Stability of Tidal Inlets; Escoffier's Analysis

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INTRODUCTION

ESCOFFIER PRESENTED HIS THEORY on the cross-sectional stability of tidal inlets in 1940 in *Shore and Beach*[3]. Since then, his semi-empirical method has been used extensively and is still the principle way of evaluating cross-sectional stability of inlets. Unfortunately, in reviewing recent engineering reports and publications dealing with inlet stability, it appears that in a fair number of these studies the intent of the Escoffier analysis has been misconstrued. The two most common misconstructions are

— the separation of stable and unstable inlets is determined by the maximum in the closure curve;

— the well-known correlation of O'Brien[6] between tidal prism and cross-sectional area of stable inlets is treated as an alternate, rather than as an integral part of the Escoffier analysis; this in spite of the clarifying technical aid by Sorensen[9] published by the Coastal Engineering Research Center. Because of the potential impact on the design of new inlets and inlet improvements, these misinterpretations are discussed in detail here. In view of the source of the original paper, *Shore and Beach* appears to be the appropriate forum for this discussion.

Because part of the problem could be in the semantics, it seems appropriate to start with a few definitions. In the context of this paper an inlet is defined as a relatively short connection between bay and ocean. The inlet is referred to as a tidal inlet when the flow is dominated by the tide as opposed to river discharge. Initially it is assumed that the tidal inlets are scoured in loose granular material. Later this condition is removed and it is shown that the stability theory is able to deal with potential shoaling of channels with a hard substrate.

Many tidal inlets are formed by barrier island breaching. As an example, the formation and subsequent evolution of a barrier island inlet at Marco Island, Florida is shown in Fig. 1.

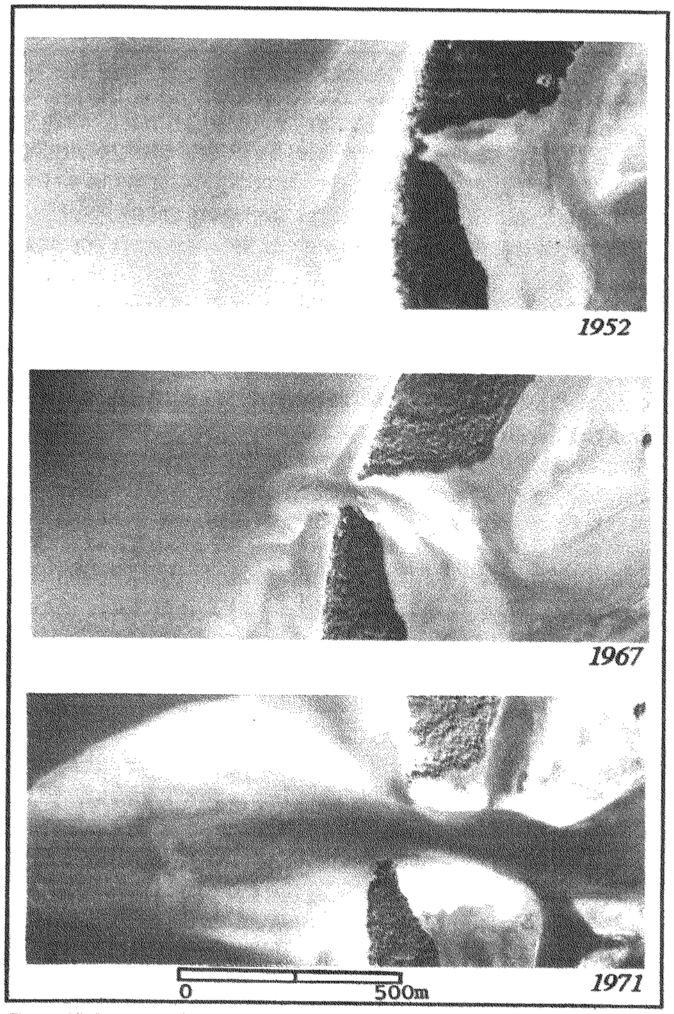

Fig. 1. Tidal Inlet Formation by Breaching of Barrier Island, Marco Island, FL.

