Batten, B. K., Kraus, N. C., and Lin, L. 2007. Long-Term Inlet Stability of a Multiple Inlet System, Pass Cavallo, Texas. *Proceedings Coastal Sediments '07 Conference*, ASCE Press, Reston, VA, 1515-1528.

LONG-TERM INLET STABILITY OF A MULTIPLE INLET SYSTEM, PASS CAVALLO, TEXAS

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Abstract: Matagorda Bay, Texas, is connected to the Gulf of Mexico by two inlets, Pass Cavallo and the Matagorda Ship Channel (MSC). Pass Cavallo is a natural inlet located at the southwest terminus of Matagorda Peninsula, and the MSC is an artificially cut, deep-draft federally maintained navigation channel approximately 7.2 km northeast. Pass Cavallo was historically stable until the 20th century, when the tidal prism was first reduced in 1935 by division of Matagorda Bay due to deltaic progradation of the Colorado River, and later in 1966 as a result of the construction of the Matagorda Ship Channel. In response to these reductions in tidal prism, the entrance width at Pass Cavallo reached historical minimums as Matagorda Peninsula and Matagorda Island prograded into the inlet. Long-term stability and potential of possible closure of Pass Cavallo are evaluated through theoretical and empirical relationships, and long-term analysis of morphologic change.

INTRODUCTION

Pass Cavallo, located on the south-central Texas coast (Figure 1), is the natural, permanent inlet between Matagorda Bay and the Gulf of Mexico. The inlet has existed for at least 2,600 years, being in approximately the same location for the past 200 years (Harwood 1973). The tidal prism through Pass Cavallo has been decreasing over the last century in response to natural processes and anthropogenic activities.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2007**	2. REPORT TYPE	3. DATES COVERED **00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE **Long-Term Inlet Stability of a Multiple Inlet System, Pass Cavallo, Texas**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Research and Development Center,Coastal and Hydraulics Laboratory,3909 Halls Ferry Road,Vicksburg,MS,39180-6199**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

Proceedings Coastal Sediments ’07 Conference, 13-17 May 2007, New Orleans, LA, ASCE Press, 1515-1528

14. ABSTRACT

Matagorda Bay, Texas, is connected to the Gulf of Mexico by two inlets, Pass Cavallo and the Matagorda Ship Channel (MSC). Pass Cavallo is a natural inlet located at the southwest terminus of Matagorda Peninsula, and the MSC is an artificially cut, deep-draft federally maintained navigation channel approximately 7.2 km northeast. Pass Cavallo was historically stable until the 20th century, when the tidal prism was first reduced in 1935 by division of Matagorda Bay due to deltaic progradation of the Colorado River, and later in 1966 as a result of the construction of the Matagorda Ship Channel. In response to these reductions in tidal prism, the entrance width at Pass Cavallo reached historical minimums as Matagorda Peninsula and Matagorda Island prograded into the inlet. Long-term stability and potential of possible closure of Pass Cavallo are evaluated through theoretical and empirical relationships, and long-term analysis of morphologic change.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**14**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The first cause of this decrease was separation of the historic Matagorda Bay into East Matagorda Bay and the present Matagorda Bay, by growth of the Colorado River Delta across the bay from 1929 to 1935 (Wadsworth 1966; Bouma and Bryant 1969). This initial decrease in tidal prism resulted in shoaling (Harwood 1973) and difficulty in maintaining the commercial navigation channel through the inlet. These issues led to the construction of the Matagorda Ship Channel (MSC), the second and more dominant reason for decrease in the tidal prism at Pass Cavallo. The MSC entrance was cut through Matagorda Peninsula in 1963 approximately 5.5 km updrift of Pass Cavallo at that time. Construction of the jetties and dredging of the inner channel were completed in 1966 (U.S. Army Corps of Engineers (USACE1992)).

The deep-draft MSC enters the bay 7.2 km (as of December 2006) to the north of Pass Cavallo and is a more efficient tidal channel by joining with a deeper and more central portion of the bay. Due to this, the MSC has captured much of the tidal prism forming flowing through Pass Cavallo, resulting in a decrease in inlet width over the last half-century. Figure 2 shows the configuration of the inlet at the time of the opening of the MSC in 1965 and in December 2006.

