EFFECTS OF COASTAL DEVELOPMENT ON SHIP MANOEUVRING AND NAVIGATION

Datuk Captain Hamzah Bin Mohd Noor1, Dr. Adi Maimun2, Dr. Ahmad Khairi b. Abd Wahab3, Prof. Hadibah Ismail4, Dr. Agoes Priyanto 2 and A. Haris Muhammad2

1Managing Director, Regship Services Sdn Bhd, Johor Bahru
Email:dchamzah@yahoo.com
2Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor Bahru
Email:adi@fkm.utm.my
3Faculty of Civil Engineering, Universiti Teknologi Malaysia, Johor Bahru
Email: drakaw@gmail.com
4Coastal and Offshore Engineering Institute, Universiti Teknologi Malaysia City Campus, Kuala Lumpur
Email:hadibah@citycampus.utm.my

ABSTRACT

Coastal development, such as land reclamation or dredging, usually changes the characteristics of the coastal waterway. A common phenomena due to restricted waterway is increase in ship resistance and reduction in manoeuvrability. The restricted water inflow under the vessel, result in increased water velocity under the hull. The increase of the inflow velocity at the rudder may result in the increase of the rudder normal force or create partial vacuum in the region near propeller and rudder. Consequently, manoeuvring of ships may become erratic in this condition.

Standard for ship maneuvrabiity have been developed by International Maritime Organization (IMO) to ensure safe navigation/ship handling operation of ships. The standards provide criteria on the ship turning ability, yaw checking ability, course keeping ability and stopping ability. Where there is uncertainty in the behavior of the vessel especially in restricted waters, the use of numerical simulation for evaluating navigational risks is highly depended upon.

In this paper, firstly, the effects on water depths and currents due to coastal development will be described. Secondly, using time domain simulation approach, the manoeuvring characteristics of vessel in two scenarios, i.e. deep and shallow water are discussed. Thirdly, actual simulations demonstrating the risks involved in navigating in a restricted waterway will be demonstrated.

Keywords: coastal engineering, navigation, restricted waterway, mathematical modeling, ship manoeuvring.

1. INTRODUCTION

A common phenomena occurring during ship manoeuvring due to the restricted water can be described as follows: there is more resistance than normal due to the inflow of water to replace that displaced by the hull. Then the water flow is restricted under the vessel, so water velocity under the hull increases. Consequently the increase of the inflow velocity at the rudders results in the increase of the rudder normal forces, as well as the propeller and rudder are operating in a partial vacuum.

The standards for ship manoeuvrability have been developed by International Maritime Organization (IMO) to ensure safe operation of ships. The standards provide criteria on the ship turning ability, yaw checking ability, course keeping ability and stopping ability. In time simulation approach for the manoeuvring characteristics of vessel in restricted water, the empirically estimated hydrodynamic derivatives for ship (Case: a pusher barge) in two scenarios of deep (water depth to ship draught ratio h/T>3) and shallow water (h/T = 1.2 – 1.5) were applied, and the simulation used the Math lab Simulink Programs based on the mathematical model of ship manoeuvring.

2. MATHEMATICAL MODEL OF SHIP MANOEUVRING

As shown in Fig. 1, U is the actual ship velocity that can be decomposed in an advance velocity (u) and a transversal velocity (v). The ship has also a rotation velocity with respect to the z-axis. This axis is normal to the XY plane and passes through the ship's centre of gravity (C.G). β is the angle between U and the x-axis and it is called drift angle. Ψ is the ship's heading angle and δ is the rudder angle. X , Y and N represents the hydrodynamic force and moment acting on the mid ship of hull. These forces can be described separating into the following component from the viewpoint of the physical meaning.
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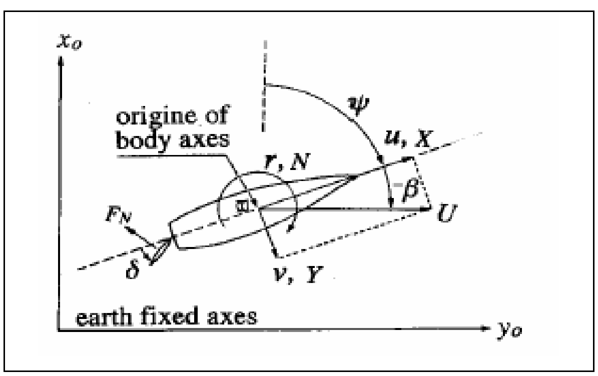