STABLE AND UNSTABLE INLETS

Cross-sectional areas of tidal inlets can vary by several orders of magnitude. To understand why cross-sections of inlets have a certain size and to evaluate their permanency, Escoffier[3] developed his stability theory. The basic assumptions underlying the theory are

1. The maximum current speed, $\hat{u}$, is a measure for the sediment transport capacity of the inlet currents.

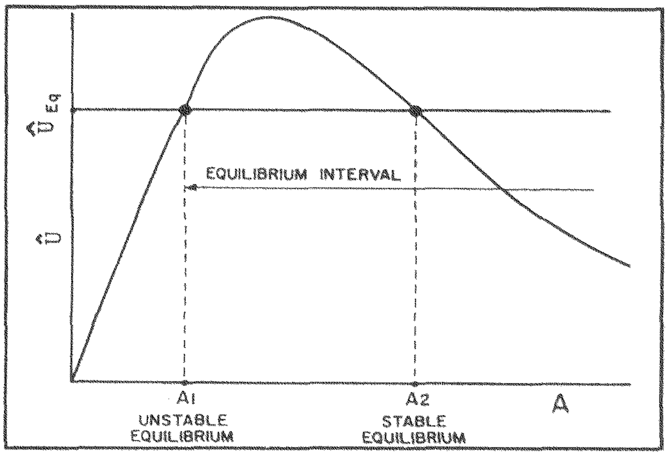

Fig. 2. Escoffier Diagram. Adapted from Escoffier [3] and van de Kreeke[10].

2. Sand is carried into the inlet by littoral drift; when the maximum velocity, $\hat{u}$, equals the value $\hat{u}_{eq}$, referred to as the equilibrium velocity, the sediment transport capacity of the inlet currents is just sufficient to remove the sediment deposited in the inlet.

In general the value of $\hat{u}_{eq}$, referred to as V_{cr} in Escoffier[3], depends on the amount of sediment carried into the inlet, the sediment characteristics, the wave climate and the tidal period. When considering a set of inlets for which these parameters are approximately the same, $\hat{u}_{eq}$ is the same for the individual inlets in the set. It then follow from assumptions 1 and 2 that

$$(1) \quad \hat{u}_i = \hat{u}_{eq}$$

In Eq. (1) the subscript i refers to the individual inlets. The value of $\hat{u}_{eq}$ is approximately 1 m/sec[1,3], the exact value depending on littoral drift, sediment characteristics, wave climate and tidal period.

Eq. (1) corresponds to the horizontal line in the stability diagram presented in Fig. 2. In addition to the sedimentary condition represented by Eq. (1), the inlet velocity has to satisfy the hydraulic conditions, i.e., for given bay and tide characteristics, inlet length and shape of cross-sectional area, the maximum inlet velocity is a function of the cross-sectional area, A. The curve $\hat{u}(A)$ is referred to as the closure curve; a term derived from the literature dealing with the artificial closure of estuaries. The general shape of the closure curve is plotted in Fig. 2. When A approaches zero, $\hat{u}$ approaches zero. This is a result of the bottom friction force per unit mass in the inlet being inversely proportional to A. For large values of A the tidal prism reaches a maximum value and therefore for increasing values of A, the inlet velocity decreases as A^{-1}.

Determination of the exact closure for a real inlet requires a full-fledged two dimensional model for the hydrodynamics of the inlet and the bay. This is beyond the budget of most inlet studies. Instead recourse is taken to lumped - paramater models[5,11] However, the assumption of a uniformly flucuating bay level, that is the basis for these models, is usually not satisfied. Consequently the accuracy of the resulting closure curves is marginal. For additonal information on the calculation of the closure curves and some of the practical problems encontered, the reader is referred to van de Kreeke[12].