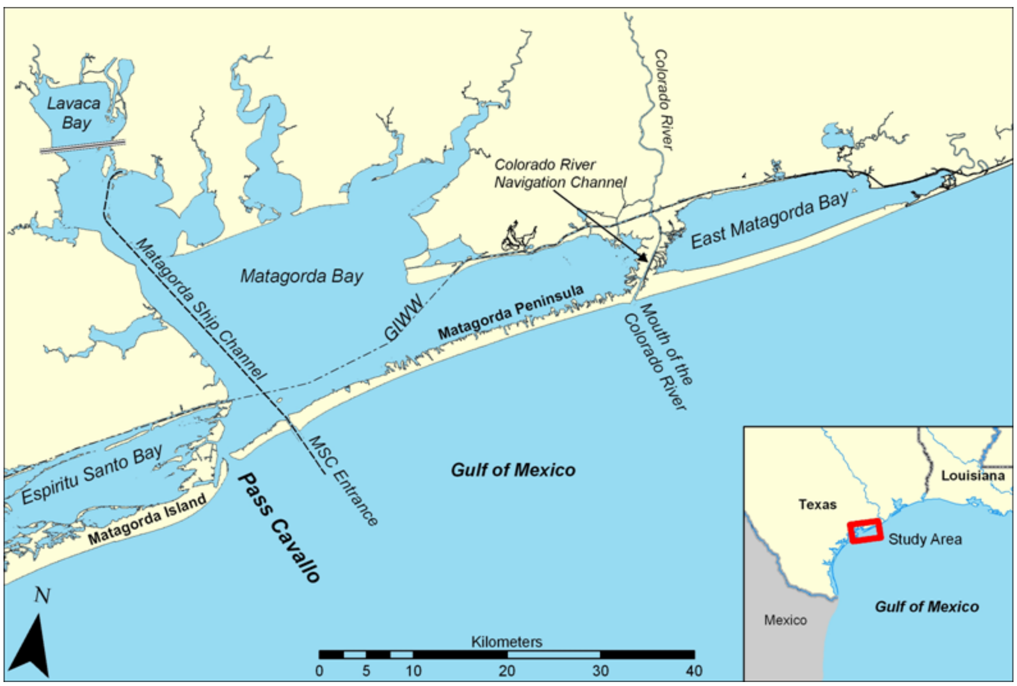

Figure 1. Location map for Pass Cavallo

Previous studies have not been unanimous about the long-term stability of Pass Cavallo. Ward (1982) concluded that the inlet was "shoal unstable," and van de Kreeke (1985) stated that Pass Cavallo would ultimately close because of the presence of the MSC entrance. Van de Kreeke (1990a, 1990b) concluded that multiple inlets to the same bay system cannot exist and that, eventually, at most one would remain. On the other hand, Price (1952) noted that northerly wind fronts, common along the Texas coast from October through May, force water into the southwest corners of Texas bays, promoting existence and stability of channels in those corners (See Kraus 2007, this volume). Wind setup of water against the southwest shore of Matagorda Bay produces an ebb discharge (wind tide) that adds to that of the astronomical tide. Price (1952) also found that Texas bays from Matagorda Bay and to the south tend to have one inlet per bay, located in the southwest or southeast corners. Harwood (1973) concluded that Pass Cavallo would remain open based on geomorphic analysis and consideration of wind tides.

Therefore, there is uncertainty and concern that the existing MSC and possible enlargement of its entrance being considered might accelerate closure of Pass Cavallo. If Pass Cavallo were to close, the discharge at the MSC entrance would become greater, promoting scour and potentially compromising navigation reliability. The natural water exchange and path through Pass Cavallo for organisms and nutrients would also be lost.

This study proceeded by conducting four separate activities as (a) a tidal inlet morphologic analysis based on existing predictive equations, (b) survey of the entrance to Pass Cavallo, (c) numerical modeling of hydrodynamics, and (d) an analysis of inlet width and spit growth shoreline change.

Figure 2. Width of Pass Cavallo has decreased due to spit encroachment and ebb shoal collapse since construction of the MSC.

ANALYSIS AND RESULTS

Empirical evaluation of inlet cross-sectional stability

It is empirically known that a stable inlet located on a sandy coast will have a mean-maximum velocity through it of approximately 1 m/sec (Escoffier 1940; Bruun 1968). By "mean-maximum velocity" is meant the average of a regularly occurring maximum velocity, such as would be generated during spring tide. The mean-maximum velocity V_{mm} can be obtained as:

$$V_{mm} = \frac{\pi}{CT} \tag{1}$$

where T is tidal period, and C =6.6x10^{-5} is an empirical coefficient with units m^{-1}. For a semidiurnal inlet, T = 12 hr, 25 min = 44,712 sec. Then, Eq. 1 yields V_{mm} = 1.06 m/sec, in agreement with empirical observations for, at least, many semi-diurnal inlets. For a tide that is predominantly diurnal, the tidal period is 89,424 sec, giving V_{mm} = 0.53 m/sec (Kraus 2007). There are relatively few inlets worldwide in a diurnal tidal setting, making empirical validation of this result difficult.

The conclusion is that an inlet in a diurnal tidal setting may require a smaller mean-maximum tidal velocity to maintain channel cross-sectional area stability as compared to inlets in a semi-diurnal setting, the more common type of inlet. For Pass Cavallo, this smaller required value of V_{mm} by astronomical forcing may be an overestimate, because the contribution to the ebb discharge by wind setup in the bay was neglected. A smaller value of V_{mm} works in favor of the preservation of Pass Cavallo.

Tidal Prism

Harwood (1973) and Ward (1982) examined tidal prism at Pass Cavallo over the last century. Figure 3 plots data compiled from those two sources as well as a point for year 2004, in addition to data for a possible deepening and widening of the MSC, based on calculations with the ADCIRC model reported in Kraus et al. (2006). Harwood (1973) studied the Pass Cavallo flood shoal and computed the tidal prism through estimation of effective bay surface area, including a portion of Espiritu Santo Bay, multiplied by the estimated tidal range. Ward (1982) estimated tidal prisms based on measurements of the current and bathymetry in 1959 (prior to opening of the MSC) and in the 1970s. He found that, by the mid-1970s, the tidal prism at Pass Cavallo had decreased by half, similar to results of Harwood (1973).

In addition, Ward (1982) reports maximum values of the current ("during the race of tide") through Pass Cavallo to be on order of 1 m/sec in 1959 and of half that value in the 1970s. Ward (1982) notes that the tidal prisms for Pass Cavallo and the MSC in the 1970s were approximately the same, as can be seen in Figure 3. Our calculation for 2004, based on a calibrated two-dimensional model (Kraus et al. 2006), indicates that the present tidal prism at the MSC is approximately three times that at Pass Cavallo. The tidal prisms for Pass Cavallo and the MSC are large and comparable to the larger Pacific coast inlets, because the surface area of Texas bays is typically several times larger than the Pacific coast inlets, compensating for the relatively small tidal range as compared to the Pacific coast.

A bathymetric survey (Figure 4) was conducted by Frontier Surveying, Inc., Corpus Christi, TX, for the present study to determine the minimum cross-sectional area of Pass Cavallo. Depth across eight transects is shown in Figure 5. Maximum depth in the channel reaches 9 m MSL, and the cross-sectional area, calculated by integrating the curves to MSL, ranged from 3,470 m^2 along Transect 1 to a minimum of 2,060 m^2 along Transect 8. The latter transect was the limit of being able to navigate the survey boat abeam to incident waves in the Gulf of Mexico that day. Transects 5-8 were interrupted to the south by a large shoal that approaches the channel from Matagorda Island.

