DREDGED CHANNEL CURVES AND THEIR RELATION TO THE TURNING CIRCLE OF SHIPS

by

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The hydrographer or engineer embarking on the development of a river or tidal waterway by means of dredging may have to consider the radius of the curve or bend to which he will align the channel, having regard to the turning circle of the ships which not only will use the channel on completion of dredging, but he may also have to provide for the growth in dimension of the shipping using the waterway and consequently future accommodation in channel depth and width.

The natural tendency in river channels is to form a series of deep water pools on the concave sides of the bends with shallows at the intervening positions where the current passes over from one side of the stream to the other.

In tidal rivers the flood tide complicates these conditions, but generally has the effect of creating a pool on the opposite or reverse curve and thus there are usually two pools in the same reach with a crossing or shoal area between them. The foregoing formations are especially common to embanked rivers or tidal waterways having a sinuous water-course. To improve these hydraulic and hydrographic conditions there are now several methods adopted. We do not intend to do more than enumerate the principal ones here :-

(1) Embanking and groyning the natural channel.

(2) Canalising and pool filling (practised in Holland to maintain a level bottom by means of mattress work).

(3) Rivetting, *i. e.*, constructing dykes which train the channel below half-tide level.

(4) Dredging, accompanied by above methods of channel training or alternatively without any artificial aids.

It is now many years since Mr. GIRARDON advocated at the 6th International Congress of Navigation the retention of the sinuous watercourse in rivers with gentle slopes at the pools and steeper ones at the bars, and to create the improvement by converting pool crossings whenever they occurred into good ones, the result to be obtained by giving a suitable direction to river currents across the bars. When combined with the investigations of Mr. FARGUE on the *Influence of Bends on Channel Depths*, it led to a new conception of the proper functions of the works constructed to improve channels.

The direction which the works of contraction gave to the confined waters became of more importance than the relative amount of contraction, and could be given such a direction as to produce the proper effect on the bars or crossings.

When this method is followed the sinuous course of the river is preserved and even intensified. It is to this limit of channel curvature that we would draw attention. In *Kempfe's Engineer's Year Book* (1917), 24th Edition, reference is also made to this matter; and it is stated that, generally speaking, for vessels of 400 to 500 tons, moving at a fair rate of speed, a radius of 500 yards should be regarded as a minimum — at low speeds 200 yards will suffice for radius of curvature. The minimum for vessels of very small tonnage (say under 200 tons) may be as low as 66 to 88 yards. It will be obvious, however, that in addition to the radius, speed and tonnage factors, there are others; for instance, the draft of the vessel is important as it governs the ratio of displacement or cross section of vessel to cross section of channel.

Mr. G. S. BAKER in his work, *Ship Form, Resistance and Screw Propulsion*, deals fully with the relation of ship to channel, this the channel designing engineer should study to fully appreciate. He explains that in restricted water channels, if a vessel is passing through a channel of gradual construction, the cross section of the stream lines around the ship must also be gradually reduced, and the changes of velocities and pressures must therefore be increased. In shoal water the conditions become more favourable for eddy making. Professor HAVELOCK has also shown that a travelling point of pressure creates waves of greater divergence in shallow than in deep water, and this divergence increases with speed, and ultimately at a critical speed they are all concentrated in a large transverse wave somewhat similar to a wave of translation. Above this speed only divergent waves are possible. The critical speed is given by $V^2 = 11.5 \times d$, V being speed in knots, d the depth of water in feet.

SCHUTTE has tested several ship forms in channels of varying width and depth and in what may be called open and unlimited water. Taking first the case of the cargo boat, the increase in resistance at any speed over the open water value was approximately the same for a broad, shallow channel as for a narrow and deep channel, provided the ratio $\frac{\text{depth of water}}{\text{draft of ship}}$ in the former and $\frac{\text{width of channel}}{\text{beam of ship}}$ in the latter were the same. This only applies to the ordinary low speeds at which such a vessel would run when wave making is not very important. Over this range of speed the percentage increase of resistance was roughly constant for any given size of channel. The result of several experiments show that, in a confined channel, the deep vessel suffers more than the shallow one, and that a cross section area of channel about 200 times that of the vessel is required at all normal speeds if the resistance is not to be affected by the boundaries. At low speeds a smaller size can be allowed, the necessary ratio of areas being about 150.

It has been shown that there must be a depth of water equal to 14.0 to 7.0 drafts when there are no side boundaries, and a breadth of channel equal to 10.0 to 8.0 beams when the water depth is very great. When both side and bottom boundaries are present these numbers naturally increase somewhat.

BEHAVIOUR OF A SHIP UNDER SPEED AND HELM.