Fig. 1 : Co-ordinate system

$$X = X_H + X_R + X_P \quad (1)$$
$$Y = Y_H + Y_R + Y_P \quad (2)$$
$$N = N_H + N_R + N_P \quad (3)$$

Where, the subscripts H, P and R refer to hull, propeller and rudder respectively according to the concept of MMG expression [1,2]. X_H, Y_H and N_H are approximated by the polynomials of β and r' in Eqs. 4 – 6. These coefficients of polynomials are called the hydrodynamic derivatives.

$$X_H = 0.5\rho LTU^2 \left(X'_{\beta r}\, r' \sin\beta + X'_{uu} \cos^2 \beta\right) \quad (4)$$
$$Y_H = 0.5\rho LTU^2 \left(Y'_\beta \beta + Y'_r r' + Y'_{\beta\beta}\beta|\beta| + Y'_{rr} r'|r'| + (Y'_{\beta\beta r}\beta + Y'_{\beta rr} r')\beta r'\right) \quad (5)$$
$$N_H = 0.5\rho L^2 TU^2 \left(N'_\beta \beta + N'_r r' + N'_{\beta\beta}\beta|\beta| + N'_{rr} r'|r'| + (N'_{\beta\beta r}\beta + N'_{\beta rr} r')\beta r'\right) \quad (6)$$

X_P, Y_P, N_P and X_R, Y_R, N_R are expressed as the following formulas

$$X_P = C_{tp}(1-t_p)n^2 D_p^4 K_T(J_P) \quad (7)$$
$$Y_P = 0 \quad (8)$$
$$N_P = 0 \quad (9)$$
$$X'_P = \frac{X_P}{\frac{1}{2}\rho L d_m U^2} \quad (10)$$

Where:

$$K_T(J_P) = C_1 + C_2 J_P + C_3 {J_P}^2 \quad (11)$$
$$J_P = U \cos\beta(1 - w_P)/(nD_P) \quad (12)$$

$$\begin{aligned} w_P &= w_{P0} \exp(-4.0{\beta'_P}^2) \\ \beta'_P &= \beta - x'_p r' \\ x'_p &\cong -0.5 \end{aligned} \quad (13)$$

t_p: thrust reduction coefficient in straight forward moving, C_{tp}: constant, n: propeller revolution, D_p: propeller diameter, w_p: effective wake fraction coefficient at propeller location, w_{p0}: effective wake fraction coefficient of propeller in straight running, K_T is the thrust coefficient of a propeller force, J_P: advance coefficient, C_1, C_2, C_3: constants for propeller open characteristics.

The terms and the non-dimensional of ruder forces describes as the following.

$$X_R = -(1 - t_R)F_N \sin\delta \quad (14)$$
$$Y_R = -(1 + a_H)F_N \cos\delta \quad (15)$$
$$N_R = -(x_R + a_H x_H)F_N \cos\delta \quad (16)$$

Where :

x_R: The distant between the center of gravity of ship and center of lateral force ($x_R = x'_R L$) & x_R represents the location of rudder ($= -L/2$), x_H: The distant between the center of gravity of ship and center of lateral force ($x_H = x'_H L$), δ :

rudder angle. and t_P, t_R , a_H , and x_H are the interactive force coefficients among hull, propeller and rudder. F_N is rudder normal force and described as the following:

$$F'_N = (A_R / LT) C_N U_R^2 \sin\alpha_R \; ; \; F'_N = \frac{F_N}{\frac{1}{2}\rho L T U^2} \tag{17}$$

Where, A_R - Rudder area. C_N - The gradient of the lift coefficient of ruder, and can be approximated as the function of rudder aspect ratio K_R .

$$C_N = 6.13 K_R /(K_R + 2.25) \tag{18}$$

U_R And α_R represent the rudder inflow velocity and angle respectively.
The Eqs. 1 – 3 were rearranged in order to the set of acceleration. The set of accelerations that need to be integrated to obtain velocities and finally displacements are:

$$\dot{u} = (X + (m' + m'y)\left[0.5\rho L^2 T\right] rv) / \left\{(m' + m'x)\left[0.5\rho L^2 T\right]\right\} \tag{19}$$

$$\dot{v} = (Y - (m' + m'x)\left[0.5\rho L^2 T\right] ru) / \left\{(m' + m'y)\left[0.5\rho L^2 T\right]\right\} \tag{20}$$

$$\dot{r} = N / \left\{(I'zz + J'zz)\left[0.5\rho L^4 T\right]\right\} \tag{21}$$