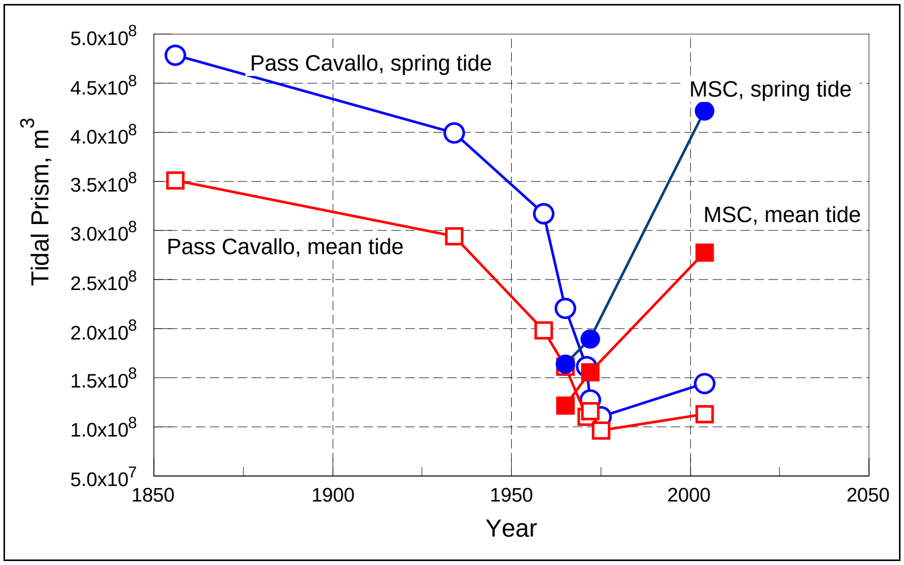

Figure 3. Estimated tidal prisms for Pass Cavallo and the MSC. Lines indicate trends and are not to be interpreted as representing intermediate values.

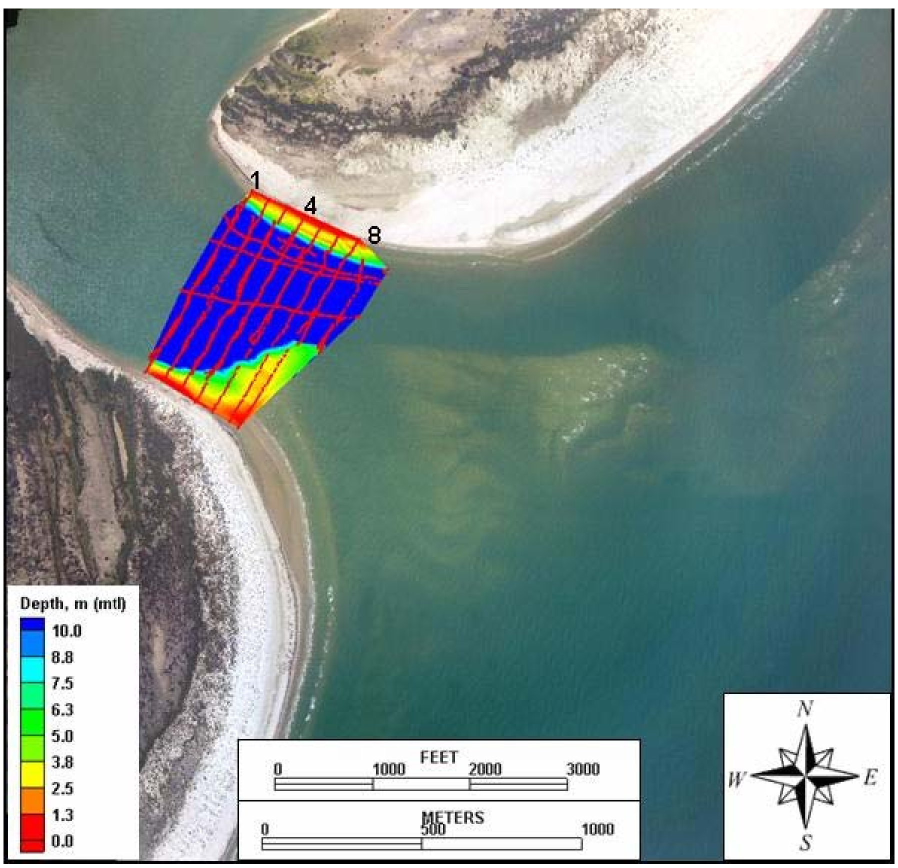

Figure 4. Pass Cavallo cross-sectional survey area of 23 May 2006, superimposed on photograph of 16 May 2006.