The cross-sectional areas A_1 and A_2 in the stability diagram, corresponding to the intersection of the line $\hat{u}=\hat{u}_{eq}$ and the closure curve, are equilibrium flow areas; for these cross-sectional areas the maximum velocity is just large enough to remove the sediment carried into the inlet by the littoral drift. When the inlet cross-sectional area is larger than A_2 its velocity follows from the closure curve $\hat{u}(A)$ and as can be seen in Fig. 2 is smaller than $\hat{u}_{eq}$. Consequently, the sediment transport capacity is too small to take care of the sediment carried into the inlet. The inlet will reduce its cross-sectional area until it reaches the value A_2. In a similar fashion it can be reasoned that for $A_1<A<A_2$, the sediment transport capacity is larger than that required to remove sediment carried into the inlet by the littoral drift and the inlet will increase its cross-sectional area until it reaches the value A_2. Following the same line of reasoning, when $A < A_1$ the inlet will close. Based on the foregoing and borrowing terminology from theoretical mechanics, A_1 represents an unstable and A_2 represents a stable equilibrium flow area. The equilibrium interval for the stable equilibrium flow area A_2 extends from A_1 to infinity. Inlets with cross-sectional areas located in the equilibrium interval are *stable inlets*. When the cross-section has an area smaller than A_1 the inlet is unstable.

As already pointed out in Escoffier[3], a stable inlet does not necessarily imply that the cross-sectional area of that inlet is constant in time and remains equal to the equilibrium flow area A_2. Rather the cross-section will exhibit change. When neglecting short term variations associated with the spring-neap tide cycle, these changes can be divided in seasonal changes and a longterm trend. Seasonal changes are associated with storm activity and are characterized by oscillations of the value of the cross-sectional area about the equilibrium value A_2. It seems reasonable to assume that the magnitude of the seasonal changes increases with a decrease in the resistance of the inlet against change. In case the value of the cross-sectional area remains in the neighborhood of A_2, a measure for the resistance against change (or restoring force) is the slope of the closure curve at A_2. It is of interest to note that using this definition of resistance against change, Skou and Fredsoe[8] have postulated that the stable equilibrium flow area of an inlet corresponds to the point on the closure curve where the slope $d\hat{u}/dA$ is maximum, i.e., at the point of inflection. With some success they have applied this concept to Rockaway Inlet and Fire Island Inlet, Long Island, New York. Because the closure curve is independent of the littoral drift in the inlet region, their concept implies that the equilibrium flow area is independent of the littoral drift. This is a significant departure of the Escoffier analysis and at first sight is contrary to physical intuition.

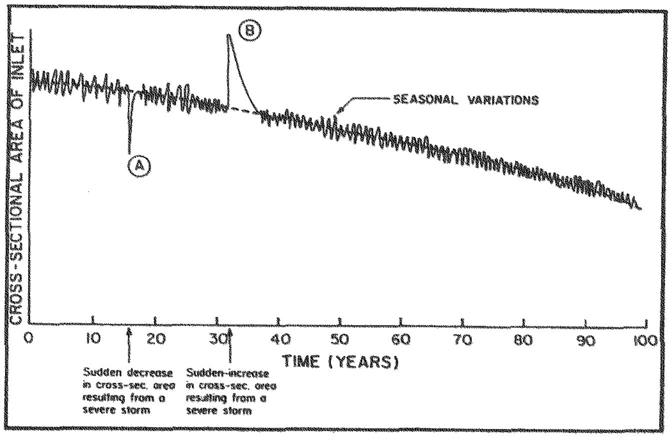

Fig. 3. Changes in Inlet Cross-Sectional Area Adapted from van de Kreeke[10].

In addition to seasonal variations, during the early stages of their existence many tidal inlets have a tendency to become longer as a result of deposition of sediment at the bay- and ocean side of the inlet channel. The elongation of the inlet channel reduces the hydraulic efficiency of the inlet, resulting in a gradual decrease in cross-sectional area. A summary of seasonal and long term changes in the cross-sectional area of an inlet is presented in Fig. 3. The trend line corresponds with the equilibrium flow area A_2.