The set of equations 19 – 21 could be integrated by using the ODE function as below:

$$u = \int \dot{u}\,dt \quad \text{And} \quad x = \int u\,dt \tag{22}$$

$$v = \int \dot{v}\,dt \quad \text{And} \quad y = \int v\,dt \tag{23}$$

$$r = \int \dot{r}\,dt \quad \text{And} \quad \psi = \int r\,dt \tag{24}$$

$$\ddot{\psi} = \dot{r} \;\; and \;\; \dot{\psi} = r \tag{25}$$

The motion velocities of the vessel in time domain can be obtained by single integration. After that the displacement of the motion could be obtained with single integration the equation of velocities. In time domain, Math lab Simulink programs [3] were used to do numerical simulation of the turning and zig-zag manoeuvers of the displacement of the motion.

3. NUMERICAL SIMULATION

The dimensions of ship (Case: a pusher-barge) are shown in Table. 1. The hydrodynamic derivatives were estimated based on the semi empirical formula [4,5] and the results are shown in Table. 2.

Table 1: Principal dimensions of ship (pusher and barge)

	Pusher		Barge		pusher-barge	
	Full scale	**Model**	**Full scale**	**Model**	**Full scale**	**Model**
Lal (m)	29.76	0.5952	95	1.9	117.92	2.358
Lpp (m)	25	0.5	94.5	1.89	116.71	2.3342
B (m)	10.208	0.2042	19	0.38	19	0.38
D (m)	3.7	0.0740	4.75	0.095	4.75	0.095
Volume (m^3)	542.147	0.004446	7502.5	0.0615	7805.74	0.06401
CB	0.5746	0.5746	0.8797	0.8797	0.723	0.723

Table 2: Hydrodynamic Derivatives

Symbol	Hydrodynamic Coefficients Value				
	h/d > 3	**h/d = 1.5**	**h/d = 1.4**	**h/d = 1.3**	**h/d = 1.2**
X'_{uu}	0.0162	0.0310	0.0355	0.040	0.050
$X'_{\beta r}$	0.0509	0.0509	0.0509	0.0509	0.0509
Y'_{β}	0.2646	0.7667	0.9382	1.2396	1.8822
Y'_{r}	0.0070	-0.2498	-0.3301	-0.4351	-0.5750
$Y'_{\beta\beta}$	0.5269	1.2090	1.4406	1.8385	2.6558
Y'_{rr}	-0.0141	-0.0883	-0.0461	0.0232	0.1357
$Y'_{\beta\beta r}$	-0.1239	0.4599	0.6968	1.0400	1.5457
$Y'_{\beta rr}$	0.4934	2.0065	2.5522	3.5500	5.8165
N'_{β}	0.0788	0.2515	0.3112	0.4172	0.6471
N'_{r}	-0.0366	-0.0760	-0.0895	-0.1126	-0.1593
$N'_{\beta\beta}$	0.0140	0.0685	0.0557	0.0331	-0.0051
N'_{rr}	-0.0245	-0.0605	-0.0630	-0.0647	-0.0645
$N'_{\beta\beta r}$	-0.1750	-0.4834	-0.3879	-0.2193	0.0677
$N'_{\beta rr}$	-0.0254	0.1676	0.0935	-0.0312	-0.2372

Table 3: Propeller and Rudder Parameters

Item	Deep water	Shallow water- h/T			
		1.5	**1.4**	**1.3**	**1.2**
Ship Speed, V (knots)	7	7	7	7	7
Number of propellers	2	2	2	2	2
P/D	0.74	0.74	0.74	0.74	0.74
Number of Blades, Z	4	4	4	4	4
Diameter, D (m)	2.67	2.67	2.67	2.67	2.67
Blade Area ratio, EAR	0.461	0.461	0.461	0.461	0.461
Revolutions, RPS, n	2.0636	2.5443	2.6852	2.7415	3.117
Wake fraction, w_{po}	0.299	0.369	0.3938	0.4236	0.461
Trust deduction, t	0.2	0.222	0.236	0.254	0.276
Advance ratio, Jp	0.458	0.333	0.305	0.275	0.2325
Thrust coefficient, K_T	0.173	0.218	0.2278	0.238	0.252
η_o	0.525	0.405	0.37	0.33	0.3
Thrust, T (kN)	76.825	145.17	166.36	193.29	250.835

C_0, C_1, C_2	0.3139	- 0.2736	- 0.1048	0.3139	- 0.2736		- 0.1048
Wake fraction, w_{Ro}	0.3189			0.3868	0.4105	0.4395	0.476
Rudder high, m	2.5			2.5			
Rudder Area m^2	10.00 (NP=2)			10.00 (NP=2)			
Number of Rudders	2			2			

Table. 3 shows the propeller diameter and rudders area used in the simulation. Resistance results was predicted experimentally, and the propulsion was calculated analytically. Rudders area was calculated based on Det norske Veritas (DnV) for minimum rudder area (Rules, 1975).