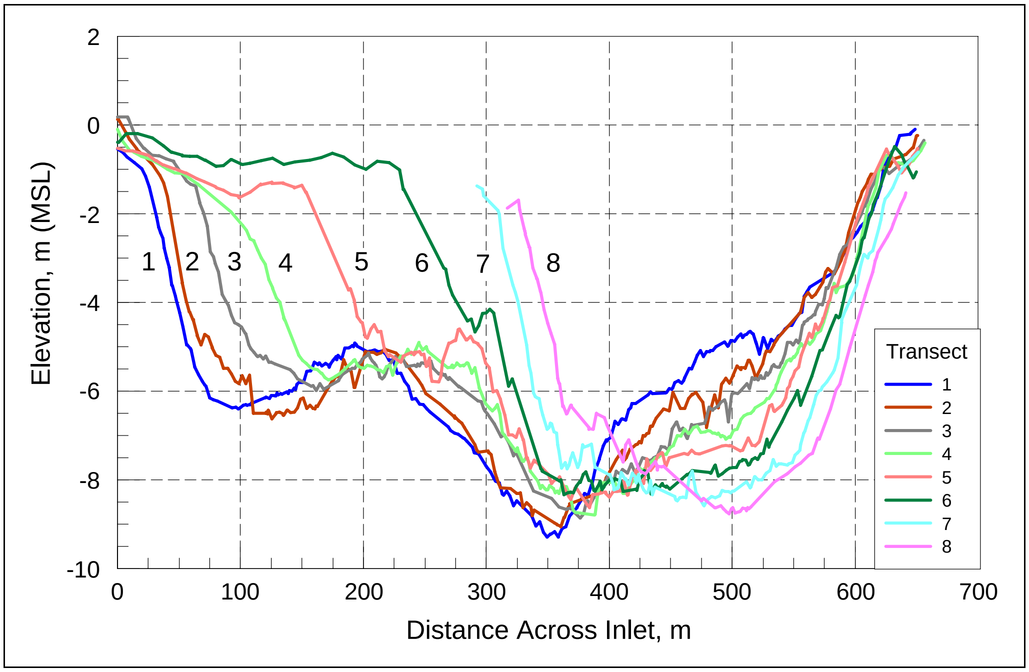

Figure 5. Surveys along eight transects in Pass Cavallo, 23 May 2006. Transect locations are numbered from 1 to 8, starting in Matagorda Bay and progressing seaward.

Accepted empirical relations are available that relate minimum inlet channel cross-sectional area below MSL for a stable inlet and tidal prism. Nishi et al. (2007) have shown that such considerations hold for tidal inlets world wide. Data compiled from six countries were consistent with the relation A_C = 1.75×10^{-04} $P^{0.952}$ (A_C in m^2, P in m^3), which may be considered a global relation that can be applied if no data are available for a given inlet.

Jarrett (1976) analyzed 108 inlets (yielding 162 data points) along the Atlantic Ocean, Gulf of Mexico, and Pacific Ocean coasts of the United States. His objectives were to determine if inlets on the three coasts follow the same inlet cross-sectional area – tidal prism relation, and if inlet stabilization altered that relation. With relatively high correlation coefficients, all predictive relations were found to fit the form:

$$A_C = C P^n \tag{2}$$

in which C (similar to that in Eq. 1) and n are empirically determined. Jarrett (1976) found the exponent n to vary between 0.86 and 1.10 for inlets with no jetty or with a single jetty and between 0.85 and 0.95 for inlets with two jetties. .

For analysis of the stability of Pass Cavallo, the Jarrett (1976) relation describing unjettied and single inlets for the Gulf Coast, developed from 30 data points, was selected as most appropriate. This relation is A_C = 6.992×10^{-04} $P^{0.86}$ (units of meters). With the 2004 value of tidal prism (1.44×10^8 m^3) from Figure 3, the result is A_C = 7,300 m^2. This predicted value of A_C is two to three times larger than those measured from the recent channel cross-sections. This result indicates that Pass Cavallo is presently experiencing a surplus of sediment, and possible sources for this surplus are identified and discussed below.

Morphology change analysis

Aerial photographs were available for this study in both digital and 9' x 9' print format, sourced primarily from USACE archives. Print photographs were scanned on an UMAX 2100XL flatbed scanner at a resolution of 600 dpi and saved in tif format. Selected photographs were then rectified to 1995 1-m resolution digital orthophoto quarter quadrangles (DOQQ) available from the Texas Natural Resources Information System (TNRIS 1995). This photoset provided a high-accuracy (National Map Accuracy Standards, see Anders and Byrnes 1991), high-resolution (1 m pixel) base for rectification.

Few high-quality control points were available in the study area; therefore, control points were improvised from geomorphologic features and vegetation. Rectification quality was evaluated by the goodness-of-fit of the output image to the TNRIS DOQQs. Uncertainty of ground positions from the rectified imagery is estimated at 6-18 m. Images having apparent gross positioning errors were excluded from the study. Shorelines were digitized in the ArcGIS environment from the aerial base using standard techniques (Kraus et al. 2006). The study shoreline was identified as high-water line as defined by National Oceanographic and Atmospheric Administration (2000) and Leatherman (2003). Additional vector shorelines were retrieved from the National Ocean Service (NOS 2005), Texas Bureau of Economic Geology (BEG 2004), and the United States Geologic Survey (USGS) (Morton et al. 2004). In total, 28 shorelines were available from 28 unique dates between 1856 and 2006.

Spit growth was evaluated by establishing two baselines fronting the Gulf of Mexico shorelines of Matagorda Peninsula and Matagorda Island. For Matagorda Peninsula, the baseline originated at the west jetty of Matagorda Ship Channel. The origin of the Matagorda Island baseline was placed at the observed origin of the Matagorda Island spit. Spit growth along each baseline was measured in ArcView 3.2 using BeachTools (Hoeke et al. 2001). Analysis transects were generated along the baseline at 3-m intervals, and the distance of the last transect to intersect the spit shoreline was recorded.

The width of Pass Cavallo was measured from the limited shoreline data that extended into the channel from both sides of the inlet. Inlet width was evaluated in ArcMap from the westernmost extent of Matagorda Peninsula to the easternmost extent of Matagorda Island. Each measurement was recorded along a reference line aligned to the axial orientation of Matagorda Peninsula. This line was positioned at the narrowest section of Pass Cavallo, and then the distance across the inlet was recorded.

Inlet width and Spit Growth

Analysis of available shoreline data showed that the evolution of Pass Cavallo can be generalized into three eras of morphologic behavior (Figures 6 and 7): (1) relative stability prior to 1963, (2) instability and rapid closure from 1963 to the mid-1980s, and (3) relative stability subsequent to 1990.

