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Stability of Tidal Inlets: Use of Hydraulic Pressure for Channel and Bypassing Stability

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ABSTRACT

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This paper reviews briefly existing procedures and methods of channel stabilization and bypassing. The objective in all cases is to achieve an even, non-interrupted stability of the channel in its full length and a reliable, continuous and economical bypassing which retains an essential part of the longshore drift material. Modulation of inlet sub-bottom hydraulic pressures are shown to increase bed load transport, to create major offshore traps, and to transport sand by fluidization to bypassing pumps.

ADDITIONAL INDEX WORDS: *Lift, fluidization, fluidized channel maintenance, fluidized sand traps (sumps), fluidized sand transfer.*

INTRODUCTION

Tidal inlet stability problems have been considered by many authors (BRUUN, 1967, 1968, 1978, 1986; BRUUN and GERRITSEN, 1958, 1960; BRUUN, METHA and JONSSON 1978; BYRNE *et al.* 1980, CZERNIAK, 1977; DEAN and WALTON 1973; DRUERY and NIELSEN 1980; JARRET 1976; VAN DE KREEKE and HARING 1980; WARD, 1982).

The definition of stability invariably has been connected with channel stability usually referring to stability of man-made improvements. This was a logical result of the historic development. Tidal entrances were improved or established to serve navigation. After experience with the adversities associated with tidal inlets on littoral drift shores, such as severe erosion downdrift, interest in bypassing of material grew steadily. Today *inlet stability* refers to *channel and bypassing stability*. Every developed country now requires that adverse effects of inlet improvements on beach stability be eliminated or at least, mitigated. While it is realized that total elimination of adverse consequences may be impossible, mitigation has been accomplished to some extent but far too often with a less-than-satisfactory result.

In Figure 1, (BRUUN, 1978), a number of practical cases of improved entrances are given, including a variety of bypassing systems for non-scouring as well as for scouring channels. Table 1 (BRUUN, 1988) is a review of existing bypassing schemes at the end of 1987 (courtesy: USACE, CERC). The history of the development of bypassing projects progressed from dredging of the inlet channel, through fixed and movable bypassing plants, to dredged traps and submerged weirs, as included in Table 1.

The stability of a tidal inlet channel is a balance between tidal flows and inputs of sediments to the channel. Stability is obtained within a rather narrow range of shear stresses ($\tau = \rho g v^2/C^2$, v = velocity, ρ = density of water; g = acceleration of gravity; C = Chezy coefficient) between flows and bottom. BRUUN (1978, 1986, 1988) gives a thorough review of pertinent factors involved in inlet channel stability. Hydraulic aspects are dealt with by BRUUN, 1978; by ISMAIL, 1983; ÖRZOY, 1977; DRONKERS, 1964; *etc.* Table 2 is just one of several tables in BRUUN (1978, 1986, 1989) which give data on $V_{max\ mean}$ in the gorge channel for spring tide conditions. Table 3 (BRUUN, 1978) is a summary of data. It may be observed that the V (mean max) in the gorge channel varies between 0.9 and 1.1 m/sec for flow over a bottom of fine sand. The lowest figure is for

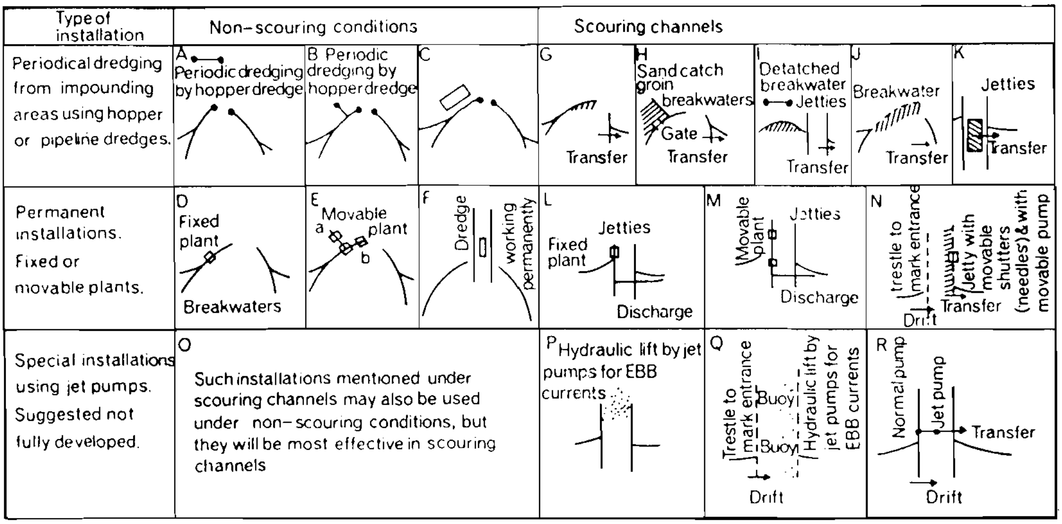

Figure 1. Various principles of by-passing material (Bruun, 1981, 1989).

