Journal of Indian Geomorphology
Volume 1, 2012 • ISSN 2320-0731
Indian Institute of Geomorphologists (IGI)

acb publications
Kolkata, India
acb20@rediffmail.com

Evaluation of the Hydraulic Stability of Tidal Inlet: A Case Study of the Shrivardhan Inlet-Bay System, Konkan Coast

Subhamita Chaudhuri
Department of Geography, West Bengal State University, Kolkata 700126

Abstract: *In an inlet-bay system where the supply of fresh water to the bay is negligible, the flow through the inlet is the only flushing mechanism by which the bay maintains itself. Shrivardhan is an example of such an 'inlet-bay system'. If on any circumstance the inlet gets choked then it will isolate the bay from the sea and eventually lead to bay reclamation. The cross sections of the main inlet reveal that it is subjected to constriction throughout its entire length. Reduction in the cross sectional area of an inlet increases its velocity up to a certain critical limit, after which, further reduction leads to choking and closure. The temporal change in the hydraulic stability of the inlet in terms of its critical and stable cross sectional area is assessed from 1965 to 2000 following computation methods proposed by Keulegan and O'Brien. The stability condition of the inlet in 1965 was such that the inlet should have enlarged its throat cross section to achieve stability but the 2000 computations show that the inlet has failed to enlarge its throat cross sectional area and hence has moved further away from its equilibrium cross section.*

Introduction

The general straightness of the sandy coasts is interrupted by the presence of inlets. These inlets may be the mouths of streams, which are falling to the sea through an estuary, or they may be of purely tidal origin, with no direct connection with the inland sources of water. However, in both cases, the effect of tide is considerable. The distance up to which the tidal effect penetrates varies from inlet to inlet, depending upon the tidal range and the slope of the inlet. The inlets are in a condition of dynamic equilibrium with the changing tidal amplitude, longshore drift and near shore wave conditions. The equilibrium gets disturbed when any one of the variables changes in such a way that the other variables fail to cope up with the change beyond a particular threshold (Brunn and Gerritson, 1960). It has been observed in various parts of the world that the inlet mouths tend to shift; mostly in direction of the long shore drift (Bruun and Gerritsen, 1960). Not only do the inlets shift in their relative location, they are also susceptible to become choked. The littoral drift brings material, which may be pushed inside the inlet during flood tide and again flushed out with the ebb current. The material flushed out by the ebb current may be pushed so far into the sea that they may be eventually lost. But sometimes the flushing mechanism is not so effective and the material remains partly inside the inlet and partly moved towards the inlet mouth, only to get re-distributed with the next incoming tide or lead to the formation of an ebb tidal delta at its mouth. Material settling inside the inlet itself may form a shoal. Such shoaling may ultimately lead to raising of the inlet bed and probable bifurcation of the flow. Continued shoaling can eventually choke the inlet.

Inlets can also experience closure by natural 'bar by-passing' i.e. prolongation of a bar in the down drift direction to by-pass the inlet mouth leading to its closure. These inlets act as natural conduits through which the adjoining bay maintains its connection to the sea. In an 'inlet-bay system', where the supply of fresh water to the bay through streams is negligible; the flow of the inlet is the only flushing mechanism by which the bay maintains itself. If on any circumstance the inlet gets choked then it will render the bay isolated from the sea and will eventually lead to bay reclamation if the same trend of events continue.

Study area

One of the characteristic features of the Konkan coast is the conspicuous alternation of bays and headlands and the presence of inlets associated with almost all the major sandy beaches, especially in central Konkan. The Shrivardhan bay, situated in Central Konkan coast is roughly elliptical in shape with a very prominent bay mouth bar developed at the entrance (Fig. 1).

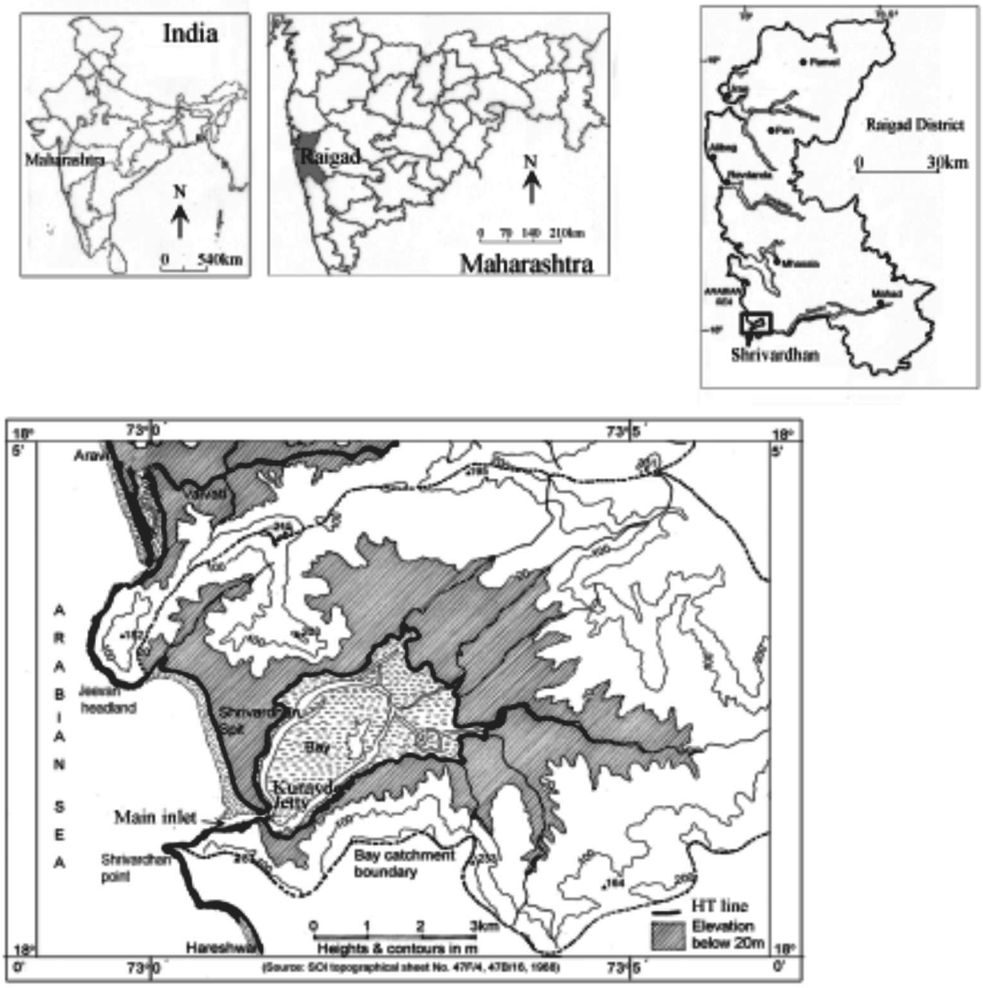
The Bay, together with its catchment area lies between 18°0'N to 18°5'N and 73°0'E to 73°7'E. Excluding the catchment, the bay itself covers only about 7.53 km^2. The bay-mouth bar extends in a north-south direction for about 3.5 km. The southern margin of the bay is bordered by rocky headland and the main inlet is situated in between the southern tip of the bar and the rocky headland. The southern end of the bar is at least 200 m away from the southern headland. Bridging the gap of this last stretch of 200 m will result in complete closure of the bay mouth, at least during low tide conditions. Hence, by virtue of its very location as well as the function of acting as a connection between the bay and the sea, the main inlet occupies a pivotal position in the whole inlet-bay system.