The initial decrease of tidal prism at Pass Cavallo due to subdivision of Matagorda Bay by the Colorado River caused significant shoaling within the inlet and a navigation concern (Harwood 1973; USACE 1992). Despite this, island morphology was stable, and minimal spit growth is observed during this time. Pass Cavallo maintained a width greater than 3 km between 1856 and 1965. Shoreline change during these years typically shows one or more (inter- or supra-tidal) islands in or around the entrance. The only emergent feature was a small island (called Pelican Island) between Matagorda Peninsula and Island, which first appeared in 1952. Hurricane Carla made landfall at Pass Cavallo in 1961 with an estimated maximum surge elevation of 3.7 m. Extreme conditions associated with this hurricane created 32 washovers along Matagorda Peninsula (Morton et al. 1976) and presumably forced sediment out of Pass Cavallo to create the maximum width of 3.5 km observed in 1965. Overall, Matagorda Peninsula receded approximately 90 m during Era I, while Matagorda Island remained unchanged.

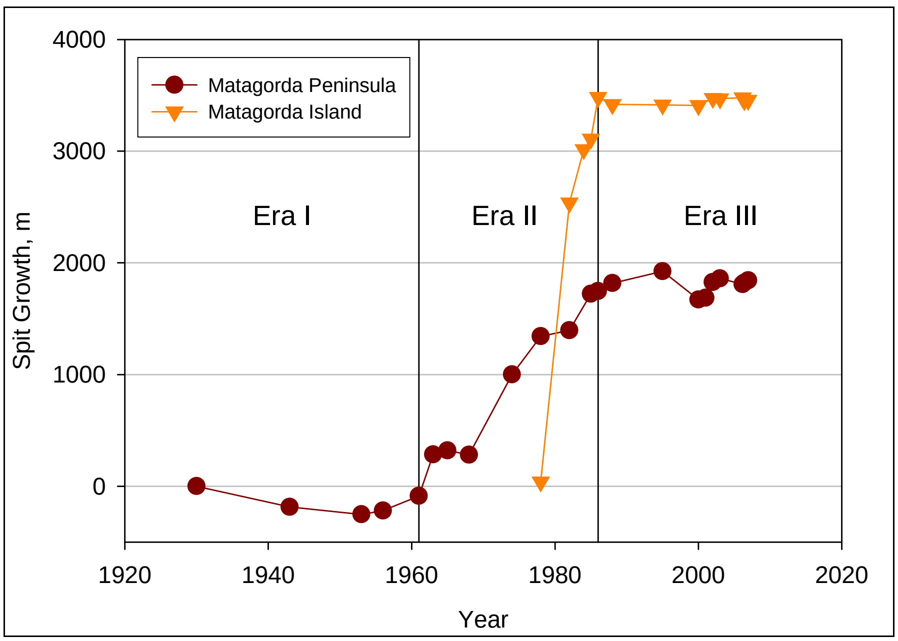

Figure 6. Spit growth by era at Matagorda Peninsula and Island.

The additional loss of tidal prism through Pass Cavallo due to the opening of the MSC (completed in 1966) resulted in significant morphologic change at the inlet, ushering in Era II. This timeframe is characterized by southwestward growth of Matagorda Peninsula that occurred in a rapid, step-wise fashion. Periods of rapid growth are followed by retarded growth and relative inactivity. Net progradation of Matagorda Peninsula between 1963 and 1988 was 1.53 km. In conjunction with this rapid growth on the east side of the inlet, a spit emerged from Matagorda Island in 1978 and rapidly prograded at a high rate to the north-northeast, recurving into Pass Cavallo by 1982. During this 4-year time span, the spit grew approximately 2.5 km. This high rate of growth continued through 1986; when total spit length reached 3.49 km from the point of origin. Inlet width decreased by approximately 2.67 km, at a rate of 127 m/year over this 21-year period. Potential sources for this material are discussed in the following section.

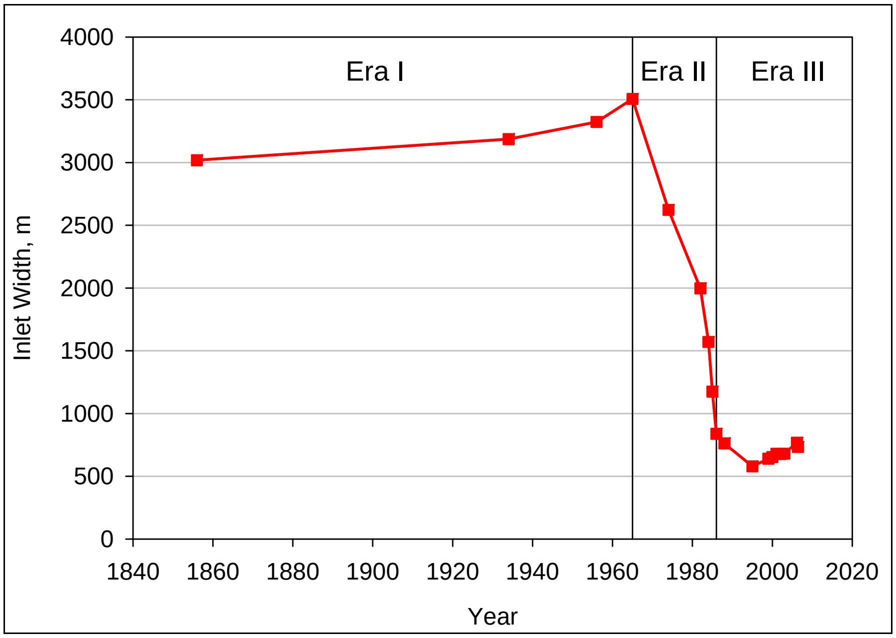

Figure 7. Width of Pass Cavallo, 1856 to 2006.

An apparent maturation of the system occurred in the mid-1980s, as Pass Cavallo achieved equilibrium with tidal forcing in the mid-1980s (Era III). Between 1986 and 2006, spit growth rates of Matagorda Peninsula and Matagorda Island decreased. Matagorda Peninsula prograded 95 m (~5 m/year), whereas the Matagorda Island spit receded west by 24 m (~ 1 m/year). Inlet width decreased by 160 m (9.5 m/year) over this time period.