Table 1. *Sand bypassing plants or arrangements (Bruun, 1989).*

LOCATION	BYPASSING ARRANGEMENT	STATUS 1987
Bakers Haulover, FL (FL = Florida)	None	Permanent transfer from bay shoal trap suggested
Boca Raton, FL	Trap in entrance	Transfer from trap behind updrift spur-jetty
Canavaral Harbor, FL	None	Erosion to be mitigated with material from offshore sand source
Channel Island Harbor California	Trap behind updrift detached breakwater	Operational. Dredged biannual Sand bypasses to downdrift Port Hueneme. Successful
Durban, South Africa	Movable Plant	Abandoned
East Pass, FL	Depressed Weir and trap	Completed 1969. Closed 1985 Serious scour and shoaling problem
Fire Island (Long Island), (NY = New York)	Transfer from bay shoal	Operational. Trap arrangement. Experimental feeder berm constructed downdrift in 1987
Ft. Pierce, FL	Transfer from bay shoals	Transfer of maintenance dredging spoil on downdrift beaches
Hillsboro, FL	Depressed weir and trap	In operation since 1952, success, but leeside erosion still a problem
Houston, Corpus Christi (TX = Texas)	Bay and ocean shoal dredging	Hopper dredging. Disposal offshore
Jupiter Inlet, FL	Transfer from trap in inlet	Downdrift erosion mitigated by nourishment from trap in inlet every two years (Inlet District)
Little River Inlet, SC (SC = South Carolina)	Depressed weir on each side	Weir initially closed, future opening depends upon project requirements
LOCATION	BYPASSING ARRANGEMENT	STATUS 1987
Masonboro, NC (NC = North Carolina)	Depressed weir and trap	In operation, but difficulties with weir experienced, redesigned. South jetty built recently stabilized condition.
Marina di Carrara, Italy	Fixed plant on platform	Operating
Mexico Beach, FL	Jet pump from Crater and Dredge	Research system operated, fixed system installed, but discontinued in 1978. Replaced by floating dredge
Moriches Inlet (Long Island), NY	Fixed plant proposed	Jetty extension with bypass authorized
Murells Inlet, SC	Depressed weir and trap	Maintenance dredging

Table 1, *continued*

LOCATION	BYPASSING ARRANGEMENT	STATUS 1987
Nagapattinam, India Bay of Bengal	Pump on trestle pier with shutters	Operational
New Pass, FL	Ocean shoal dredging	Occasional transfer from ocean shoals
Newport, CA (CA = California)	Undetermined	Recirculation by trap at lower end of ½-mile reach being considered
Oceanside, CA	Jet pumps	Authorized, scheduled to operate by Jan. 1, 1988. Mobile platform for pumping, north fill.
Palm Beach, FL	Fixed Plant	30 year old. Improved through the years. Partly successful.
Paradip, India (Bay of Bengal)	Movable plant on trestle	20 year old Operational, but not successful due to too limited capacity, additional dredging in harbor entrance.
Perdido Pass, AL (AL = Alabama)	Depressed weir and trap	Operational since 1969, successful.
Ponce De Leon, FL	Depressed weir and trap	Weir closed 1985. Transfer of material from shoals to downdrift.
Port Everglades, FL	Ocean shoal dredging for nourishment downdrift (south)	Transfer of material from entrance shoals (federal)
St. Lucie, FL	Jetty weir and trap for bypassing proposed	Construction recommended.
Santa Barbara, CA	Trap in entrance channel	Bypassing to downdrift beaches
Santa Cruz, CA	Dredging of entrance channel	Operating, dredged once per year by Port Commission
Sebastian Inlet, FL	Channel sand trap with periodic transfer to downdrift beaches which erode	Partly successful. Problem with silt in trap
Shinnecock (Long Island), NY	Being studied	Bypass authorized
South Lake Worth, FL	Fixed plant	Partly successful, but limited capacity
Twin Lakes Harbor Santa Cruz, GA	Fixed plant	Operational since 1972
Ventura, CA	Trap behind detached breakwater	Operational, but difficulties with reversals in transport direction
Virginia Beach (Rudee Inlet) (VA = Virginia)	Weir	Jet pumps operated since 1975, supplemented by City's own dredge
Visakhpatnam, India Bay of Bengal	Detached breakwater-trap and transfer by pipeline across entrance to harbor	Operational. Successful at this time

At this time several bypassing projects based on dredging of entrances by hopper dredgers are operated in various parts of the world. New technology is in the testing stage including split hull barges, jet pumps and fluidization pumps which in particular seem promising.

This table was reviewed by Dr. James R. Houston, Chief, Coastal Engineering Research Center, U.S. Army Corps of Engineers, Vicksburg, MS (December 1987).

jetty-improved inlets. This is due to less need for larger stresses.