3.1. Turning Circles

Figs. 2 and 3 show the results of simulation of turning circles with 35^0 rudder angle to starboard and port respectively for different water depth to draught ratio h/T. It is clear from the simulation runs that the turning circles in shallow water have greater turning diameter (radius) than that in deep water which indicates that the effect of shallow water increases with the decrease in water depth to h/T=1.2. This may be due to the fact that when the water depth becomes shallower, the diffusion of the propeller slipstream becomes smaller, and the increase of the inflow velocity at the rudders results in the increase of the rudder normal forces. In addition, the hydrodynamic forces acing on the hull become larger as the depth becomes shallower.

Referring to the IMO criteria [6,7], the results of the simulations show that the Advance, A_D value for all conditions of deep and shallow water did not exceed 4.5 pusher-barge lengths. In addition, the Tactical Diameter D_T did not exceed 5 pusher-barge lengths for all conditions of deep and shallow water.

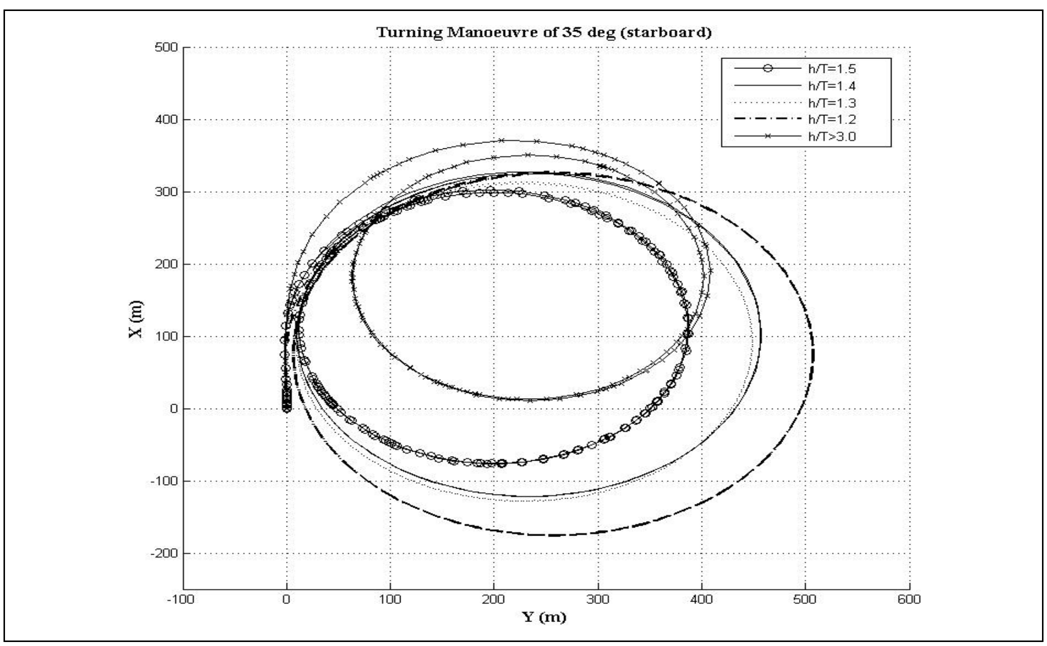

Fig. 2: Comparison of simulated turning trajectories between deep and shallow water condition [h/T= 26.5 and h/T=1.2, where Ship Speed is 7 Knots]