The Shrivardhan bay has very few small seasonal streams which drain into it, and the contribution from these streams play a negligible role in maintaining the capacity of the bay. The main source of water and sediment coming in to the bay is the sea. The flood and ebb tide has managed to maintain the bay to a considerable extent via one tidal inlet, which connects the bay to the sea.

Objectives

The Shrivardhan bay, though partially silted up has not yet been fully reclaimed. But from frequent field visits since 1996 it appears that the process of siltation is ongoing. The bay was suffering from high rate of siltation. This was reflected in the extensive development of mudflats in the central portion of the bay, which has restricted the water inside the bay into two narrow arms – the northern arm and the southern arm during the time of low tide. The two fishing jetties situated inside the Bay – Mulgaon and Kalinje (Fig. 1) become non-functional during the low tide period and the Kuravde jetty situated at the inlet-bay junction have been inactive for more than a decade. According to local fishermen, Kuravde jetty has become inactive because the depth of water near the throat of the inlet has become so shallow that except during high tide the boats cannot go out or enter the bay. These problems faced by the local people makes one think about the stability condition of the inlet which may be determined by analysing the following points:

- The temporal changes in the morphology of the inlet with respect to its cross and long profiles have to be assessed.
- If the southward extension of the spit is



(Source: SOI topographical sheet No. 47F/4, 47B/16, 1968)

Figure 1. Location of the study area. Scales of the maps increase clockwise from the upper left diagram.

identified as a dominant cause behind the shallowing at the throat of the inlet, then the possibility of the channel getting by-passed by the extension of the spit has to be examined. One has to further consider how the channel will try to maintain its stability and how far it will be able to maintain the bay-capacity in the future.

- The trend in spit extension has to be studied to have some idea about the future existence of the inlet.

Database

Sounding charts of two years prepared by the Maharashtra State Hydrographers' Office, Mumbai – 1965 (Chart No. 4/66) and 2000 (Chart No. and 590/2001) were used in the present study. The tide data of Murud-Janjira (18°19'N, 72°58'E), published by the Maharashtra Maritime Board for minor ports (2001) has been taken into consideration as it is the nearest tide gauging station. Survey of India topographical sheet No. 47F/4 and 47B/16 (1925) and 47F/4 (1968) and IRS LISS-2 and PAN merged image (1998) was used for mapping temporal change in spit extension.

Previous works on inlet stability

Number of investigators like Escoffier (1940),

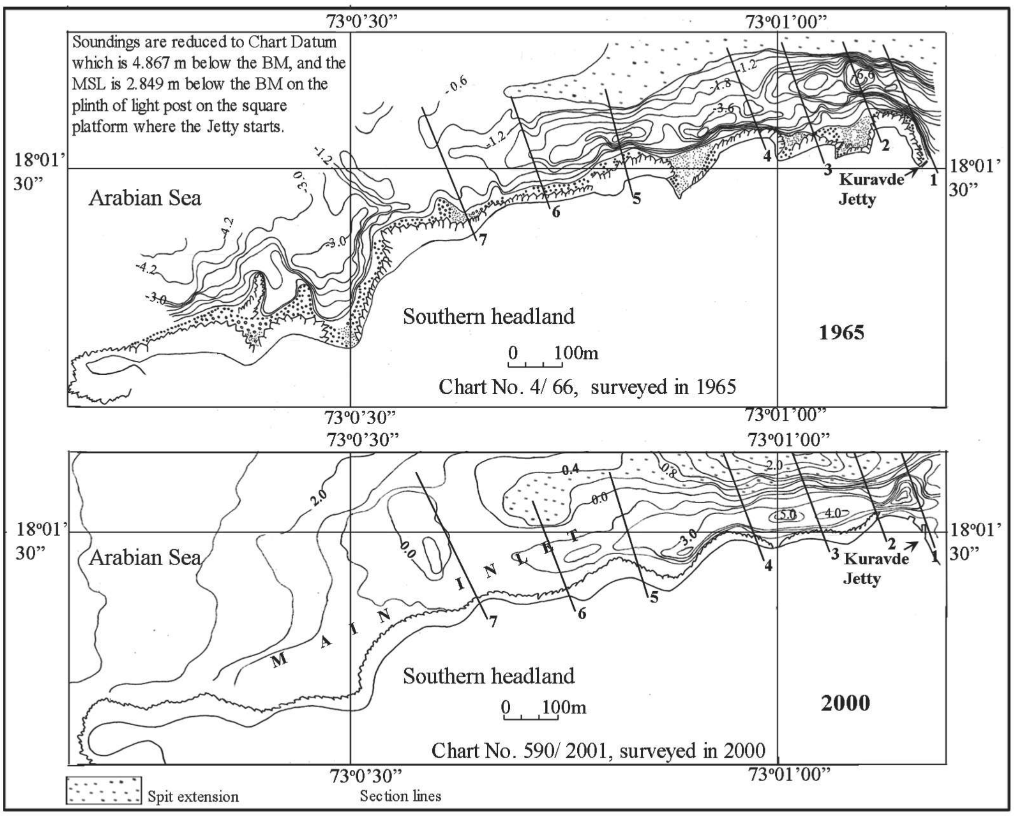


Figure 2. Section lines taken across the Shrivardhan inlet

O'Brien (1931, 1969), Bruun and Gerritsen (1960), Keulegan (1967) and Mehta (1975) have dealt with the stability criteria of coastal inlets. Some of the investigators studied the relationship among various geometric parameters of the inlet, such as cross sectional area, channel length, maximum depth, ebb delta area etc. Many have established statistical correlation among these parameters. O'Brien (1931) tried to establish a relation between throat cross-section and tidal prism. Escoffier (1940) states that plot of velocity versus cross-sectional area can give good idea about the stability of the inlet. Mehta (1975) developed his stability criteria on the basis of the relation between longshore wave power and the flushing and scouring capacity of the inlet, which he attributed to the inlet cross sectional area, the flow velocity and tidal prism.