In Figure 2, (BRUUN, 1978, 1986, 1989), the development of stability with time is illustrated. It includes the possibility of a sudden closure of the inlet by an overwhelming material supply to the entrance.

If currents increase, the cross section opens up due to increased bottom shear. The same happens, if shear stresses are increased due to wave action. Conversely the cross section may decrease by shoaling, if currents decrease below a certain limit. At a stable inlet channel, material flushed by the inlet currents must be deposited "somewhere," perhaps on ocean or on bay shoals, or in a trap dredged in the inlet. The sedimentary balance system in a tidal entrance is shown schematically in Figure 3 (BRUUN, 1978, 1986, 1989). Coefficients α and β with subscripts are ratios of drift. The main activity in the sedimentary system is on the ocean side, with deposition on bay shoals as the major effect on the bay side. Only very fine particles (clay size) will be carried back to the ocean by

Table 2. *Hydraulic characteristics of ten inlets (Bruun, 1978).*

	Inlet	Ω 10^6 m^3	Q $10^3 m^3/sec$	A $10^3 m^2$	M_{tot} $10^6 m^3/yr$	$\frac{\Omega}{M}$	$V_{mean\ max}$ m/sec ± 5%
Brown Cedar Cut, TX	Flood Ebb	ave. 8	1.7	2.4	Varying con-	—	0.7
Mason and Sorensen, 1971)			2.5		siderably		1.05
John's Pass, FL		14	0.9	0.9	0.1	140	1.0
Mehta *et al.*, 1976)							
Sarasota Pass, FL		30	1.8	1.6	0.1	30	1.1
(University of Florida report, 1962)							
Masonboro Inlet, NC		2	1.2	1.2	0.2	100	1.05
before improvement (Magnuson, 1967)		2	1.3	0.95	0.2	100	1.35
Bolinas Bay, CA	Flood Ebb	1.8	1.0	1.3	varying	—	0.8
(Ritter, 1970, 1972)		2	1.1	1.4		—	0.9
North Inlet, SC		10–26	varying	~ 1.0	> 0.4	25–65	up to 1.2
(Finley, 1976)							
Calibougie Sound, SC		200	13.5	13.5	0.2	~ 1,000	1.0
Bimini, Bahamas (Harrison *et al.* 1970)	Ebb						0.8–1.0
Tan My Vietnam (Lee, 1970)		47	2.9	~ 2.9	1.6	30	~ 1.0
Penang Harbor at Georgetown, Malaysia		700	43	44	0.6	~ 1,200	0.9–1.0

Ω = Tidal Prism (104^3 per cycle, ref. spring tides) Q = maximum discharge coresp. to Ω ($10^3 m^3/sec$)
△ = George Acea (minimum cross sectional area (10^2m) M_{tot} = total amount of drift towards the inlet entrance per year ($10^6 m^3$/year) Ω/M − ot = determining ratio.
Vn 2x = mean max velocity in the gorge section during spring tide conditions (m/sec).

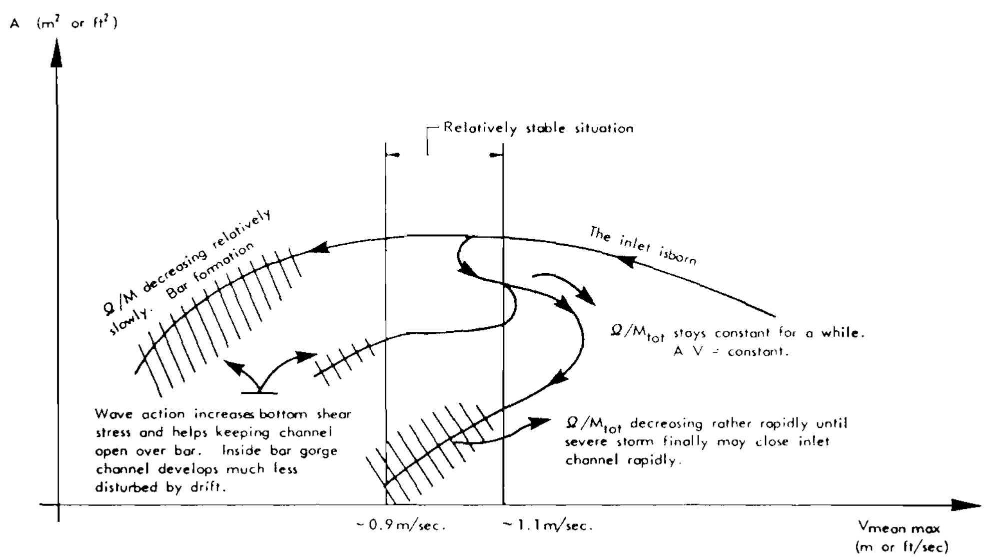

Figure 2. Development of inlet channel under various assumptions (from Bruun, 1978, 1986).

ebb currents. Density currents, however, could become active in the case of strong river flows, causing deposition in wedge or mixing areas.