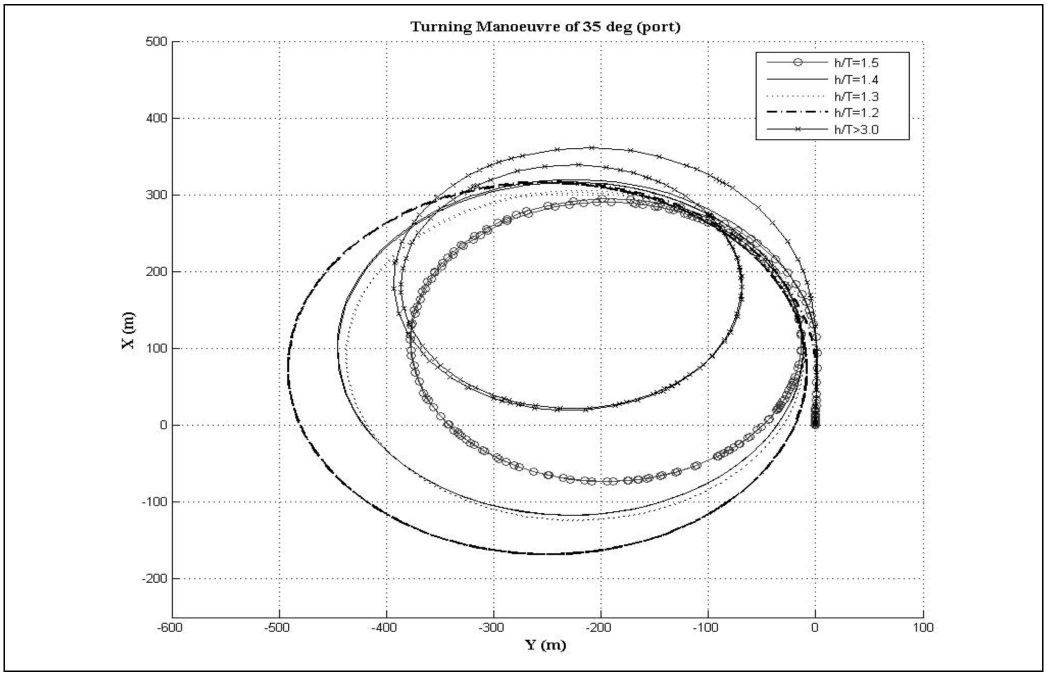

Fig. 3: Comparison of simulated turning trajectories between deep and shallow water condition [h/T= 26.5 and h/T=1.2, where Ship Speed is 7 Knots]

3.2. Zig-Zag Manoeuvres

Figures 4 and 5 show comparison of time histories of 10°/10° and 20°/20° zigzag manoeuvres. For all conditions, the IMO criteria [6,7] for zigzag manoeuvre are satisfied.

Table 4: Simulated manoeuvring results in deep water condition

Turning Circle	**IMO Criteria**	**Simulated results in deep water**	
		h/T >3.0	
		Turning Starboard (TR)	**Turning port (TL)**
Advance A_D	4.5 L_{PP}	3.0857	3.0073
Tactical Diameter D_T	5.0 L_{PP}	3.4060	3.2814
Transfer	-	1.3283	1.2778
'Z' manoeuvre	**IMO Criteria**	**h/T >3.0**	
1 st overshoot 10°/10°	15°	8° 06'	
2 nd overshoot 10°/10°	30°	15° 31'	
1 st overshoot 20°/20°	25°	8° 08'	

Table 5: Simulated manoeuvring results in shallow water conditions

Turning Circle	IMO Criteria	Simulated results in shallow water conditions							
		h/T =1.2		h/T =1.3		h/T =1.4		h/T =1.5	
		TR	TL	TR	TL	TR	TL	TR	TL
Advance A_D	4.5 L_{PP}	2.781	2.705	2.662	2.60	2.772	2.708	2.554	2.49
Tactical Diameter D_T	5.0 L_{PP}	4.330	4.201	3.824	3.73	3.885	3.789	3.285	3.20
Transfer	-	1.942	1.884	1.65	1.60	1.628	1.586	1.345	1.31
Z manoeuvre	**IMO Criteria**	**h/T =1.2**		**h/T =1.3**		**h/T =1.4**		**h/T =1.5**	
1 st overshoot 10°/10°	15°	10° 34'		16° 40'		14° 46'		16° 29'	
2 nd overshoot 10°/10°	30°	09° 59'		18° 50'		18° 22'		22° 28'	
1 st overshoot 20°/20°	25°	4° 41'		8° 13'		8° 16'		10° 44'	

