Line and Claus Zimmermann (2001). In this study, an extensive physical model on a scale of 1:25 with modelled ships passing in front of the outfall structure was performed as illustrated in Figure (8).

    Comparison of the attainable model results was carried out with 3-D numerical simulations applying the Computational Fluid Dynamics (CFD) technique. Several alternatives to dissipate the induced transverse momentum on the ships were tried in such a way so that the ship pathway would not exceed a certain safety clearance of 2 m between the traffic lanes for exceptionally low ship speeds of 3 km/h (equals 1.62 Knots or 0.83 m/s). The satisfactory solution was achieved by introducing a combination of an overflow weir with a

submerged wall at a certain position that produces rather uniform flow distribution within the outfall structure.

Additional studies concerning power plant cooling systems were carried out by the HRI of the National Water Research Centre in (2001, 2003 and 2004). The studies comprised the application of physical modeling for each of Cairo North; El-Nubaria; and El-Kureimat combined cycle power plants respectively. In order to accomplish the safety of the inland navigation at the outlet structure through each of the three mentioned streams, performance of cooling systems for each study was considered as hydraulically secure and successfully achieved when the generated cross currents at the vicinity of the intake and outlet structures are less than 0.30 m/s. Such a value was decided upon by agreement between the Egyptian River Transport Authority "RTA" and the Institute in the year 2001.
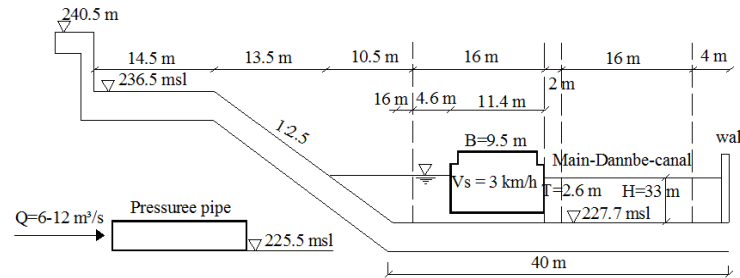
Fig. 8: Tested physical model cross section.

Fig. 9: Flow pattern downstream the additional lock at Esna barrages.

Moreover, to check different alternatives for controlling the induced cross currents downstream, the new multiple functions hydraulic structure at Esna to examine the best guide wall length for the additional lock, a physical model investigation was carried out by the Hydraulics Research Institute (2002) and reported by Mansour et. al. (2002). A Froude fixed bed physical model of an undistorted scale of 1:60 was constructed to simulate 2.1 km of the prototype reach to guarantee safe inland navigation in the vicinity of the navigation locks, and the emerged flow pattern downstream the additional lock chamber was investigated as shown in Figure (9). The model was constructed in a geometrical scale of 1 to 60 to simulate 2200 m length of the river reach including the existing new multiple functions hydraulic structure and the additional lock chamber. Mid-depth velocity fields at different locations representing various possible releases that ranged from 800 to 2900 m^3/s from powerhouses and gated sluiceways were acquired. The resulted lateral transverse velocity components upstream and downstream the modeled additional lock chamber and corresponding to each flow case were then deduced. Considering that the representative barge length (ls) is 72.0 m, and width (b$_s$) is 13.5 m, the developed formula by Romisch (1998) was reprocessed to suit the condition for the exposed transverse flow velocity component downstream the hydropower plant and sluiceway on the navigation units while reaching or leaving the navigation lock.

So the final recommendation was to extend the wing wall which will improve the safety of navigation at the vicinity of Barrages; this wing wall helps to separate the induced crosscurrunts from the navigation path. In Essna barrages, it was found that the only required modification to the original design of the additional lock is to extend the length of the wing wall to the downstream direction, while an extension of 20m was essential in order to reach the safety of navigation.