Earlier in this paper, reference was made to inlets with a hard substrate. Using the diagram in Fig. 2, when the cross-section bounded by the hard substrate, A_h is larger than A_2, the inlet is stable with an equilibrium flow area A_2. The equilibrium interval is reduced from A_1 to ∞ to A_1 to A_h. When $A_1<A_h<A_2$ the inlet remains stable, the equilibrium flow area is A_h and the equilibrium interval is A_1 to A_h. An example is Sebastian Inlet, Florida[2]. For $A_h<A_1$ the inlet will close.

It follows from the foregoing that, based on the stability theory of Escoffier[3], the separation of stable and unstable tidal inlets is at A_1 and not at the cross-sectional area corresponding to the maximum of the closure curve as suggested by O'Brien and Dean[7] and more recently by Skou and Fredsoe[8].

CROSS-SECTIONAL AREA AND TIDAL PRISM.

The use of O'Brien's cross-sectional area-tidal prism relationship as an alternate to the Escoffier analysis results from the fact that in Escoffier's[3], Eq. (1) is never associated with the cross-sectional area-tidal prism relationship. However, the two can easily be reconciled. Assuming $u_i = \hat{u}_i \sin \omega t$, in which ω is the angular frequency of the tide and t is time, it follows

$$\Omega_i = \frac{A_i \hat{u}_i T}{\pi} \tag{2}$$

in which Ω is the tidal prism and T is the tidal period. As before the subscript i refers to the individual inlets in a set of inlets. O'Brien's original set of inlets consisted of inlets on the Pacific Coast [6]. Later, Jarrett[4] determined cross-sectional area-tidal prism relationships for inlets along the US Pacific Coast, Gulf of Mexico Coast and Atlantic Coast and made a distinction