Figure 3 shows how large-scale circulations may take place on the ocean side (BRUUN 1978, 1986; NIELSEN and GORDON, 1980;

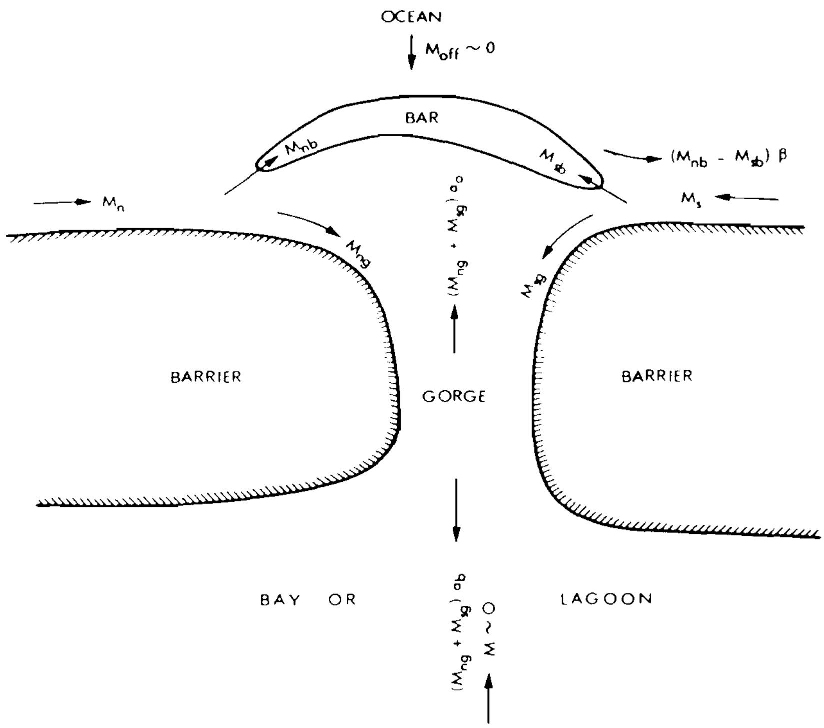

Figure 3. Material transport pattern of an inlet entrance (Bruun, 1978, 1986).

Table 3. *Comparison between* $V_{mean\ max}$ for eight American, six Dutch, and one Danish inlets (Bruun, 1968, 1978).

Velocity	8 American	6 Dutch	1 Danish
$V_{mean\ max}$ m/sec	1.05	1.00 for ebb 1.08 for neutral channels	1.08
	(computed)	(measured)	(computed)

VAN DE KREEKE and HARING, 1980; WALTON and ADAMS, 1976, FITZGERALD, *et al.* 1976; JOSHI and TAYLOR, 1983).

Natural bypassing may take place by tidal currents, or as bar-bypassing, and by combinations of the two different modes. (BRUUN 1968, 1978, 1986, 1989; NIELSEN and GORDON, 1980). Tidal inlet currents carry the material oceanward and/or bayward. The inlet entrance may be designed to facilitate bypassing of material downdrift as shown in later figures. Most tidal entrances on littoral drift shores, however, have an ocean bar or shoal, the magnitude of which depends upon littoral drift and flow characteristics (BRUUN, 1968, 1978, 1986, 1989).

Table 4 gives bar characteristics in relation to the total sediment drift, M_{tot}, and tidal flow or prism, Ω, characteristics (BRUUN, 1978, 1986, 1989). Bars or shoals are undesirable in relation to navigational requirements, but they are usually hard to avoid or control. The oldest system of maintenance was dredging to remove the bar (example San Francisco). At many other localities improvements were attempted by the establishment of bypassing systems which were supposed to improve channel stability as well as to reduce downdrift erosion simultaneously. Such systems are shown in Figure 1. Experience has shown that none of the existing bypassing systems have been able to solve the problems satisfactorily. The result has been continued shoalings and loss of a considerable part of material, mainly to the offshore, thereby aggravating the problem of downdrift erosion. As an example, inlets on Florida's East Coast are probably responsible for approximately 80% of the rosion (BRUUN, 1978; DNR, report by Department of Natural Resources, Florida 1987). Consequently there is a great need for improvement of bypassing procedures, so that material can be transported across a channel instead of being lost to the ocean or being deposited in the inlet channel (BRUUN, 1978, 1986, 1989; WARD, 1982; WINTON and METHA, 1981).

INLET STABILITY, RECENT DEVELOPMENTS

The objective is to obtain satisfactory navigation and bypassing, by achieving minimum variation in channel depth and beach width. Occasional dredging is impractical. We do not want a channel that shoals or a downdrift beach that erodes. The preferable system must assure minimum variation of the channel and must effectively bypass most of the material arriving from either side and from offshore.