In practical navigation, when it is found that the depth accompanied by width and curvature of channel are such as to make steering uneasy or the vessel unresponsive to the helm, two actions may be taken. If the vessel has twin or multiple screws the speed on one set of engines can be eased or stopped and the other increased, thus imparting a better turning movement to the ship. If the vessel is a single screw vessel or of the larger dimensions with twin or multiple screws, the occasion may render it advisable in practice to make a tug fast ahead to assist in the navigation of such bends.

A vessel, when turning under the influence of helm and engines only — that is to say, the propeller or propellers working in the direction to force the vessel forward — behaves in a manner now properly defined.

The vessel usually turns or pivots on a point well forward in her middle line, and the curve described by the centre of gravity of the ship is slightly outside the circle described by the stem or forefoot. The centre of gravity, in fact, travels outward immediately from the line of original course when the helm is put over, and the stem of the ship is involuntarily carried into the channel if the vessel is on the starboard side of the fairway and the vessel under starboard helm. The maximum distance that the ship's centre of gravity travels in her original direction after the helm is put over is termed the "advance".

For an approximate investigation of the forces in operation during the turning of a ship, the motion may be divided into three stages :-

(*a*) When the rudder is first put over and the pressures on the hull are those which produce angular acceleration.

(*b*) When the accelerated forces are combined with those caused by the resistance of the ship to rotation.

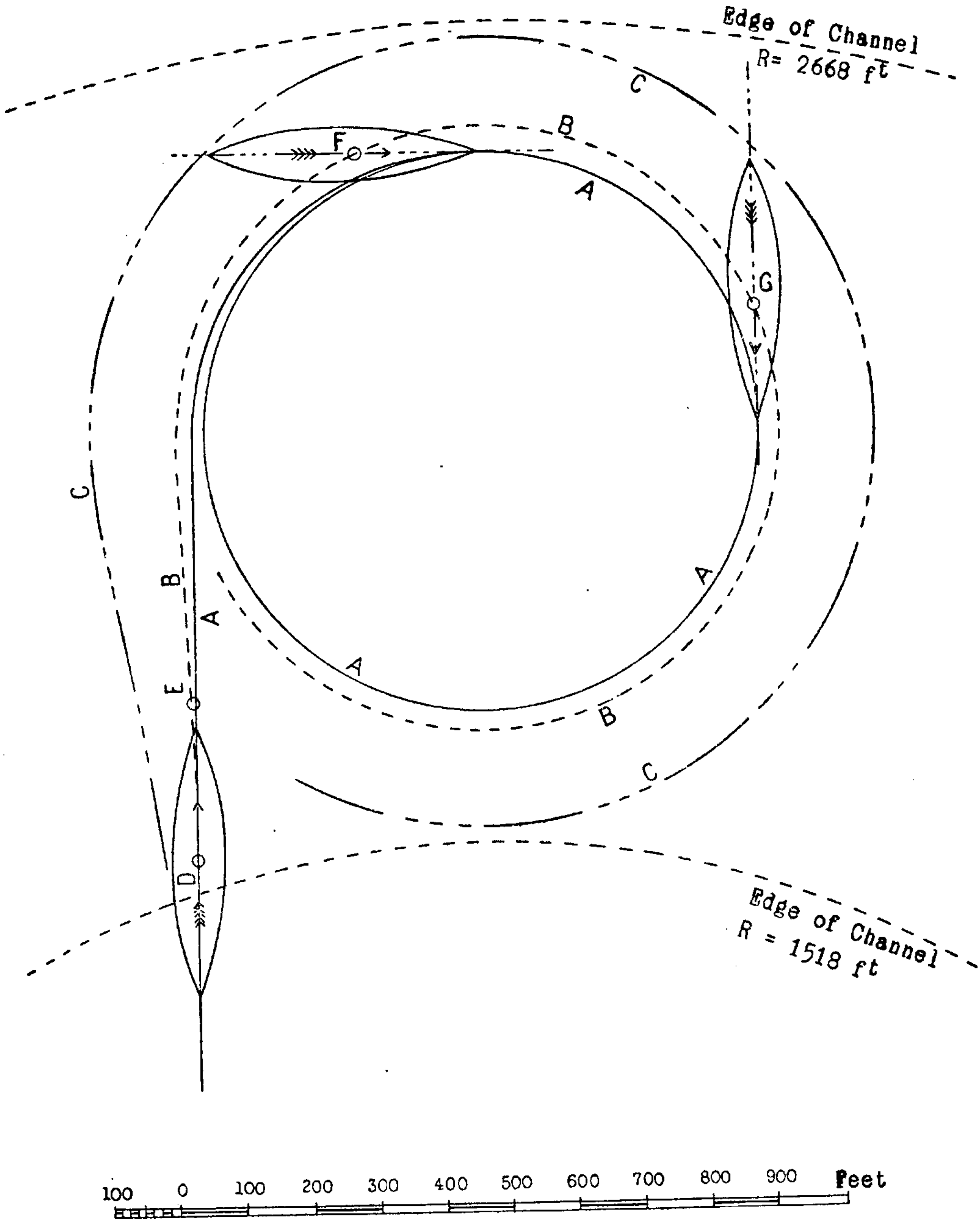
(*c*) When finally turning uniformly in a circular path.