The Geomorphic character of the main inlet

Six cross sections have been drawn across the inlet, starting from Kuravde jetty and extending to 888 m towards the sea. Up to this point the confinement of the inlet between the southern spit and the southern platform adjoining the headland is clearly defined. A seventh cross section has been taken at 1074 m from Kuravde Jetty, where the inlet does not have a clear confined boundary but it was taken to understand the condition of the inlet mouth and the subsurface extension of the southern spit. Comparable cross sections were drawn with the 1965 and 2000 sounding data, so as to detect the morphological changes of the main inlet bed over a span of 38 years. The location of the section lines on the 1965 and 2000 sounding maps have been shown in Fig. 2.

Section 1: The maximum depth attained in 1965 was 5.5 m. the southern margin of the spit also had considerable steepness. In 2000, it could be seen that the general trend of the cross sectional shape is more or less maintained, but the channel has somewhat narrowed down. The southern bank shows significant shallowing of the channel due to deposition at the foot of the platform slope (Fig 3).

Section 2: The 1965 cross section resemble the first section in terms of its steep banks and flat bottom. The slope of the northern bank of the channel was exceptionally steep, showing a drop of about 6 m within a distance less than 8 m. The condition in 2000 shows drastic reduction in cross sectional area (Fig. 3). Not only has the cross sectional area decreased but the slope of the northern bank has become much gentler and the thalweg has been pushed towards the southern platform, probably owing to the southward extension of the spit margin.

Section 3 and 4: Both the cross sections show considerable reduction in cross sectional area, though there is only marginal decrease in the hydraulic radius. In Section 3 the shape of the channel cross section during 1965 to 2000 has not changed much, except that, the line of the thalweg shows some amount of shifting

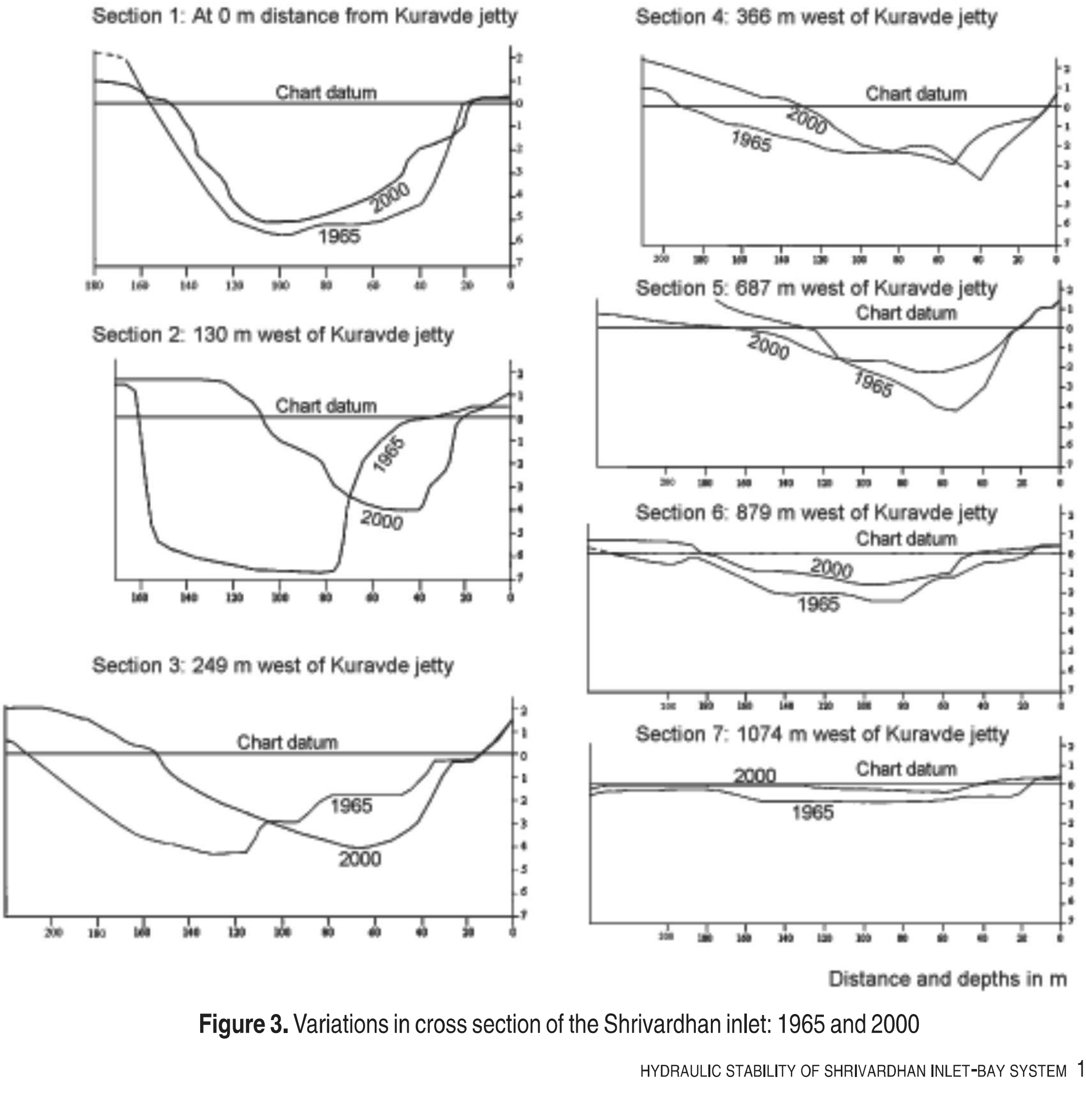


Figure 3. Variations in cross section of the Shrivardhan inlet: 1965 and 2000

Table 1. Variation in the cross sections of the main inlet at Shrivardhan: 1965 and 2000

Cross section	Distance from Kuravde Jetty (m)	Cross sectional area A_x (m^2): 1965	Cross sectional area A_x (m^2): 2000	Changes in Cross sectional area from 1965 to 2000 (m^2)
1	0	729.5	616.8	-112.7
2	130	761.7	360.6	-401.1
3	249	732.4	547.8	-184.6
4	366	572.8	390.8	-182
5	687	447.4	474.1	+26.7
6	879	558.2	401.4	-156.8
7	1074	436.3	315.8	-120.5

towards the south. The southern end of the spit at this location has prograded almost 50 m towards the channel from 1965 to 2000 (Fig. 3). Section 4 in 2000 indicates that the spit has accreted almost 40 m on an average towards the main inlet. The thalweg moved about 15 m towards the north, cutting through the sand deposits of the northern bank and making the slope much steeper.