In summary, Matagorda Peninsula prograded by 1.56 km from 1963 to 2003 and Matagorda Island prograded 3.45 km between 1974 and 2003. Overall, inlet width at Pass Cavallo decreased by 2.76 km. Shoreline change from 1965 through 2006 is shown in Figure 8. Note that although lateral growth of the spits decreased in the 1990s, the planforms began to extend seaward as more sediment was deposited within the inlet complex (1988-2006).

Sediment Sources

Tidal prism calculations indicated that Pass Cavallo was experiencing a surplus of sediment. Morphology change at the inlet subsequent to the opening of the MSC has confirmed that Pass Cavallo has been functioning as a sink within the local sediment budget. This section discusses potential sources for the large amount of material that has accumulated within the inlet complex over the last 40 years.

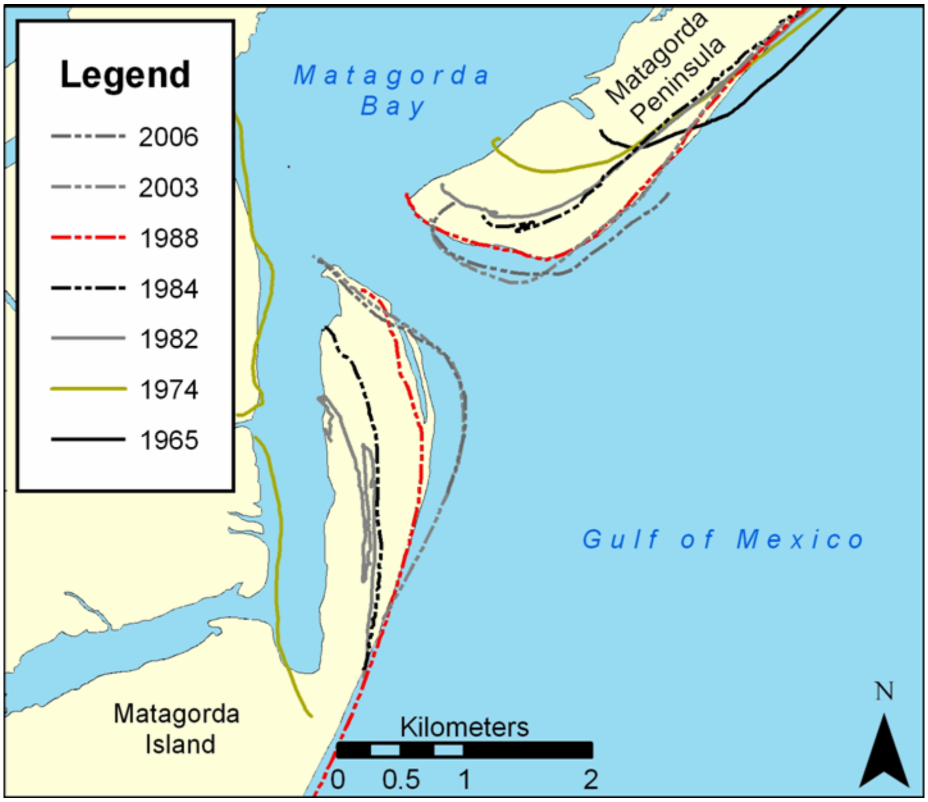

Figure 8. Shoreline time series showing spit progradation into Pass Cavallo.

Ebb-tidal shoals form as a balance between the transporting capacity of the ebb current at an inlet and the capacity of waves to transport material to and away from the inlet. Harwood (1973) studied the flood shoal at Pass Cavallo, which is an extensive sandy platform that protrudes into Espiritu Santo Bay. Flood shoals do not directly depend on wave action for their formation and consist of sediment entering the channel that is transported toward the bay by the flood current. Ebb shoals and flood shoals greatly differ in that, if the inlet reduces in size, migrates, or closes, the ebb shoal will be acted upon by waves and partially or completely disperse, whereas the flood shoal will remain intact. An entire ebb shoal or just a portion of it can become abandoned if an inlet is relocated, if jetties are constructed to confine the ebb current, or if the tidal prism, hence ebb current, decreases. Pope (1991) documents inlets on the southeast coast of the United States for which jetty construction restricted the width of the ebb jet and caused abandonment of lateral portions of the ebb shoal, which then migrated on shore. Kraus (2006) gives a more general discussion of ebb–shoal abandonment and cites other references to the literature. The abandoned portions of ebb shoals will migrate onshore, called "ebb-shoal collapse," if those portions are within the littoral zone.

Ebb shoal volume has been well correlated with tidal prism by Walton and Adams (1976), who concluded that ebb shoal volumes can be larger on coasts receiving less wave exposure, because there would be less transporting capacity to remove the sediment deposited by the ebb current. The following empirical formula was presented by Walton and Adams (1976) to compute the ebb shoal volume V_E for inlets in equilibrium on mildly exposed (to waves) coasts. The Galveston Entrance, TX, and Aransas Pass, TX, were among the 16 inlets analyzed to obtain this correlation:

$$V_E = 8.458 \times 10^{-3} \ P^{1.23} \tag{3}$$

in which V_E and P are expressed in m^3, a conversion from units of cubic yards and ft^3, respectively, from the original formula.

For 1856, Harwood (1973) estimated the tidal prism of Pass Cavallo to be 4.79×10^8 m^3, and for year 2004, we estimate it at 1.84×10^8 m^3 (includes wind tide). By Eq. 3, these tidal prisms give V_E-values of about 400 million m^3 and 124 million m^3, respectively, assuming the ebb shoal achieved equilibrium volume for each of the tidal prisms. If these estimates are approximately correct, they indicate that since about 1966, when the MSC was cut, the excess volume (400 – 124 = 276 million m^3) has been abandoned by the gradually declining tidal prism at Pass Cavallo. Most of the abandoned sand-sized material in the ebb shoal will migrate down coast and on shore and be partially responsible for growth and volume increase of the spits to either side of the inlet.