The character of the forces acting during states (*a*) and (*c*) can be ascertained and the type of motion under the complex represented by (*c*) will consist of a gradual replacement of the motion at (*a*) by that at (*c*) (*See* diagram of turning circle).

The "tactical diameter" is the perpendicular distance between the original line of advance and ship's position after turning through 16 points.

The "final diameter" is the diameter of the circular path which the ship traverses if the helm is kept over, when the path becomes a circle, it can be measured between any two opposite points.

	Type of Ship.	*Length feet.*	*Advance yards.*	*Tactical diameter yards.*
Ma	Battleships	390	420-450	480-510
F	Battleships	400	400-440	470-510
K	Battleships	425	430	420
P	Cruisers	500	750-800	1000-1100
D	Cruisers	500	550-650	750-800
E	Cruisers	435	600-650	820-930
Mo	Cruisers	440	520-590	720-750
Destroyers		—	220-300	320-420



Survey of track traversed by ship under the action of 32 degrees of helm, corresponding to the initial speed of 17.5 knots.

A, A, A. Curve described by pivoting point.
B, B, B. Curve described by centre of gravity.
C, C, C. Curve described by outer edge of stern.
D. Position of ship's centre of gravity when helm commenced to move over.
E. Position of ship's centre of gravity when helm had reached 32 degrees.
F. Position of ship's centre of gravity when vessel had turned through 90 degrees. Time from *D*, 49 ½ sec.
G. Position of ship's centre of gravity when vessel had turned through 180 degrees. Time from D, 1 min. 20 sec.

The smaller figures in the third and fourth columns in the above table are for speeds of from 10 to 12 knots; the larger for the ships at speeds corresponding to full natural draught power. Some points of interest are to be noted from this table, in that with battleships the advance and tactical diameter are nearly equal and are each from three to four times the length of the ship.

The second, that in cruisers the advance and tactical diameter are somewhat more than in battleships of nearly the same length (see *K* and *Mo*); and that in cruisers and destroyers the tactical diameter is about one-third more than the advance.

Lastly, in the older cruisers *E.*, the tactical diameter is from 5-½ to 6-½ times the length, whilst in newer cruisers (*D* and *Mo*) it is from 4-½ to 5 times the length respectively.

These differences in the steering qualities of different classes of ships can only be explained by considering the various features upon which the movement of a ship depends when the helm is put over. These are principally four in number, *viz*:-

(*a*) The time taken to put the helm over to the maximum angle.

(*b*) The pressure on the rudder.

(*c*) The moment of inertia of the ship and water moving with her about a vertical axis through the centre of gravity.

(*d*) The moment of resistance of the ship in rotation.

(1) It is not difficult to see that if the helm is put over very slowly the turn and space taken by the ship to turn through a given number of points will be greater than if the helm were put over quickly. This was of special importance to ships before the introduction of the steering engine. To put the rudder over to the full angle by hand occupied nearly as many minutes as it now does seconds, and at high speeds it was often impossible to get the full angle. The manœuvring power of ships was thus rendered very small and led to the use of balanced rudders and the introduction of the steering engine. With steam steering engines the time taken to put the helm over from amidships to hard over varies from 5 to 20 seconds, the mean time being generally 10 to 12 seconds.

(2) The pressure on the rudder varies with the area, angle of helm, and speed of the ship, as follows:-

Pressure on rudder. — The normal pressure on a rudder is usually obtained by use of the formula:-

$$P = \frac{1}{530} AV^2 \sin \Theta,$$

where P is the pressure in tons,
A is the area in square feet,
V is the speed in knots,
Θ is the angle of helm.

For an angle of 35°, the usual maximum helm angle,

$$P = \frac{A\ V^2}{920}$$

The formula is empirical and may be used for all types and shapes of rudders.