Section 5: In 2000 the inlet at this part has not only become shallow but it has widened its channel to accommodate the incoming water. It can be seen from the Table 1 that the cross sectional area has marginally increased from 1965 to 2000 but the hydraulic radius has decreased.

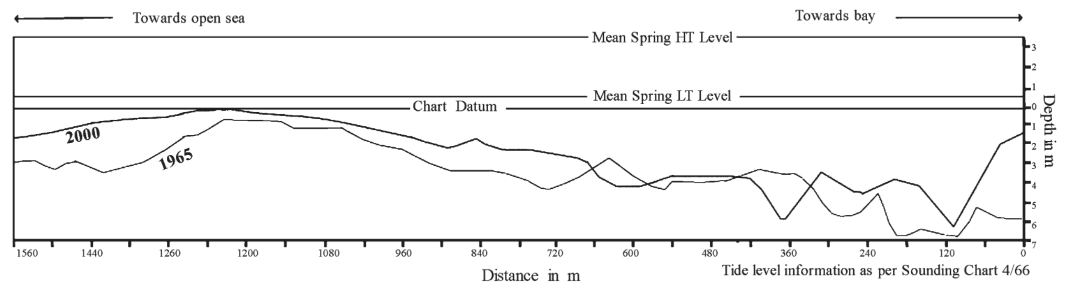
Section 6 and 7: These represent almost the mouth portion of the main inlet, where the south-western tip of the bar terminates and the inlet looses its well defined channelised course, to open out into the sea. The maximum depth of the channel in the sixth cross section reduced from 2.5 m to only 1.5 m within 1965 to 2000. There is accumulation of sand on the spit side as well as the platform side of the main inlet (Fig. 3). The seventh cross section shows an even more deteriorating depth condition with the maximum depth of the inlet decreasing from 1.0 m to 0.4 m from 1965 to 2000.

In most of the cross sections drawn across the main inlet there is appreciable reduction in cross sectional area and a tendency to shift towards the southern platform. The long profiles under discussion also show the same trend of siltation and shallowing of the inlet bed. The long profile of the inlet has been drawn along the thalweg line, starting from the Kuravde jetty and continuing up to 880 m towards the sea. The peculiarity of the profile is that, for larger part of it, it shows a bay ward gradient instead of a seaward one. Once we have crossed the Kuravde jetty, depth again starts decreasing towards the bay, where maximum depth attained is around 0.3 m below datum (as per sounding charts of 1982 and 1990). This indicates that, as we move towards the bay, the bottom configuration shows a slope from bay to sea. However, this slope is much gentle than the slope of the inlet channel from sea to bay. The vary nature of the profile is indicative of the fact that the flood tidal flows dominate the inlet and the bay as compared to the ebb tide-flow.

Superimposition of the long profiles drawn along the thalweg line of 1965 and 2000 gives a clear picture of its deteriorating depth conditions (Fig. 4). In both 1965 and 2000 chart maximum depth was observed just 30 m away from the first cross section, but the maximum depth has decreased from 6.7 m to 6.2 m within this period. In 1965, the minimum depth of 0.9 m was noticed at the sea ward opening of the main inlet. In 2000, almost at the same location the depth was reduced to a meagre 0.3 m below the chart datum. This portion of the inlet bed may be termed as the ‘threshold’. In general the long profile of 2000 depicts a much shallower channel than that of 1965. From the point of minimum depth, near the mouth of the main inlet, the slope of the inlet goes on increasing both towards the bay and the sea. The depth of the main inlet at its bay ward opening also shows considerable shallowing. Here the depth has reduced from 6.0 m in 1965 to only 1.4 m in 2001. This drastic shallowing of the inlet is reflected in the formation of a shoal at this location (Fig. 4).

Flow condition of the main inlet

With a reverse gradient from sea to bay some explanation can be given of the probable flow conditions that can be expected in the main inlet channel. Aided by wind, tidal force and being confined within the rocky platform on one side and the spit on the other, the incoming water moves with considerable velocity through the inlet channel. But as the water comes out of the inlet at its eastward end, it suddenly spreads out as it enters the bay. This sudden spread in the width of the cross section results in sudden decrease in velocity and subsequent deposition giving rise to the formation of a shoal. It is likely that the shoal has an underwater connection with the south-eastern edge of the bay mouth spit. Crossing the shoal, the water has to move against the slope inside the bay. Hence, the flow velocity further decreases. As a consequence the rate of sedimentation is likely to increase as one move in to the interior of the bay. While draining out of the bay during ebb, the outgoing water is principally aided by gravity; hence it is the natural tendency of the water to follow the general slope of the ground. When this outgoing water reaches the Kuravde jetty it becomes increasingly difficult for the water to move against the slope (as the slope of the inlet is not towards sea but towards bay). The deposition at the mouth of the inlet acts as a threshold above which the water has to pass. Water in the upper part of the water column, i.e. up to a depth of 1m below chart datum can easily pass over the threshold towards the sea. But water below the depth of one metre will find it difficult to move up-slope.



Profiles drawn on the basis of Sounding Charts No. 590/2001 and 4/66 (Maharashtra State Maritime Board)

Figure 4. Changes in long profile of the Shrivardhan inlet: 1965 to 2000

A reverse gradient from sea to bay is not an uncommon phenomenon in case of tidal inlets. 'At the seafloor, in the immediate vicinity of the coastal inlet the interrupted littoral sediment tends to accumulate and raise the floor, leading to the formation of an ebb delta' (Dombrowski and Mehta, 1996). The threshold at the entrance of Shrivardhan inlet may represent the formation of an ebb delta. However, the trend of the bathymetric contours does not give the impression of an ebb delta, which usually has a lobe facing the sea and these are usually well defined by the bottom contours. Hence the deposition at the inlet throat as a subsurface extension of the bay mouth spit seems more probable.

The stability criteria and the condition of the main inlet

The stability of an inlet depends on the cumulative effect of two opposing factors: the near shore wave climate and the flow regime of the inlet (Mehta, 1975). Depending on the wave climate and the range of the tide, one of these two factors may dominate and cause either erosion or accumulation of sand in a particular inlet. Sudden influx of sand due to storm may choke an inlet, but on a long term basis the inlet should have enough scouring capacity to counter the obstruction against the flow due to sand accumulation and to maintain a state of non-silting, non-scouring equilibrium (Mehta, 1975). If the inlet fails to do so in the face of wave domination, then the accumulated sand will begin to constrict the throat, thereby reducing the tidal prism. The resultant unstable inlet will try to shift and orient itself according to the direction of long shore current or lengthen its course – rendering it more unstable (Mehta 1975). The Shrivardhan inlet being backed by the rocky platform on one side has little chance of re-orientation. Wherever the wave and longshore drift dominates over the tidal flushing of the inlet, the inlet throat is choked off and this situation is designated as 'bar by-passing' by Bruun and Gerritsen (1960) and 'poor stability' by Mehta (1975).