Nevertheless, an extension of the wing wall length of at least 40m was required in order to provide a wider safety margin between the induced crosscurrunts and the critical values. The wider safety margin was needed to

assure the safety of navigation in case of other passing navigational units which might navigate through the navigational channel of the additional lock to the New Esna Barrages. The Romish formula was mathematically formulated for a restricted waterway width condition and fair ship maneuverability while the acting transverse flow velocity component can be neglected. The measured cross current velocities acting on a ship were compared with those calculated from the above formula and presented along the lock wing wall starting just downstream the barrages. Using the available information about the ships and flow conditions, the above equation was applied and the permissible cross velocity was determined as 0.3 m/s in the vicinity of the guide wall downstream the new Esna barrages. However, comparison of comprised terms and description of the involved variables within the Romish formula would lead to conclude such uncertainty and complexity in applying.

Moreover, a physical modelling technique was employed by Abdel-Muttalib, M. A. (2006) at the Hydraulics Research Institute. The main purpose was to assess the effect of the outlet inclination angle of the outlet structure on the generated transverse velocity component which consequently leads to shift the pathway of the navigation units. Magnitude and direction of the resulted transverse current velocities were experimentally measured at the outlet of the intruded construction as well as at several locations over the modelled channel. Therefore, in order to assess the applicability of model tests, the attainable physical model results were compared with those deduced from the theoretical approach of the derived formula by Romisch (1998).

In addition, a numerical model was carried out by Fahmy, W. A., (2012), representing a 6.0 km straight reach symbolizing the main River Nile characteristics. The main purpose was to evaluate the effect of the hydraulic structure components arrangement of the Assuit barrages on inland navigation. Distribution of the acting transverse velocity components on the east and west lock chamber boundaries were deduced for 600 m downstream the lock. Magnitude and location of the maximum transverse velocity components were recorded for each test. The results revealed that 33.3% and 79.2% of the prevailing velocity components on west and east sections respectively exceed the maximum permissible value of 0.30 m/s. This also showed a maximum velocity component of 1.508 m/s and 0.910 m/s perpendicular to the mentioned sections when the lock chamber is surrounded by the hydropower plant and the sluiceway. Evaluation of the attainable results revealed that the most efficient and optimum hydraulic structure components arrangement is fulfilled when the navigation lock is located on the eastern river followed by the hydropower plant, gated sluiceway, and then the closure dam.

Conclusion and Recommendation:

Background knowledge on the effect of transverse flow velocity on passing ships is necessary in order to provide operational traffic safety for the navigational units. In previous years, the Waterways Administration in Germany allowed cross-water currents velocities not to exceed 0.3 m/s, (Novak, 1996). As a result of that, some studies took this value as a reference without proper studies having been done, taking into consideration all the surrounding conditions' effect on navigation.

Moreover, there were two mathematical investigated formulas concerning that point, the first having been presented by Pulina, 1993. This formulae takes the characteristics of the ships mainly into consideration, such as length, width, draught, weight, water depth, and ship speed, but it neglected many other variables which belongs to both the fairway characteristics, such as the main stream velocity and the distance between the ship and the field of cross water current, in addition to the field of cross water current characteristics, such as the induced velocity, its width, and its angle of inclination. The other one was developed by Romish, 1998 which was concerned with some parameters, such as the ship length, ship speed, the main stream velocity, the cross water current velocity, and the width of cross water current field, but it neglected other variables such as the distance between the ship and the field of cross water current, the angle of inclination of that field, the water depth, and the ship draught. Therefore, to achieve safety requirements in inland waterways, a physical model is necessary to simulate the effect of cross currents on ships, taking into consideration the above negligible variables. The suspected result of that simulation is to measure the lateral transverse movement of the navigational unit, as it is considered a main factor to ensure that the ship doesn't leave its permitted manoeuvring lane.

REFERENCES

Abd Almotaleb, M.A., 2006. "Effect of the Outflow Water on the Navigation of Water Channels", M.Sc. Thesis, Faculty of Engineering, Banha University, Civil Engineering Department, Cairo, Egypt.

Ahmed, A.F., 2004. "Inland Waterway Design Manual in Egypt", Nile Research Institute (NRI).