Optimum Channel Stability by Continuous Operation

Intermittent dredging does not offer the optimum solution. The system which is needed must be *fully effective at all times*. Such a system may consist of one or more jet pumps, producing a series of holes in the bottom. These holes would function as sediment traps. By operating the jets properly, material would be moved in or out in sequence. Such a system has not yet been implemented due to projected high costs of operation, but jet-"craters" have been established (Santa Cruz, California). Jet arrays are used for silt flushing at piers in San Francisco Bay and Grays Habor, Washington, on a testing basis (JESSEN, 1987). To be acceptable, a system in semi-continuous operation must not involve large energy consumption. The "hydrodynamic lift system" may offer the inlet and beach stability potentially at low cost. A discussion is given below.

Table 4. *Entrance conditions described by Ω and M_{tot}* (Bruum, 1978, 1986.)

Location	Ω $10^6 m^3$/cycle	M_{tot} $10^6 m^3$/year	Ω/M_{tot}	Condition Depth Gorge	Ocean Bar
Calibogue Sound South Carolina, USA	200	0.2	1,000	12 m (40′) no protection	6 m (20′)
Penang Harbour at Georgetown, Malaysia	700	0.5	1,400	18 m (60′) no protection	9 m (30′)
Eyerlandse Gat Holland	200	0.5-1	300	12 m (40′) no protection	6 m (20′)
Port Aransas Texas, USA	40	0.2	200	Dredged and jetty protected to provide greater depth	
Longboat Pass Florida Gulf Coast	15	0.1	150	4.5 m (15′) groin updrift	2.7 m (9′)
Thyborφn Denmark	100	0.8	125	12 m (40′) short jetties	9 m (30′)
Gasparilla Pass Florida Gulf Coast	10	0.1	100	4.5 m (15′) groin updrift	1.2 m (4′)
Masonboro Inlet, North Carolina (before improvement)	20	0.3	70	4.5 m (15′) unprotected	3 m (10′)
North Inlet South Carolina, USA	10 (20)	0.4	25 (50)	6 m (20′) varying unprotected	3 m (10′)
Oregon Inlet North Carolina, USA	60	1	60	9 m (30′) unprotected	3 m (10′)
Ponce de Leon Inlet Florida Atlantic Coast	15	0.4	40	5 m (17′) unprotected	3.6 m (12′)
Sarasota Pass Florida Gulf Coast	3	0.1	30	7 m (23′) unprotected	1.5 m (5′)

Bypassing Stability—Improvement of Pumping Procedures

Jet pumps arranged in arrays were introduced (*e.g.* Neerang, Australia) but have not experienced wide acceptance. In selecting an array of 24 jet pumps for its St. Lucie proposal, the U.S. Army Corps of Engineers (1986) also considered a Splat Lagoon Tool, which is a barge-mounted submersible hydraulically-powered pump, and a Crater Sink System, which is a submerged hydraulically-powered pump fed by six hydraulically-rotated augers. A ducted jet fluidization system was proposed by scientists at Scripps Institute of Oceanography and tried at several inlets (WILSON 1970). The USACE is also proposing fluidization systems at Oceanside, California (CLAUSNER, 1986). Ship-based pumping equipment has been improved but a breakthrough is needed in the tidal inlet bypassing area. In the U.S.A., there is a shortage of effective shallow draft rough water multi-purpose dredging equipment.

THEORY OF HYDRAULIC LIFT BY PRESSURE TO INCREASE BED LOAD TRANPSORT

Figure 4 shows equi-potential and streamlines for a pressure pipe buried in a sand bottom.

r_o = radius of buried pipeline (m)
d = depth of bottom of buried pipeline (m)
H = pressure-potential in pipe compared to pressure at the bottom for a certain discharge; (Q m^3/sec/m, permeability (m/sec), d and r_o (m)
k = permeability co-efficient (m/sec)
(k = 0.8 .10^{-4} for 0.1 mm sand; 1.5 10^{-4} for 0.17 mm sand and 3.0 10^{-4} for 0.2 mm sand)
Q = discharge (m^3/m/sec)
The following relations exist:
Potential

$$H_{pipe} = \frac{Q}{2\pi k}\left(\ln\frac{2d}{r_o}\right) \qquad Q = \frac{2\pi kH}{\ln 2d/r_o}$$

$$dh/dy = \text{average pressure gradient} = \frac{-Q}{k\pi d} = \frac{-H}{d\ \ln(2d/r_o)}$$

For fluidization the gradient dh/dy must be ~ 1 (WEISMAN, COLLINS, and PARKS, 1982; BRUUN, 1984).

Steady-State lift theory may be derived from classic permeability equations by determining the hydraulic head necessary to create various flows through sands. Of particular interest is the hydraulic head per unit depth (pressure gradient). The pressure gradient is then used to increase bed load transports by the reduction in effective weight of sediments due to the changed hydraulic pressure at the shear stress interface.