The Shrivardhan inlet shows a deteriorating condition within a span of 35 years. The throat cross-sections show reduction of 86.8 m^2. The reverse slope of the inlet long-profile itself is a limiting condition for the stability of the inlet. It can be seen that the main inlet is being plagued by the dual effect of extensive shoaling on the bay ward extremity and the south-eastern extension of the bay-mouth spit. These two events have resulted in constriction of the throat cross-section, general shallowing of the channel bed and decrease in the tidal prism. The reduced tidal prism indicates that the flushing mechanism of the inlet is slowly breaking down. According to Bruun *et al.* (1974), such conditions of poor stability would encourage the bay mouth bars and spits to grow faster and block the inlet mouth by 'bar by-passing'. The sounding charts reveal that the bay-mouth spit have already by-passed the inlet mouth, but it is yet to accrete over the HT level. The spit has definitely extended southwards at the sub-surface level but it has not been able to reduce the tidal prism substantially as compared to the marked decrease in the throat cross-sectional area (A_c). In spite of considerable extension of the bay-mouth spit, as seen from the oldest available Survey of India topographical sheet (1925) and the current satellite images, it can be seen that the inlet has managed to keep its seaward mouth open. This characteristic of the inlet gives an interesting dimension to its stability condition.

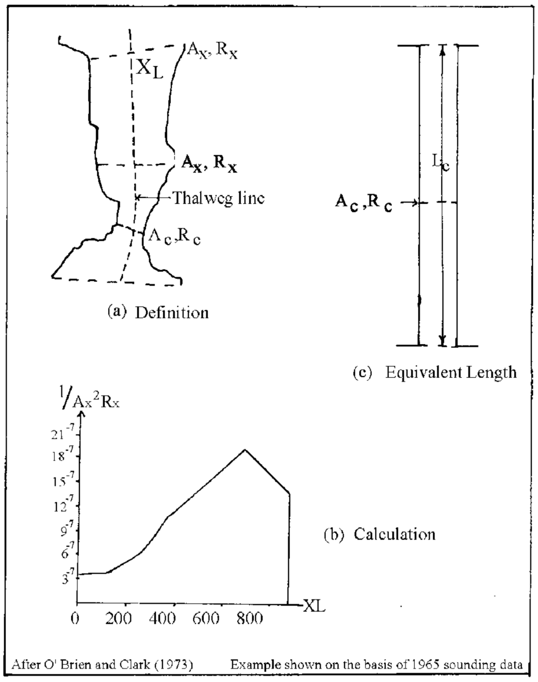
Critical and stable cross sectional area

The above discussion indicates that the main inlet shows a definite trend of moving towards the poor stability conditions. However, there is no appreciable change in the quantity of water exchanged between the bay and the sea. This indicates a possibility that, the shallowing of the channel and extension of the spit is getting compensated somehow and somewhere in order to maintain the transfer of water to and from the bay. In order to understand this situation and account for the same it was thought necessary to extend the stability analysis a step forward towards assessing the stable (A_{CE}) and critical cross sectional area (A_{cr}) following Keulegan (1967) and O'Brien (1931).

The most important aspect in determining the hydraulic geometry of the inlet is the identification of the throat cross-section, i.e. 'a constricted portion of the inlet with minimum cross-sectional area' (O'Brien, 1931). Following the above definition, the 5th cross section of 1965 and the 2nd section of 2000 have been chosen as the 'throat cross-sections' for the respective years. For the above mentioned cross sections the throat cross-sectional area (A_c), wetted perimeter (W_p), hydraulic radius (R_c) and length of equivalent channel (L_c) were calculated.

At this juncture the meaning of the term 'length of the equivalent channel' should be explained properly, since the later computations need to find out the value of L_c. The problem of working with the hydraulic geometry of inlets is that they do not have a constant cross section. Therefore velocity – U_m changes along the channel. To overcome this difficulty O'Brien and Clark (1973) tried to formulate an idealised channel with cross section area equal to the throat area and the length of the equivalent channel (L_c) is adjusted, so that the slope is not altered in the hypothetical channel. The procedure of calculating L_c has been discussed in subsequent paragraphs.

To find out the L_c one simple graphical method has been used by O'Brien and Clark (1973). A number of cross sectional areas (A_c) and wetted perimeters (W_p) were measured across the main inlet for the years 1965 and 2000 from the available sounding charts No. 4/66 and 590/2001 (Table 2).



After O' Brien and Clark (1973) Example shown on the basis of 1965 sounding data

Figure 5. Determination of the length of equivalent channel

The hydraulic radius (R_c) of each cross-section and the corresponding values were calculated.

Table 2. Computation of equivalent channel length (L_c)

Year	Section	A_c (m^2)	R_c (m)	XL(m)	$R_cA_c^2$	$1/R_cA_c^2$
1965	1	729.5	5.66	0	301.21 X10^4	3.32^{-07}
	2	761.7	4.73	120	274.43 X 10^4	3.64^{-07}
	3	732,4	3.09	252	165.75X 10^4	6.03^{-07}
	4	572.8	2.74	372	89.90 X 10^4	11.12^{-07}
	5 (throat)	**447.4**	**2.64**	**693**	**52.84 X 10^4**	**18.93^{-07}**
	6	558.2	2.23	888	69.48 X 10^4	14.39^{-07}
2000	1	616.8	3.62	0	137.72 X 10^4	7.26^{-07}
	2 (throat)	**360.6**	**3.06**	**95**	**39.79 X 10^4**	**25.13^{-07}**
	3	547.8	3.086	225.5	92.61 X 10^4	10.79^{-07}
	4	390.8	2.167	372	33.01 X 10^4	30.21^{-07}
	5	474.1	1.99	726	44.73 X 10^4	22.36^{-07}
	6	401.4	1.61	883.5	25.94 X 10^4	38.55^{-07}

TThe $\frac{1}{RcAc^2}$ values wer plotted in the y axis of a graph, against the corresponding distance (XL) of each cross-section (Fig 5, Table.2). Straight lines were drawn to join the points and the area under the curve was measured. The calculated value was then multiplied by the throat cross-sectional area and hydraulic radius ($R_cA_c^2$) to get the value of L_c. The length of the equivalent channel was found to be 533.14 m and 830.1m for 1965 and 2001 conditions respectively.