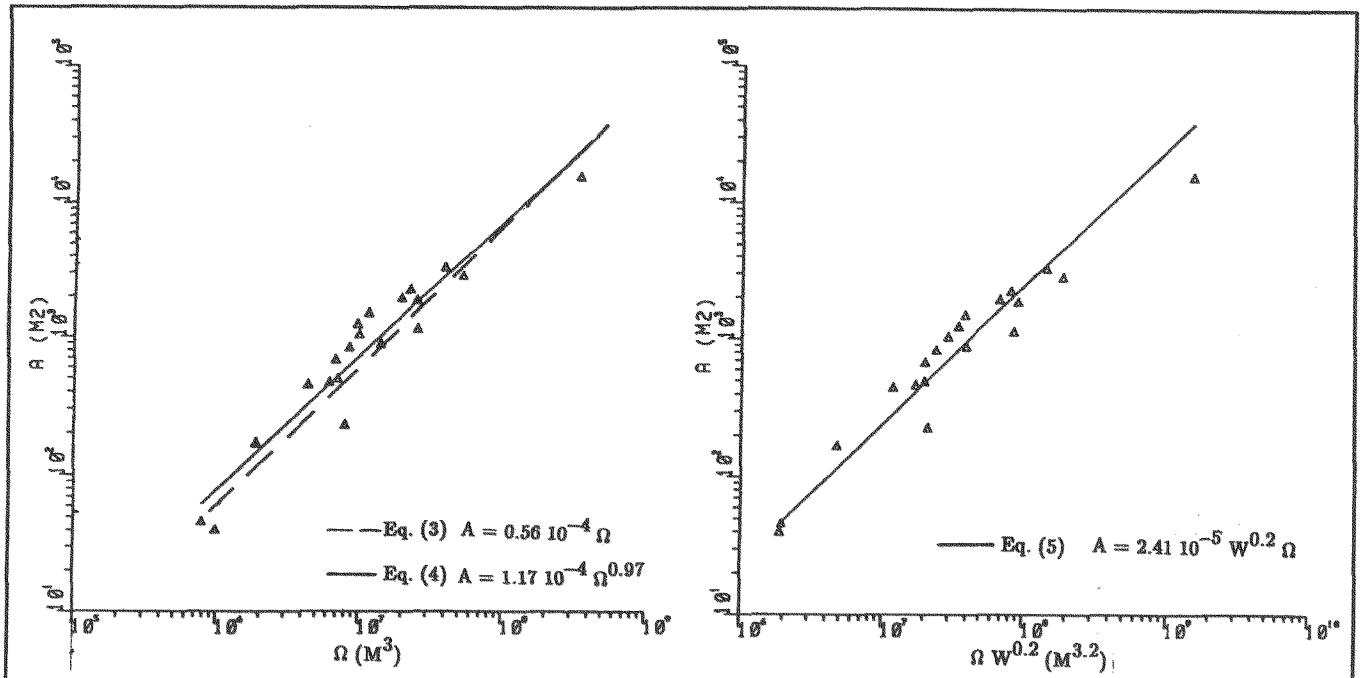

Fig. 4. Cross-Sectional Area-Tidal Prism Relationship for Three Different Correlation Functions. Data Pertains to Inlets Located on the Southwest Coast of Florida. (Yanez[13]).

Ω

between inlets with and without jetties. Here the set of inlets is narrowed down even further and will be restricted to inlets that satisfy the conditions imposed when deriving Eq. (1) i.e., inlets are subject to the same littoral drift, have the same type of sediment, wave climate and tidal period. Making use of Eq. (2) it then follows from Eq. (1) that for that set of inlets

$$A = C\,\Omega \tag{3}$$

in which $C = \pi / (\hat{u}_{eq} T)$ is a constant. Eq. (3) is the most simple form of the O'Brien relationship.

Instead of Eq. (3) the cross-sectional area - tidal prism relationship is usually presented in the form[3,4]

$$A_i = C\,\Omega^n \tag{4}$$

in which C and n are free parameters, or in the form of (Yanez)[13]

$$A_i = C\Omega_i W_i^{1/n} \tag{5}$$

in which W is the width of the inlet channel and n has a value between 3 and 5 depending on the preferred sediment transport theory. Therefore in Eq (5,) C is the only free parameter. Eq. (5) is based on the assumption that the sediment transport capacity of the inlet currents is proportional to $W\hat{u}^n$ rather than $\hat{u}^n$ as assumed in the Escoffier analysis.

To compare the goodness of fit, the three correlation functions are applied to a data set pertaining to twenty stable tidal inlets located on the Southwest Coast of Florida. The results are presented in Fig. 4, which is reproduced from Yanez.[12] The goodness of fit for the three correlation functions differs little and ranges between 41% and 43%. Here goodness of fit is expressed in terms of the fractional error in A. In judging the foregoing it should be realized that even though the data set pertains to stable inlets, the observed values of A do not necessarily correspond to the stable equilibrium flow area. As discussed in some detail in the previous section, values of cross-sectional areas of stable inlets oscillate about the equilibrium value. In addition, the accuracy of the value of the tidal prism (pertaining to spring tide conditions) is marginal . It follows that even if the correlation functions were based on true physics, the fit would not be perfect. In any case the narrow range of the goodness of fit values precludes a conclusion as to what is the better correlation function.

Will we ever be able to improve the goodness of fit? First of all this requires improving the accuracy of the data set, in particular the estimates of the equilibrium flow areas. Secondly it depends on whether there actually exists a relationship between cross-sectional area and tidal prism independent of other parameters. The answer to this lies in field experiments focusing on the small scale physical processes in combination with numerical modelling. It appears that in view of the physical basis and relative simplicity, Eq. (3) is the preferred way of expressing the empirical relationship between cross-sectional area and tidal prism for stable tidal inlets.

In conclusion, the cross-sectional area-tidal prism relationship, Eq 3, constitutes an integral part of the stability analysis and by itself provides insufficient information to determine the equilibrium flow area and corresponding equilibrium interval. Furthermore, it is recalled that Eq. 3 was derived starting from the assumptions underlying the Escoffier analysis. Conversely, when using Eq (3) as the correlation function to describe the relationship between cross-sectional area and tidal prism, it can be argued that the goodness of fit can be used as a measure for the correctness of the premises underlying the Escoffier stability analysis.