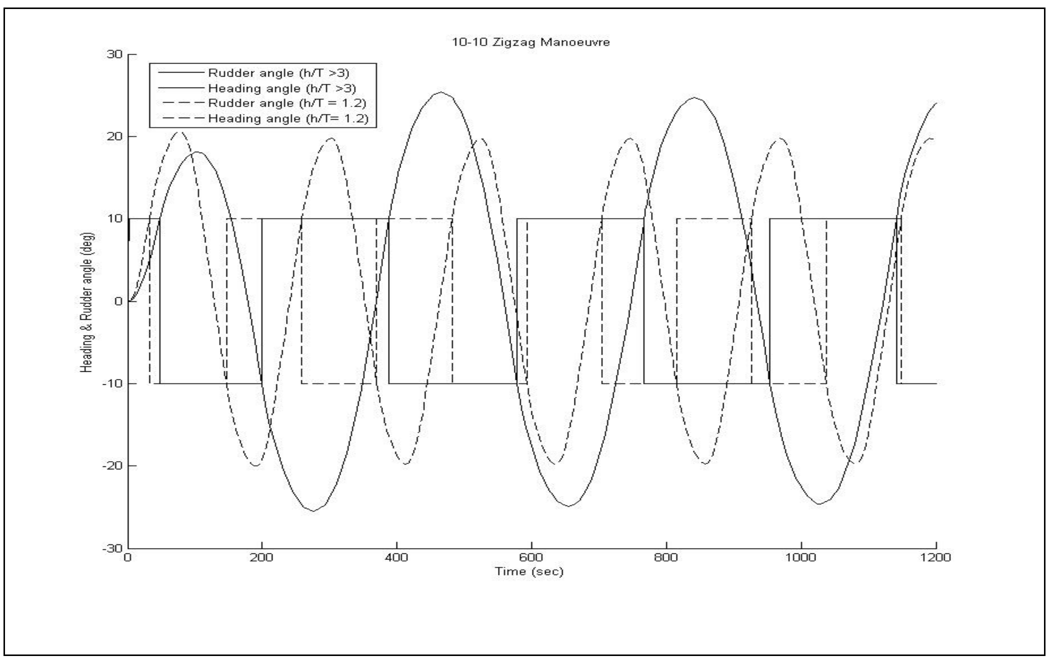

Fig. 4: Comparison of time histories of 10/10 Zig-Zag for deep and shallow water (h/T=1.2) [Ship Speed = 7 Knots]

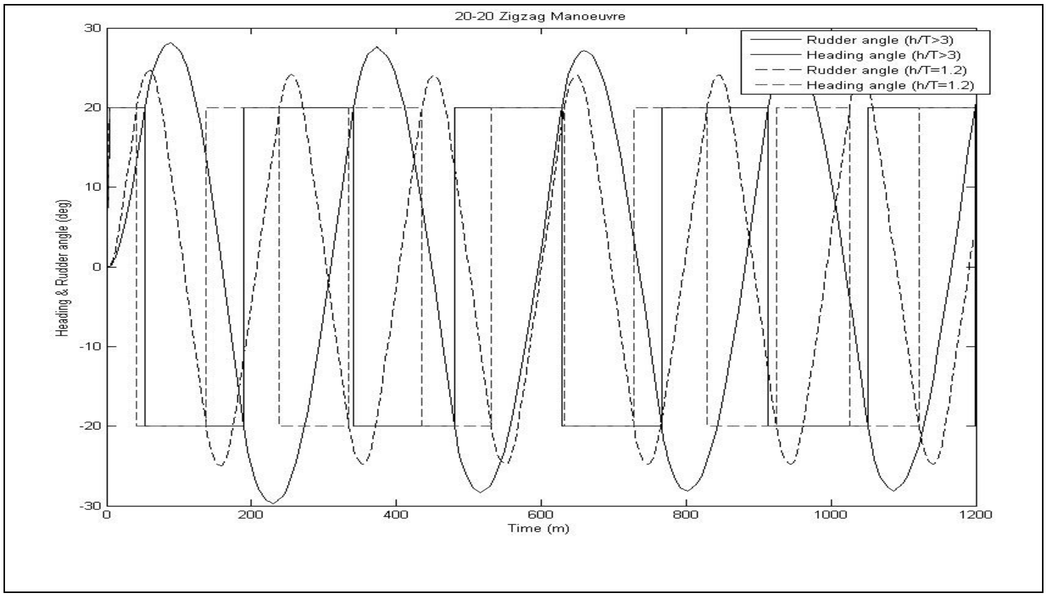

Fig. 5: Comparison of time histories of 20° /20 Zig-Zag [Ship Speed 7 Knots]

4. CONCLUSIONS

The Time Domain Simulation approach is a useful tool to simulate and analyze the effect of coastal development on the ship manoeuvrability. The ship turning circles and zigzag manoeuvres will degrade when the depth of the coastal waterway decreases.

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