In an attempt to understand the stability condition of the inlet it is necessary to estimate its critical cross sectional area (A_{cr}). At this juncture, there is a need to explain the concept of critical cross-sectional area. O'Brien (1931), observed that for inlets which are in sedimentary equilibrium, i.e. inlets in which sediment erosion and deposition are in balance; the ratio of the tidal prism (P) and the throat cross-section (A_c) is either constant or gradually changing function of the tidal prism, depending on whether the inlet has jetties or not. The following relationship was proposed by O'Brien (1931), which has found world wide applicability:

$A_c = 1.58 \times 10^{-4}P^{0.95}$ .... (1)

where, P is in m^3 and A_c is in m^2

This relationship holds good for inlets, which are in a state of 'non-scouring, non-silting equilibrium' i.e. the channel geometry, is stabilised when the rates of sediment scour and sediment deposition become equal over the tidal cycle. If the actual P/A_c ratios vary substantially then there can be two situations –

a) P/A_c is much smaller. This can happen when the throat cross-section is much larger than the equilibrium size and therefore the inlet throat will contract until the velocity increases up to a level and equilibrium is established.

b) P/A_c is much larger. In this case A_c is too small. Under these circumstances the inlet can expand until the equilibrium is achieved or it may contract further and lead to closure. To determine which of these two ways the present inlet will follow the following computations are made.

The P/A_c ratio indicates that the Shrivardhan inlet falls into situation b. It is seen that when an inlet has a large A_c than required, then it shoals and contracts its cross- sectional area to increase its velocity. However, the A_c cannot continue to contract without limit. If sedimentation continues and the A_c crosses a certain critical value (A_{cr}), then further reduction no longer increases the velocity and the inlet will be unable to recover from the 'shock' of excessive sedimentation and lead to closure.

Keulegan (1967) has given a new concept of inlet stability. He explains stability by a 'repletion co-efficient' – K, the larger the K, faster the tide water will pass through the inlet. He relates the ocean tide amplitude, the inlet cross section (A_c), the bay surface area (A_B), and an 'impedance' factor (F) to the flushing capacity of the inlet. According to him the F is related to frictional loss of the flood and ebb current while entering (k_{en}) and going out of the bay (k_{ex}). F can be obtained by the following equation:

$$F = k_{en} + k_{ex} + \frac{fL_c}{4R_c} \qquad \text{...... (2)}$$

Dean (1983) states that, from the practical point of view, it will be sufficiently accurate to assume $k_{en} + k_{ex}$ equal to 1.

The Repletion Coefficient is thus defined as:

$$K = \frac{T}{2\pi a_o}\frac{A_c}{A_B}\sqrt{\frac{2ga_o}{F}} \qquad \text{....... (3)}$$

Where, T is the tidal period, a_o is semi tidal range of the ocean and the other terms have been already defined. The friction factor (f) is calculated by:

$$f = \frac{8g}{C^2} \qquad \text{(Bruun, 1978)} \qquad \text{...... (4)}$$

where C is the Chezy discharge coefficient.

Under the assumption that the flow through the tidal inlet results from the ocean driven tide and the maximum velocity (U_m) is found at the throat, Keulegan (1967) obtained a relationship between U_m at the throat and the repletion co-efficient (K) and it can be expressed as:

$$U_m = U'_m \times \frac{2\pi a_o A_B}{TA_c} \qquad \ldots\ldots. (5)$$

The linear method of obtaining the dimensionless velocity (U'_m) has been proposed by Bruun (1978):

$$U'_m = \left[\frac{\left[\left(1-\alpha^2\right)^4 + \mu^2 \right]^{1/2} - \left(1-\alpha^2\right)^2}{\frac{1}{2}\mu^2} \right]^{1/2} \qquad \ldots\ldots.. (6)$$

Where,

$$\alpha = \left(\frac{L_c A_B}{gA_c} \right)^{1/2} ; \ \mu = \frac{16\alpha^2\beta}{3\pi} ; \ \beta = \frac{FA_B}{2L_c A_c} a_o$$

Based on equation No. 5 and 6, U_m values were calculated for a selected range of A_c values (1 to 10,000 in logarithmic scale) for the Shrivardhan inlet, both for the 1965 and 2000 conditions. The variation of U_m with A_c is shown in the hydraulic curve of the main inlet for 1965 and 2000 (Fig 6). The data sets used for the stability calculation of the inlet in these two years have been given in tabular form in Table 3.

Here, $2a_o$ has been taken as 1.83m (average of spring and neap tidal range as mentioned in sounding chart No. 4/66) for 1965 conditions, and the bay area A_B is 7.53 km^2. For 2000 condition, the $2a_o$ has been taken as 2.082 m (average of the spring and neap tidal range of 2000) and the bay surface area remains almost unchanged. The computations for calculating the U_m for the throat cross sections have been shown in detail in Table 4. It has already been noted that for stable inlets a sedimentary equilibrium relationship exists between the tidal prism and the throat cross sectional area. This relationship between the stable cross sectional area (A_{cE}) and the tidal prism has been shown in equation No. 7. In an attempt to relate the tidal prism to U_m and A_c, Keulegan (1967) proposed the equation:

$$P = \frac{U_m TA_c}{\pi C_k} \qquad \ldots\ldots (7)$$

Combining equation No. 1 and 7, *sedimentary curves* are drawn for the years 1965 and 2000 (Fig 6) where the variation of U_m is plotted against a range of A_c values for the inlet, which enjoys a sedimentary equilibrium. The *sedimentary curves* are superimposed on the hydraulic curves for the two years. C_k is a constant usually taken as 0.86.

The *hydraulic curve* has two falling arms and it can be seen that the *sedimentary curve* intersects the *hydraulic curve* twice; once in the left falling arm, which marks the critical cross sectional area (A_{cr}) and once in the right falling arm, which indicates the stable cross

Table 3. Dataset used for stability calculation: 1965 and 2000

2000 data				**1965 data**			
L_c(m)	830.1	F	5.75	L_c(m)	533.1	F	4.58
A_c(m)	360.6	g	9.81	A_c(m)	447.4	g	9.81
A_B(m^2)	7530000	a_o(m)	1.43	A_B(m^2)	7530000	a_o(m)	0.915
R_c(m)	3.06			R_c(m)	2.64		
T	44640			T	44640		
f	0.07			f	0.07		

Table 4. Calculation for hydraulic and sedimentary curves at the throat of the Shrivardhan inlet: 1965 and 2000

Year	Sedimentary curve		Hydraulic curve						
	A_c	U_m	R	F	á	â	µ	U'_m	U_m
1965	447.4	0.837236	2.364847	4.94497	0.134609	71.42415	2.19707	0.771129	1.671487
2000	360.6	0.827786	2.123087	7.842268	0.187194	141.0545	8.391128	0.46191	1.941416

sectional area (A_{cE}). The nature of the hydraulic curve is such that for any $A_c > A_{cE}$, i.e. in the right falling arm of the curve, a reduction in area may be due to sand deposition will increase the maximum velocity (U_m), thus increasing the scouring capability of the flow, so that the inlet will be able to flush out the sand and the cross-sectional area will be restored. In contrast, for any inlet with the $A_c < A_{cr}$, corresponding to the left falling arm of the *hydraulic curve* will be different. Here, a reduction in A_c will lead to a corresponding reduction in U_m and this will enhance the possibility of further deposition and ultimate closure of the inlet. If A_c is between A_{cr} and A_{cE}, the inlet velocity being higher than that required by the *sedimentary curve*, the area should increase until it returns to A_{cE}.