The hypothesis for abandonment and collapse of a portion of the ebb shoal at Pass Cavallo is qualitatively supported by the analysis of Morton (1977), who noted that spit progradation and shoreline advance at Decros Point (western end of Matagorda Peninsula) did not appear compatible with recession of the shoreline downdrift of the MSC. Morton (1977) found excess material in the downdrift compartment, described the source as “problematic,” and suggested bank and channel erosion as potential sources. These sources are considered by the authors to be inadequate to account for the observed long-term spit growth.

It is hypothesized here that sediment from offshore deposits are also contributing to growth at the end of Matagorda Peninsula and Matagorda Island. The likely source is partial abandonment and collapse of the ebb shoal at Pass Cavallo. This theory is supported by the limited bathymetric data available for the inlet (modern data are not available for comparison). Figure 9 shows a 1934 NOS hydrographic survey (NOS 1934) of Pass Cavallo, overlaid with the 1995 shoreline (BEG 2004). At the time of the survey, the inlet channel was located at the western side of the inlet, and a large ebb shoal is apparent offshore of the terminus of Matagorda Island. Shoreline recession along the eastern extent of Matagorda Island, in addition to the volume of material contained within this shoal, support the deposit as being the source of material for spit progradation into the inlet complex.

Most of the abandonment has occurred gradually over the 43 years since opening of the MSC. After the material in the abandoned shoal is depleted, a significant source of sand tending to close Pass Cavallo will be eliminated, and it is feasible that the inlet will grow (but not return to its historic maximum because of the reduction in tidal prism). The trend in Pass Cavallo for a new equilibrium or possible growth is consistent with the shoreline change analysis of inlet width.

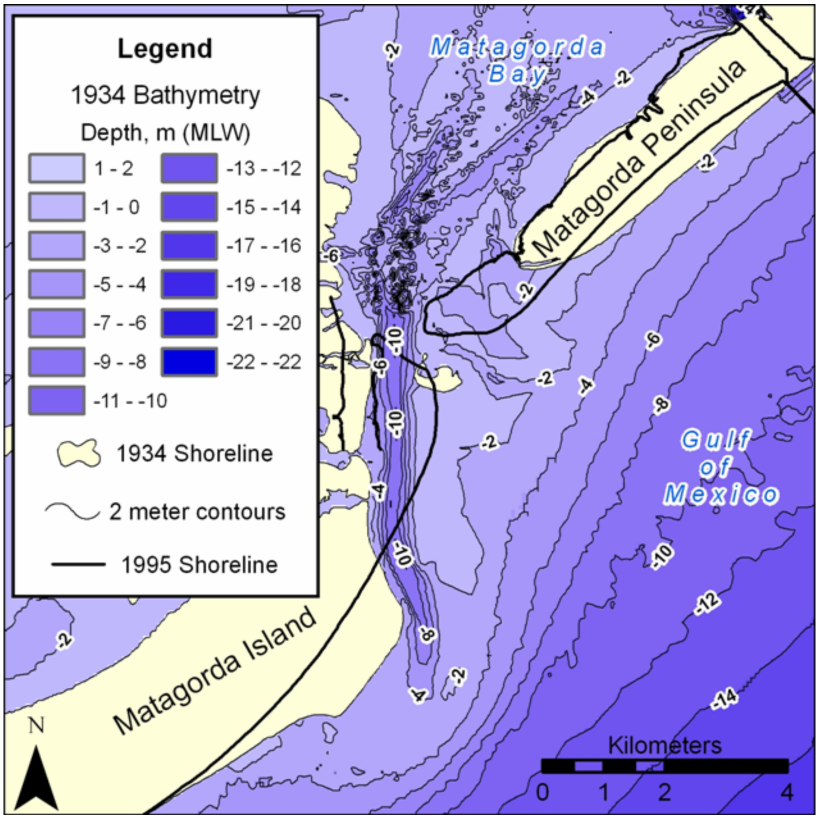

Figure 9. Pass Cavallo channel and ebb shoal in 1934.

Spit progradation on the west side of Pass Cavallo probably also occurs as part of the down-drift inlet offset process (Hayes et al. 1970). The predominant direction of littoral drift is from the northeast to the southwest along Matagorda Peninsula. There are reversals in transport during southerly winds and some storms. Under these conditions, a spit emerged from Matagorda Island and prograded 3.5 km northeast into the inlet. The southwest tip of Matagorda Island shoreline experienced recession (Paine and Morton 1989), and this eroded material could also contribute to support growth of the spit.

CONCLUDING DISCUSSION

Measurements and modeling indicate that the flow through Pass Cavallo is approaching a dynamic equilibrium. This natural inlet has withstood the ebb shoal collapse associated with reduced tidal prism and deposition within the inlet geomorphic complex. The evidence present herein demonstrates that it is not likely that Pass Cavallo will close in the near future. Simple theory indicates that tidal inlets on diurnal tide coasts require a weaker mean-maximum current for cross-sectional channel area stability (Kraus 2007), and the location of Pass Cavallo in the southwest corner of Matagorda Bay works to its favor in having an increased ebb flow due to wind prevalent from the north and northeast in the autumn and winter.

ACKNOWLEDGEMENTS

This research was supported by the Calhoun County Navigation District, through the U.S. Army Engineer District, Galveston, Texas. Permission was granted by Headquarters, U.S. Army Corps of Engineers, to publish this information.

REFERENCES

Anders, F.J., and Byrnes, M.R. (1991). "Accuracy of shoreline change rates as determined from maps and aerial photographs," *Shore & Beach* 59(1), 17-26.