The bed-load function (BRUNN, 1978; FREDSOE, 1984; MADSEN AND GRANT, 1976, TAYLOR AND GRANT, 1976) may be written:

$$\phi(t) = 40\ (\psi_w)^3$$

$\phi(t)$ is the instantaneous value of the sediment transport function, $\psi(t) = \tau_o(t)/(S-1)\rho gd$ is the instantaneous value of Shields parameter (BRUUN *et al.*, 1978, section 4.3). (τ_o = bottom shear stress (force/m^2), ρ = density, d = grain diameter).

$$S - 1 = \rho s - \rho w/\rho w \qquad \rho_s \sim 2.6\ \text{ts/m}^3\ \text{(sand)}$$

From expression "(S-1)" it may be seen that by increasing the pressure gradient, S-1 decreases, because S-1 is now S-(1 + dh/dy). For a gradient of 0.5, ϕ (t) increases $(1.6/1.1)^3$ = 3 to 4 times.

Increase in pressures therefore increases bed load transport. Tests by CARSTENS *et al.* in Norway (1976), however, showed that to achieve an increase in transport and a lowering in threshold stresses, the intergranular stresses, σ, have to be overcome first. Because the intergranular stress plus the excess pore pressure p is a constant, ($d\sigma = -dp$), dh/dy has to be raised to 0.7 to 0.8, before threshold-stresses by the flow and transport are influenced materially. When this has been done and "bonds" have been broken, dh/dy may drop again. Further testing is needed to clarify all soil mechanics aspects of this problem. In practice it is possible to change pressures according to needs. The pressure gradient on the bottom layers has the same effect on bottom material as wave action would have (BRUUN, 1978, 1986, 1989). Using Özhan and Yalciner's results (BRUUN, 1989, chapter 9), it may be shown that wave

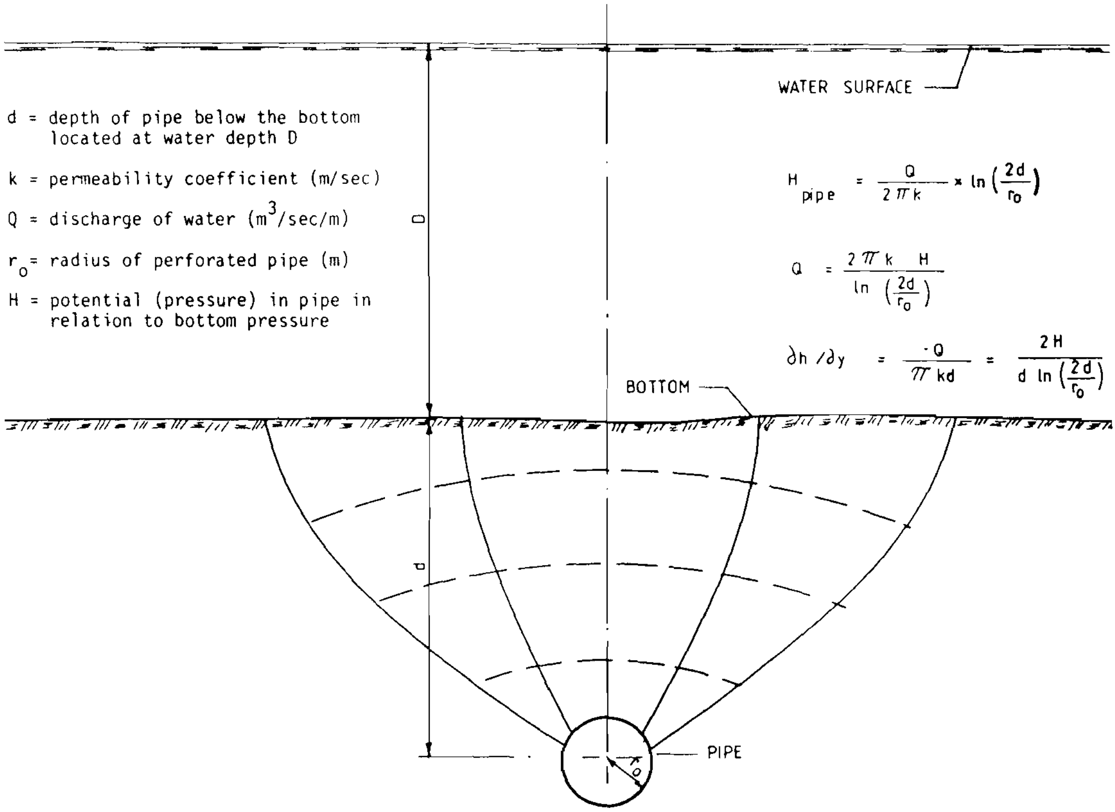

Figure 4. The Development of Pressure by Potential in Perforated Pipe.

action is able to push bottom material in the direction of wave propagation. A gradient pressure increases this capacity further, allowing migration of bottom material towards land. This material is then used "automatically" to increase bypassing capacities, assuming the right trap and pump are installed (Figures 6, 7, and 8).