Discussion

From the *hydraulic* and *sedimentary curves* of 1965 and 2000, one can have some idea about the stability condition of the main inlet. The 1965 curve shows that the A_{cE} was somewhere nearing 1000 m^2 and the A_{cr} was around 3 m^2. The A_c was 447.4 m^2. Thus, on the Hydraulic curve, the position of A_c was on the right falling arm. Since, the A_c was between A_{cE} and A_{cr} the inlet had sufficiently high velocity than what was required (Fig 6). Normally in such circumstances, the inlet should enlarge its cross-sectional area so that it can attain equilibrium. Further reduction in cross-sectional area would have increased its velocity and lead to more scour, but the possibility of the inlet getting choked was not there.

In 2000 condition it can be seen that the A_{cE} has increased a little more than 1000m^2 but the A_{cr} has remained more or less same as that of 1965. The position of A_c (360.6 m^2) has shifted to the left falling arm of the hydraulic curve, from its position in the right falling arm in 1965. However, the A_C is still much larger than A_{cr}. At this juncture it must be mentioned that from the condition of the inlet

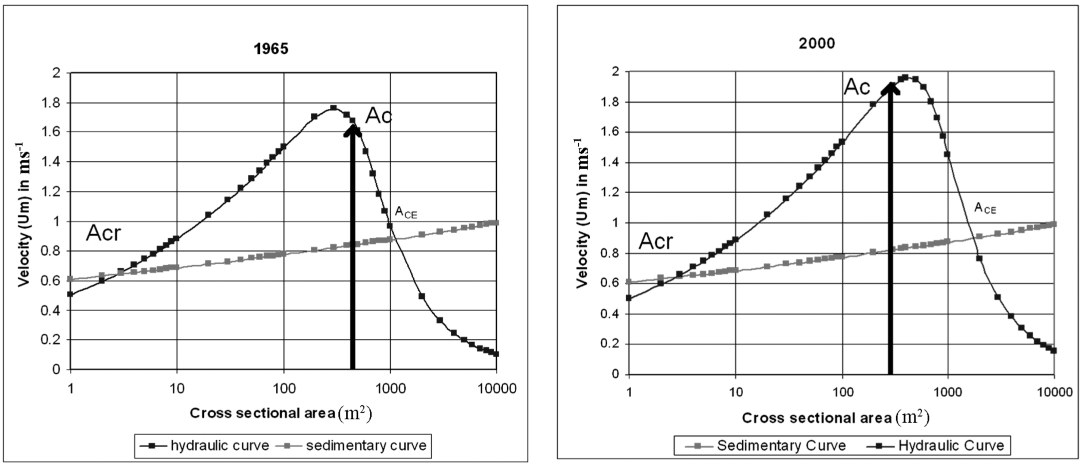


Figure 6. Determination of the stable and critical cross section of the Shrivardhan inlet: 1965 and 2000

in 1965 it could be predicted that the inlet should enlarge its A_C and reduce its velocity until it comes back to A_{CE}. But in 2000 condition it can be seen that the inlet has failed to enlarge its throat cross sectional area and hence has moved further away from its equilibrium cross-section. Though the inlet still has sufficiently high velocity than what is required, it has started showing signs of further reduction in A_C and corresponding increase in velocity. This will result in further scour of the inlet bed at some favoured locations and the excess sand will be re-distributed within the inlet. Since, the inlet has a reverse gradient, there is little chance for the sand to move out of the inlet and hence, shoaling within the inlet will become inevitable. The main inlet has been able to keep its throat cross-sectional area well above the $A_{cr,}$ mainly because of the moderately high tidal prism. However, it must be mentioned here, that the throat cross section, with which all computations have been done, does not reflect the condition of the inlet in all portions. And the alarming fall in cross sectional area, in almost all cross sections (Table 1) indicates that the inlet is undoubtedly suffering from excess sediment input. It may be stated that if the same trend of events continue, then the A_c will go on decreasing, and it will not be long when it may eventually become choked. The mouth of the inlet (towards the sea) has already become extremely shallow due to the sub-surface extension of the bar and has so far maintained itself due to its formidable depth condition near the Kuravde jetty. When this portion of the inlet will start filling up, then there is high probability for the inlet to experience closure. Moreover, the satellite image of the Shrivardhan Bay (2001) shows that the bay interior has filled up substantially, indicated by the development of a central mudflat. From regular field visits it could be ascertained that a formidable part of this central mudflat has accreted above the neap high tide level. In view of this ongoing within-bay siltation it may be stated that the reduced bay capacity will lead to further reduction in the tidal prism and hence less flushing capacity of the inlet.

Conclusion

In view of the poor stability condition of the inlet, it may be stated that the Shrivardhan inlet-bay system is heading towards a “bar-bypassing” situation. In order to understand the temporal changes in bar extension the low tide lines of maps, charts and images have been superimposed with the help of image processing software – Geomatica (version 9.0). The changes within the period have been incorporated from Survey of India topographical map of 1925 and 1968, sounding charts of 1965 and 2000, satellite images of 1998 and 2001, theodolite survey data of 1997 and GPS survey data of 2003 and 2005 (Fig. 7).