Anthony F. Molland, 2011. "A Guide to Ship Design, Construction and Operation", Text Book.

Bakowies, F., 1987. "Der Einflub von Querstromungen auf ein schiff bei beschrankter Fahr- Wassertiefe" Universitat Karlsruhe, Nr. 176.

Fahmy, W.A., 2012. "Effect of Barrage Components on Navigation Waterway", Ph.D. Thesis, Faculty of Engineering, Banha University, Civil Engineering Department, Cairo, Egypt.

Hydraulics Research Institute, 2001. "Testing Results of Physical model study for the New 750 MW Cairo North Power Plant", Report No. 36/2001. Delta Barrages, Egypt.

Hydraulics Research Institute, 2002. "Physical Scale Model Study for the Additional Navigation Lock For the New Isna Barrages – Final Report", Delta Barrages, Egypt, Report No. 28.

Hydraulics Research Institute, 2003. "Testing Results of Physical Model Study for El-Nubaria 2X750 MW Combined Cycle Power Plant", Report No. 16, Delta Barrages, Egypt.

Hydraulics Research Institute, 2004. "Testing Results of Physical Model Study for El-Kureimat 2X750 MW Combined Cycle Power Plant", Report No. 97/2004, Delta Barrages, Egypt.

Jansen, P. Ph., Bendegom, L. Van, Berg, J. Van den, M. de Vries and Zanen, A., Eds., 1979. "Principals of River Engineering, The Non-Tidal Alluvial River", Pitman Publishing Ltd, London, England.

McAleer, J.B., C.F. Wicker, J.R. Johnsion, 1963. "Design of Channels for Navigation", U.S. Army Engineers.

Novak, P., A.I.B. Moffat and R. Narayanan, 1996. "Hydraulic Structures", Published by E & FN Spon, An Imprint of Chapman & Hall, London, SE1, UK, Second Edition.

PIANC, 1992. "Capability of Ship Maneuvering Simulation Models for Approach Channels and Fairways in Harbors", Permanent International Association of Navigation Congresses, Report of Working Group no. 20 of Permanent Technical Committee II.

"PIANC" and "IAPH", 1997. "Final Report of the Joint Permanent International Association of Navigation Secretariat (PIANC) and International Association of Ports and Harbors (IAPH)", Approach Channels, A Guide for Design", June 1997.

Pulina, B., 1993. "Bestimmung der zulässigen Strömungsgröße für seitliche Einleitungesbauwerke an Bundeswasserstraßen (Determination of permissible cross currents for inlets arranged at the bank at waterways)", Mitteilungen der BAW, Heft 70.

Romisch, K., 1998. "River Hydraulics and Inland Navigation", Text Book.

Ross, G., 1984. "Querströmungen und Rückgabebauwerke an Wasserstraßen (Cross Currents and Inlets on Water Ways)", DVWK-Schriften, Heft 67, Verlag P. Paray, Hamburg, in German.

Sabit, A.S., 2006. "Ship Design", Text Book.

Steven A. Hughs, 1993. "Physical Models and Laboratory Techniques in Coastal Engineering", Text Book.

"Tobias Linke" and "Andreas Huesig", 2000, "Effects of cross currents induced by lateral water introductions on ship operation on inland waterways", ASCE Conf., 104(63): Seq. 1.

"Tobias Linke" and "Claus Zimmennann", 2001, "Minimizing Transverse Flow Effects on Passing Ships at Inland Waterways", ASCE Conf., Volume 104, Page 63, Seq. 1.

Wicker, C.F. (ed), 1965. "Evaluation of present State of Knowledge of factors affecting Tidal Hydraulics and Related Phenomena", Report No. 3. Committee on Tidal Hydraulics, U.S. Army Corps of Engineers, May 1965.

Wicker, C.F., 1971. "Economic Channels and Maneuvering Areas for Ships", Journal of Water Ways, Harbors and Coastal Engineering, Proc. ASCE, 97(WW3): pp. 443-454.