A DISCUSSION ON PRACTICAL APPLICATIONS

Four examples on practical applications, all involving stability of channel and bypassing stability, are mentioned. The definition of stability is: to achieve minimum variation in inlet depth and width of beach downdrift.

Case One, Figure 5, is an inlet with a dredged, otherwise unprotected channel. It may be improved by lift-pipes placed across the bar, at the same time improving bypassing by combined wave and (ebb) current action. A trap may also be placed in the channel to accumulate materials carried to the trap by ebb as well as by flood currents. This trap has a "lift-system" in the middle which may be emptied whenever needed, *e.g.* by a fluidization pump.

Case Two, Figure 6, has a dredged channel protected by two straight jetties or training walls. The channel over the bar is maintained by hydraulic lift operating solely for ebb currents for simultanous channel maintenance and bypassing. A large trap for bypassing is shown in the entrance as well as outside. The latter is so large that it captures most, if not all of the bed load carried by littoral currents, but it will also be able to trap bottom creep material from the offshore (CARTER *et al.* 1973; BRUUN,

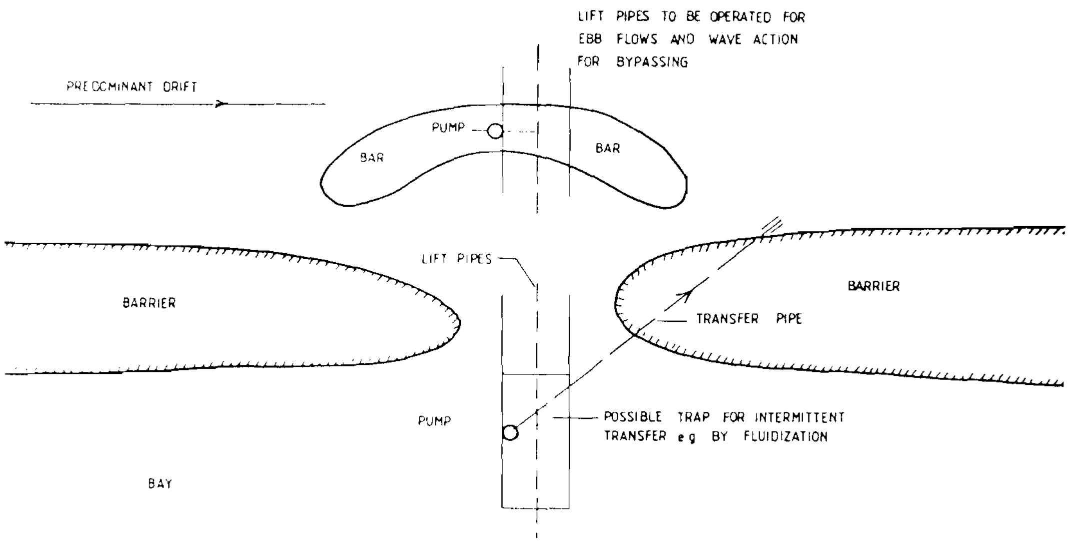

Figure 5. Case one: Stabilization of dredged unprotected channel for navigation and bypassing.

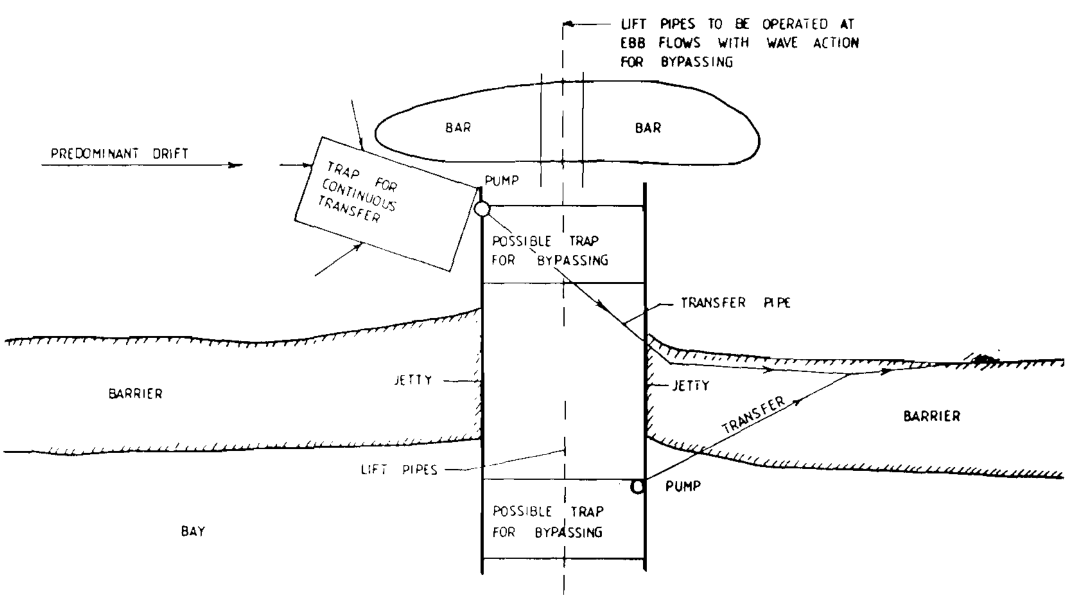

Figure 6. Case two: Stabilization of dredged protected channel for navigation and bypassing.