The main inlet, marking the corridor opening into the bay is plagued by sedimentation. This is evident from the expansion of the southern end of the spit. From 1968 to 2000 the spit end shows a southerly extension of almost 131 m. it can be seen from the figure that in the period 1925 to 1968, the southern part of Shrivardhan bar showed 150 m extension in its south-eastern portion and marginal increase (25–30 m) in its south-western end. Since 1968, the south-eastern end started showing a receding trend towards west and maximum spit extension is seen in the south-western extremity. From 1968 to 1997 the south-western end of the bar shows an increase of 100 m towards the west. This trend of westward extension seems to get reversed since 2000, when the south-western end started becoming feeble and the south-eastern part again started showing signs of extension. In 2003 and 2005 the bar shows a prominent bulge of about 75 m towards the east. This oscillatory growth of the bar at its south-western and south-eastern end seems to be a cyclic phenomenon. The role of relative

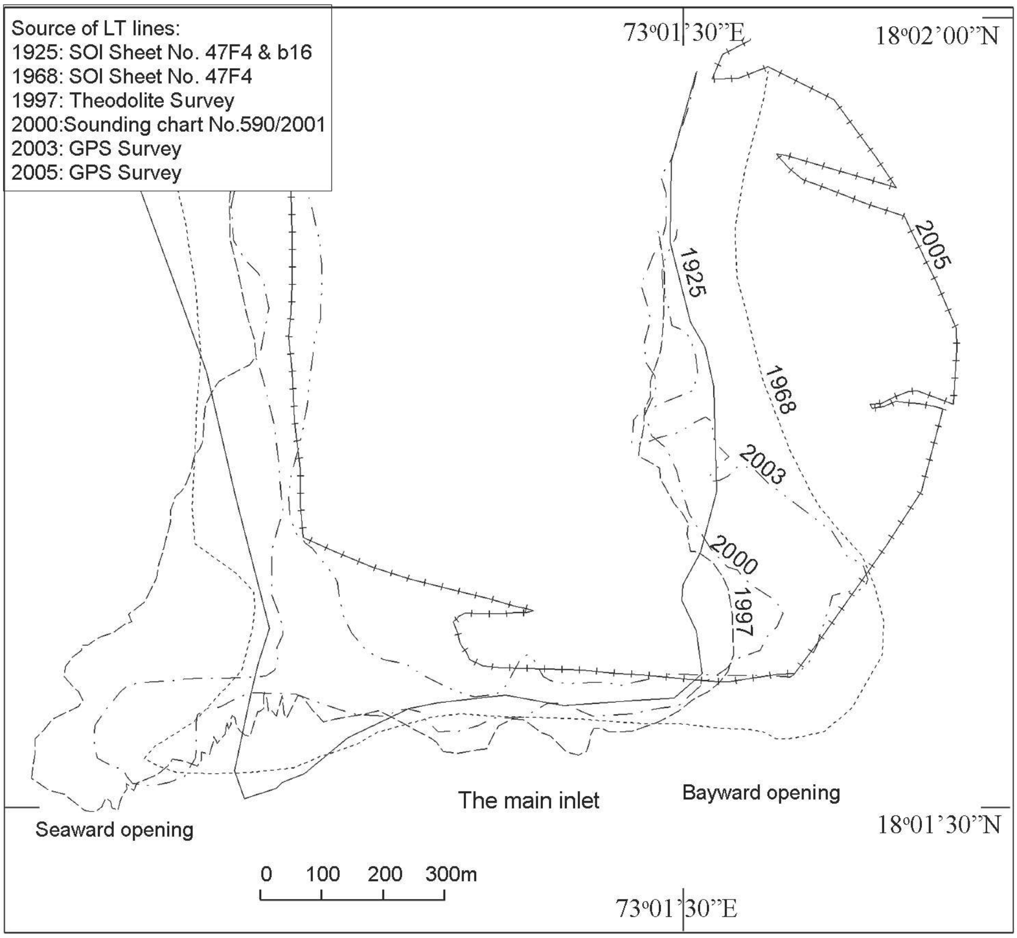


Figure 7. Temporal change of Shrivardhan bar indicated by superimposition of low tide lines.

dominance of the flood and ebb flow may be attributed to such changes in the direction of bar extension. The recent trend of bar development indicates the increasing dominance of the flood flow over the ebb flow. Since 1997, the southern margin of the bar, bordering the main inlet has receded for about 75-100 m towards the north probably due to the northward shifting tendency of the main inlet. Due to poor stability condition, accompanied by shoaling on the southern bank, adjoining the platform the inlet seems to have no option but to try to shift towards the north in order to regain stability. However, observing the trend of within channel siltation in the main inlet and the rate in which the bed levels have increased it is doubtful whether the inlet will be able to establish its equilibrium condition again.

Acknowledgement

The author would like to express deep gratitude to Prof. S.R. Jog, who provided constant inspiration and eminently sound guidance all through. Prof A.J. Mehta, Professor, College of Engineering, University of Florida, helped by providing with his valuable papers and lecture notes. The author is also indebted to Dr. L.K. Ghosh, Civil Engineering Division, CW&PRS for inputs regarding stability of the inlet.

References

Bruun, P. (1978) *Stability of tidal inlets, theory and engineering*. Elsevier, Amsterdam: 376 p.

Bruun, P., Gerritsen, F. and Bhakta, N.P. (1974) Evaluation of overall entrance stability of tidal entrants, *Proceedings of the 14th Coastal Engineering Conference*, ASCE, 2, Copenhagen: 1566–1584.

Bruun, P. and Gerritsen, F. (1960) *Stability of Coastal Inlets*, North Holland Publishing Company, Amsterdam: 123p.

Dean, R. G. (1983) Hydarulics of inlets, In *Reports, Coastal and Oceanographic Engineering Department*, University of Florida, Gainesville, Florida.

Dombrowski, M.R., and Mehta, A. J. (1996) Ebb tidal delta evolution of coastal inlets. In Billy L. Edge (ed) *Coastal Engineering*, Proceedings of the 25th International Conference: 3270–3283.

Escofier, F.F. (1940) The stability of tidal inlets, shore and beach, Journal *of the American Shore and Beach Preservation Association*, 8(4): 114–115.

Keulegan, G.H. (1967) Tidal flow in entrances: Water level fluctuations of basins in communication with the seas, Committee on Tidal Hydraulics, *Technical Bulletin, No. 14*, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Mississippi.

Maharashtra Maritime Board (2001): *Tide tables for minor ports – Murud Janjira.*

Mehta, A.J. (1975) *A Long Term Stability Criteria for Inlets on Sandy Coasts*, Coastal and Oceanic Engineering Laboratory, College of Engineering, University of Florida, Gainesville, Florida: 28p.

O' Brien, M. P. (1931) Estuary tidal prisms related to entrance area, *Civil Engineering*, ASCE, 1(8), 738–739.

O' Brien, M. P. (1969) Equilibrium flow areas of inlets on sandy coasts, Paper 6405, *Journal of Waterways and Harbour Division*, ASCE, 95(WW1): 43–52.

O'Brien, M. P. and Clark, R. R. (1973) Hydraulic constants of tidal entrances: Data from NOS Tide Tables, Current Tables and Navigation Charts, *Technical Report No 21*, Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, Florida

---

Date received: 4 January 2012
Date accepted after revision: 21 August 2012