Bouma, A.H., and Bryant, W.R. (1969). "Rapid delta growth in Matagorda Bay, Texas," *Coastal Lagoons, a Symposium*, Univesidad Nacional Autónoma de México, 171-189.

Bruun, P. (1968). "*Tidal inlets and littoral drift*," University Book Co., Oslo, Norway.

Bureau of Economic Geology (BEG). (2004). "Upper coast Gulf of Mexico vector shoreline data," Texas BEG, The U. of Texas at Austin, Austin, TX.

Escoffier, F.F. (1940). "The stability of tideal inlets," *Shore and Beach*, 8(4), 114-115.

Harwood, P.J.W. (1973). "Stability and geomorphology of Pass Cavallo and its flood delta since 1856, central Texas coast," M.A. thesis, The U. of Texas at Austin, Austin, TX, 185 p.

Hayes, M.O., Goldsmith V. and Hobbs, C.H. III (1970). "Offset coastal inlets," *Proceedings12th Coastal Engineering Conference*, ASCE, 1187-1200.

Hoeke, R. K., Zarillo, G. A., and Synder, M. (2001). "A GIS based tool for extracting shoreline positions from aerial imagery (BeachTools)," Coastal and Hydraulics Engineering Technical Note CHETN IV-37, U.S. Army Engineer Research and Development Center, Vicksburg, MS, 12 p.

Jarrett, J. T. (1976). "Tidal prism-inlet area relationships," GITI Report 3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kraus, N. C. (2006). "Coastal inlet functional design: Anticipating morphologic response," *Proceedings Coastal Dyanmics '06*, CDROM, ASCE, 14 p.

Kraus, N. C. (2007). "Coastal Inlets, Texas, USA," *Proceedings Coasal Sediments '07*, ASCE, this volume.

Kraus, N.C., Lin, L., Batten, B.K., and Brown, G.L. (2006). "Matagorda Ship Channel, Texas: Jetty stability study," Technical Report ERDC.CHL-06-7, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS, 153 p.

Leatherman, S.P. (2003). "Shoreline change mapping and management along the U.S. east coast," *Journal of Coastal Research* Special Issue 38, 5-13.

Morton, R.A. (1977). "Nearshore changes at jettied inlets, Texas coast," *Proceedings Coastal Sediments '77*, ASCE, 267-286.

Morton R.A., Miller, T.L., and Moore, L.J. (2004). "National Assessment of Shoreline Change: Part 1, Historical Shoreline Changes and Associated Coastal Land Loss Along the U.S. Gulf of Mexico," USGS open file report 2004-1043, 44 p.

Morton, R.A., Pieper, M.J., and McGowen, J.H. (1976). "Shoreline changes on Matagorda Peninsula (Brown Cedar Cut to Pass Cavallo), an analysis of historical changes on the Texas Gulf shoreline," Geological Circular 76-6, Bureau of Economic Geology, The U. of Texas at Austin, Austin, TX, 37 p.

National Oceanographic and Atmospheric Administration (NOAA). (2000). “Tide and current glossary,” U.S. Department of Commerce, NOAA, NOS, Center for Operational Oceanographic Products and Services, 29 p.

National Ocean Service (NOS). (2005). “Shoreline data rescue project of Matagorda Bay, Texas. Vector shorelines,” National Ocean Service, National Oceanographic and Atmopheric Administration, Silver Spring, MD.

National Ocean Survey (NOS). (1934). “Lead-line survey of Gulf Coast of Texas at Pass Cavallo, NGDC number 03F11494, Survey H05864,” U.S. Department of Commerce, NOAA, NOS, Silver Spring, MD.

Nishi, R., Kraus, N. C., and Kawamori, A. (2007). “Fundamenal study of inlet geomorphology: An approach for a global A-P relationship,” *Proceedings Coastal Sediments ‘07*, ASCE, this volume.

Paine, J.G ., and Morton, R.A. (1989). “Shoreline and vegetation-line movement, Texas Gulf coast, 1974 to 1982,” Texas Bureau of Economic Geology, Geological Circular 89-1, The University of Texas at Austin, Austin, TX, 50 p.

Pope, J. (1991). “Ebb delta and shoreline response to inlet stabilization, examples from the southeast Atlantic Coast,” *Proceedings Coastal Zone '91*, ASCE, 643-654.

Price, W.A. (1952). “Reduction of maintenance by proper orientation of ship channels through tidal inlets,” *Proceedings 2nd Coastal Engineering Conference*, Council on Wave Research, 243-255.

Texas Natural Resources Information System (TNRIS). (1995). Digital orthophotograph quarter quadrangles, 1 meter resolution, 20 February 1995, URL: http://www.tnris.state.tx.us/digitaldata/1mdoqs.htm.

U.S. Army Corps of Engineers (USACE). (1992). “Inlets along the Texas Gulf coast,” Section 22 Report, Planning Assistance to States Program, U.S. Army Engineer District, Galveston, TX, 56 p.

Van de Kreeke, J. (1985). “Stability of tidal inlets - Pass Cavallo, Texas,” *Estuarine, Coastal and Shelf Science* 21, 33-43.

Van de Kreeke, J. (1990a). “Can multiple tidal inlets be stable?,” *Estuarine, Coastal and Shelf Science* 30, 261-273.

Van de Kreeke, J. (1990b). “Stability analysis of a two-inlet system,” *Coastal Engineering* 14, 481-497.

Wadsworth, A.H. (1966). “Historical deltation of the Colorado River, Texas,” in *Deltas in their Geological Framework,* M. L. Shirley, ed., Houston Geological Society, 99-105.

Walton, T.L., and Adams, W.D. (1976). “Capacity of inlet outer bars to store sand,” *Proceedings 15th Coastal Engineering Conference*, ASCE, 1,919–1,937.

Ward, G.H. (1982). “Pass Cavallo, Texas: Case study of tidal-prism capture,” *Journal of Waterway, Port, Coastal and Ocean Division* 108(WW4), 513-525.