The following table shows the result of varying the helm angle in a certain warship :-

Helm Angle.	*Tactical Diameter.*	*Time turning thro' 8 points.*
5	1230 feet.	89 secs.
10	1090 "	86 "
32	850 "	80 "

With the foregoing information derived from experiments in naval vessels, we are able to form deductions which are of value and are applicable in part to mercantile vessels.

No shipowner or shipbuilder can afford to undertake the expensive operations which the naval experiments involve and which are essential for tactical work and warfare.

Reference to tabulated data for length, advance and tactical diameter, previously shown, demonstrates that the ratio of length of ship to mean of the tactical diameters has some points of instruction for mercantile considerations.

The ratios are as follows (approx.) :-

Ma	Battleships	3.70 times.	(Ratio of T. D. to Length).
F		3.70 "	
K		3.00 "	
P		6.33 "	
D	Cruisers.................	4.67 "	
E		6.00 "	
Mo		5.00 "	

These vessels, although differing somewhat in underwater and above-water form, and having rudder area and design of their own, nevertheless compare in turning circle — with merchant ships — with less divergence in results than one would expect.

The experiments which have already been described are presumably dependent on :-

(1) Smooth seas.
(2) Suitable depth of water for manœuvring.
(3) Little or no tidal stream.

In applying seaway results obtained from warships to the manœuvring of vessels which carry cargoes, we are beset with two factors which are seldom constant, namely, draft and trim of ship.

To apply the turning circle of either types to tidal waterways, other factors may appear, *viz*:-

(1) Choppy or broken water.
(2) Unsuitable depth of water for manœuvring.
(3) Strong currents.

We should consequently approach our conclusions with regard to the conditions existing at the time and place.

(*a*) I am indebted for some information regarding diameter of turning circle in the *Lusitania* and *Mauretania* from the builders of the latter vessel.

The *Mauretania* possesses a diameter of turning circle of 950 yards or approximately 3.7 times the length.

This was obtained with the ship steaming 23 knots before the helm was put over and the vessel presumably in ballast or trial trip trim.

This ratio is similar to battleships, at full natural draft:

Ma	3.7	Twin screws.
F	3.7	
K	3.0	Speed 11 knots.

The following rough results were obtained by estimated distance and are less reliable — they refer to merchant vessels, varying draft and dimensions, co-efficient of fineness between .7 and .8 at light draft: —

Length of ships B. P.	DRAFT.		*Speed of ship before commencing to turn.*	*Approx. dia. of turning circle-length of ship.*	*State of Wind.*	*State of Sea.*
	Ford.	*Aft.*				
ft. ins.	ft. ins.	ft. ins.				
271. 4.	7. 11 ½	11. 7 ½	12.5	3-½	Light.	Smooth.
235. 0.	14. 1 ½	14. 7	8.5	2-½	Gentle Breeze.	
252. 10 ½	17. 5 ½	17. 10 ½	10.5	3-½	Light.	Smooth.
448. 0.	12. 0	20. 7	about 12.	3	Fresh.	Rgh. wvs. 4 ft.
485. 0.	12. 0	24. 6.	about 13.	3		Smooth.
270. 0.	9. 8 ½	13. 7 ½	about 14.	2-½	9 knots.	Wawes ½-2 ft.
270. 0.	9. 7	13. 10.	14.1	2-½	5 knots.	Waves ½-2 ft.

Further actual data refer to varying conditions of trim, tonnage, speed, etc...:

Twin screws.

(*b*) Length of vessel 536 ft. B. P. Draft 23 ft. 2 ins. ford.; 25 ft. 3 ins. aft. Full speed 18 knots. Angle of rudder 38°. Wind N.W. by W. Average speed during turn 13.25 knots. Diameter of circle about 2100 ft. Revolutions outside screw came down from 85 to 78. Inside screw from 81 to 65.

(c) Length of vessel 535 feet B. P. Steaming at 16-1/4 knots.

To Port.	*No. of points.*	*To Starboard.*
M.S.		M.S.
1.45	8	1.52
3.30	16	3.30
5.16	24	5.8
7.—	32	—

The tactical diameter for the circle to starboard was 3078 feet and for the port one 2790 feet. The latter gives a circumference of 8766 feet and an average speed for covering it of 12.33 knots.

The reduction in speed is for the complete circle 3.92 knots, equivalent to 24-1/8th. per cent of the initial speed.

The average drift angle, which is the angle the keel makes with the momentary tangent to the curve, was 10.6°.

(*d*) Length of vessel B. P. 514 ft., draft 21 ft. 6 ins. ford.; 24 ft. 2 ins. aft. Displacement 12,360 tons. Speed 14 knots. G. M. 13.18 ft. Revolutions per minute 65. Helm angle 36°. Trim by stern 37 ins. Heel during turn 2° to 3°. Wind S.W. force 2. Time for turning 32 points: 7 minutes. The tactical diameter was 2154 ft. or say 4.19 times length B. P.