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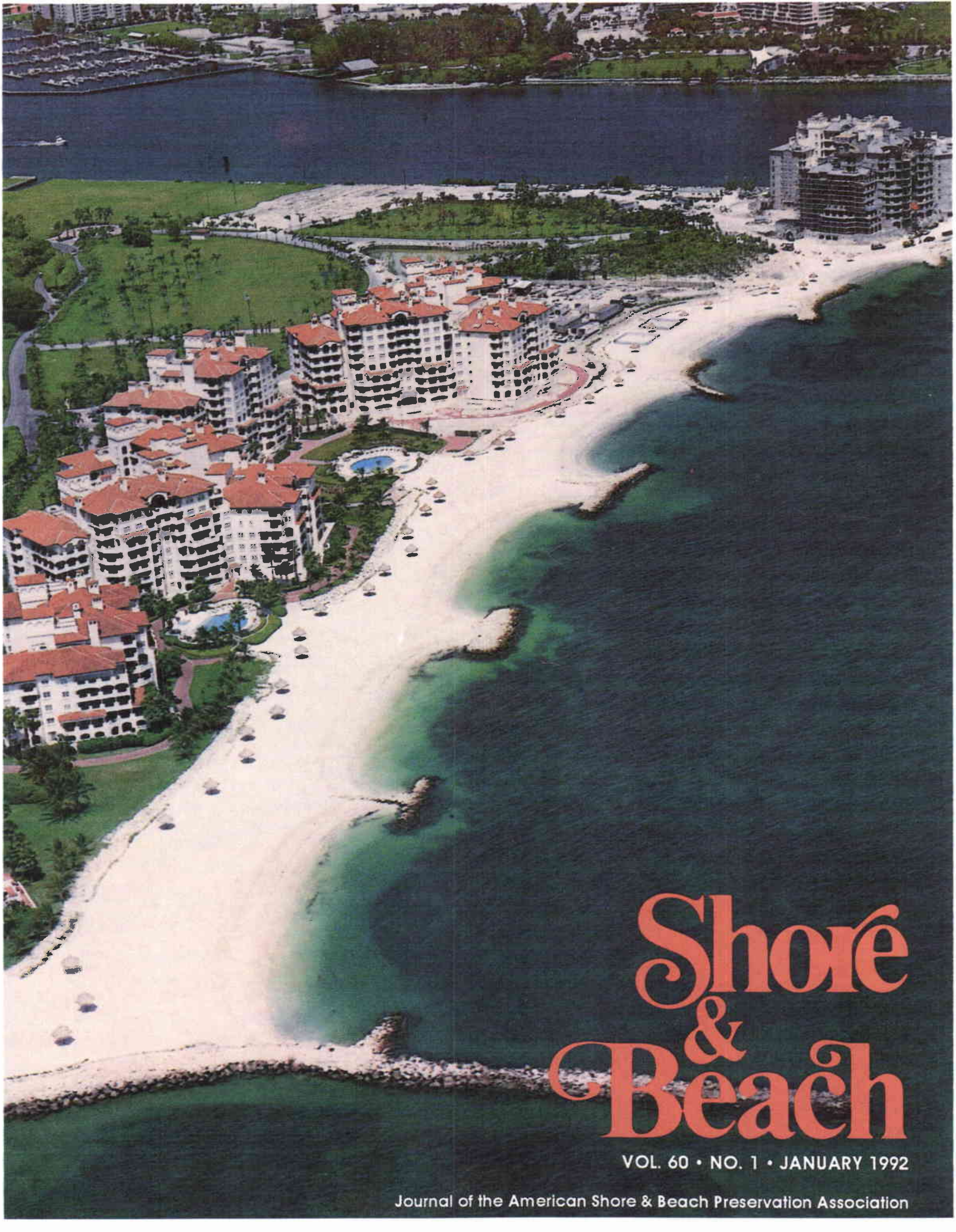

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