Average speed during the turn 9.4 knots, a reduction of 4.6 knots from original speed. The outer screw was reduced 3 revolutions and the inner screw 12 revolutions.

A second set of observations when steaming 13 knots with almost the same displacement gave very nearly the same results.

(*e*) Length of vessel B. P. 490 ft. Speed 63 revolutions, 14 knots. Helm angle 36°, taking 18 secs. to put hard over. Helm hard-a-port, Diameter of circle 2330 ft., Time 7 mins. 35 secs. With helm hard-a-starboard, Time 7 mins. 46 secs., Diameter of circle 2230 ft. Draft 24 ft. 11 ins. ford., 24 ft. 2 ins. aft. G. M. 2.50 feet. Sea smooth; no wind.

Single screws.

(*f*) A cargo liner.

Length 440 ft; draft 14 ft. ford.; 18 ft. aft., 4000 I. H. P., speed 14 knots. With helm hard-a-port, smooth water, no tide. The first half of the diameter of circle 1170 feet. Second half 1070 feet. Time turning 5 mins. 17 secs. Single screw vessel with 3000 tons cargo, coal, etc., on board.

(*g*) Length of vessel B. P. 465 ft. Ship steaming 13 knots. Wind SSW. moderate. Sea moderate. Helm hard-a-starboard. Time occupied turning 8 mins. 10 secs. Diameter of circle 2456 ft. Circumference of circle about 7720 feet. Same vessel. 14 knots. Light wind. Sea smooth. Helm hard-a-port. Time occupied 7 mins. 30 secs. Diameter of circle 2815 ft. Circumference of circle 8847 ft.

Now the problem before the Hydrographic Officer or Engineer is to provide a channel curve with as convenient a depth and stream line flow as nature will permit. Water in flow tends to hug the concave bank in sympathy with the pool formation.

When resistance increases by the combination of ship form and channel form to an extent which makes the navigation difficult for large vessels, channel rectification by dredging or re-alignment may be desirable.

We have actually found that a decrease in the radius of curvature of a dredged channel previously having a mean radius of 1,736 yards to a mean radius of 1,389 yards has improved rather than restricted the manœuvring of larger vessels by (*a*) increasing the water area permanently by adoption of the pool area on the concave side ; (*b*) leaving the convex point or salient in repose producing better channel maintenance above and below the salient.

To crystallise the matter of dredged curves at bends in rivers, tidal or non-tidal, we have therefore to consider :-

(1) Size of vessels and whether twin or single screw.

(2) Facilities for assistance around bends by tugs.

(3) To what extent the known factors of cross sectional area of channel to cross section area of ship will operate in the bend or curve under consideration.

(4) Hydrographic conditions upstream and downstream of the bend or curve under consideration.

There remains also for study in this connection the theories and experiments of Professor James THOMPSON regarding the formation of pools and salients at bends in rivers flowing under the action of gravity to the sea.

Professor James THOMPSON pointed out (Proc. Roy. Soc. 1877, Proc. Inst. Mech. Eng., 1879, page 456), that the usual supposition is that water tending to go forward in a straight line rushes against the outer bank and scours it, at the same time creating deposits at the inner bank. That view is an incomplete account of the matter, the Professor having given a more ingenious account of the action at the bend,, which he completely confirmed by experiment. Thus, when water moves round a circular curve under the action of gravity only, it takes a motion like that of a free vortex. Its velocity is actually greater, parallel to the axis of the stream, at the inner side than at the outer side of the bend. Hence the scouring at the outer side and depositing at the inner side of the bend are not due to mere difference in velocity of flow in the general direction of the stream, but in virtue of centrifugal force, the water passing round the bend presses outwards and the free surface in a radial cross section has a slope from the inner side upwards to the outer side. For the greater part flowing in curved paths, this difference of pressure produces no tendency to transverse motion, but the water immediately in contact with the rough bottom and sides of the channel is retarded and its centrifugal force is insufficient to balance the pressure due to the greater depth at the outside of the bend. It therefore flows inwards towards the inner side of the bend, carrying with it detritus which is deposited at the inner bank. Conjointly with the flow inwards along the bottom and sides, the general mass of water must flow outwards to take its place.

Professor THOMPSON'S observations were obviously directed more to fluvial curvatures sensitive to scour, but in tidal rivers with pitched embankments the same conditions may apply on the ebb tide at certain bends, the velocity being greater at the inner side of the axis than at the outer side, and the duration of the ebb tide being the dominating period of flow.