1989, Vol. 2). In this way bypassing quantities may be increased considerably above normal. Inside the jetties another trap is established to capture material brought straight in by flood currents and by bottom creep due to wave action. Both traps are best operated by fluidization systems which can transport the sand to the pump. Finally a third trap may be established further "upstream" to catch bed load material from either side. This trap may be operated for lift only, or intermittently, for transfer by fluidization. This all depends upon hydraulic and sedimentary characteristics which must be known and analyzed properly.

Case Three, Figure 7, is an inlet entrance improved by special-geometry jetties for channel stability and bypassing. Lift-pipes are used to obtain optimum stability of the channel across an entrance bar or shoal (almost standard). This also improves bypassing by combined ebb currents and wave action. Channel stability is further improved by a trap in the channel operated continually for lift during ebb flows, so that the channel always stays clear. The trap may be emptied intermittently for transfer, by fluidization. Outside the updrift jetty a large trap is established for continuous transfer of material carried to the trap by littoral currents and onshore bottom creep due to wave action. This transfer may also be undertaken by fluidization using the same pump as for the bar lift. The magnitude of the creep may be investigated by (fluorescent) tracers.

Case Four, Figure 8, is an inlet entrance improved by special geometry jetties and a weir in the updrift jetty for channel and bypassing stability (PURPURA, 1977). Lift pipes are placed in the entrance across the bar or shoal as well as in the channel at the trap area to ensure that trap-deposits do not extend into the channel. Transfer from the weir-trap is handled intermittently by fluidization pumps. In addition a large trap to intercept littoral drift and bottom creep material may be installed at the tip of the updrift jetty. This trap is operated continually by fluidization systems, which also operate the bar-lift.

Advantages Associated with the Use of Hydraulic Lift for Channel Stability

The advantages of using hydraulic lifts to increase flushing abilities is well demonstrated in nature by the influence of wave action in "opening up" a cross section (BRUUN, 1978, 1986, 1989). It may also be observed at places where nature delivers—free of charge—the hydraulic pressure. Some natural tidal inlets placed themselves accordingly all over the world. The lift may be operated according to needs and particularly during and after heavy storms. The lift is able to direct the sediment transport oceanward or bayward, as it fits the local situation best including consideration to bypassing. The consumption of water may be of the order of 0.001 m^3 to 0.003m^3/sec/m for the

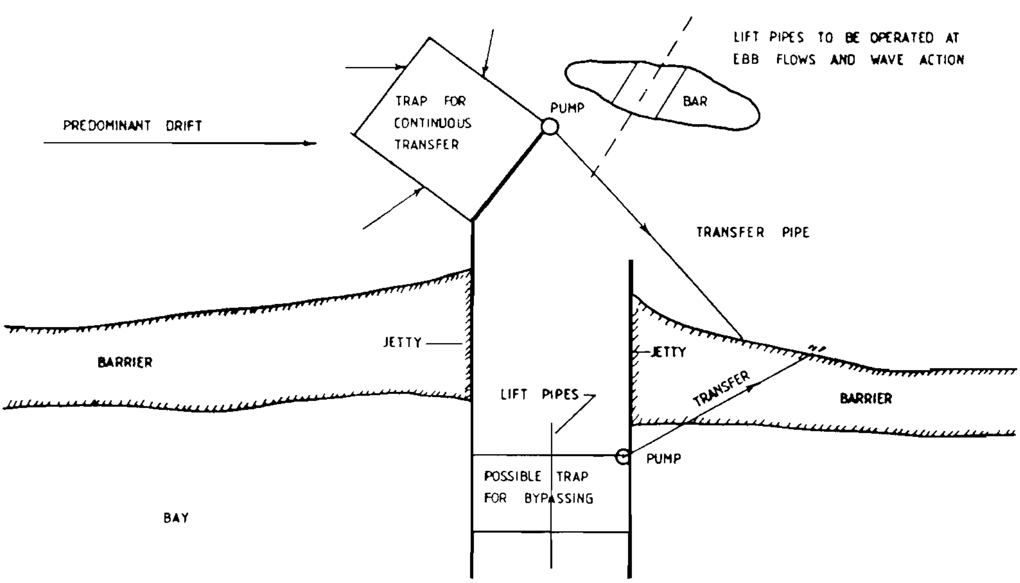

Figure 7. Case three: Stabilization of dredged protected channel for navigation and bypassing.

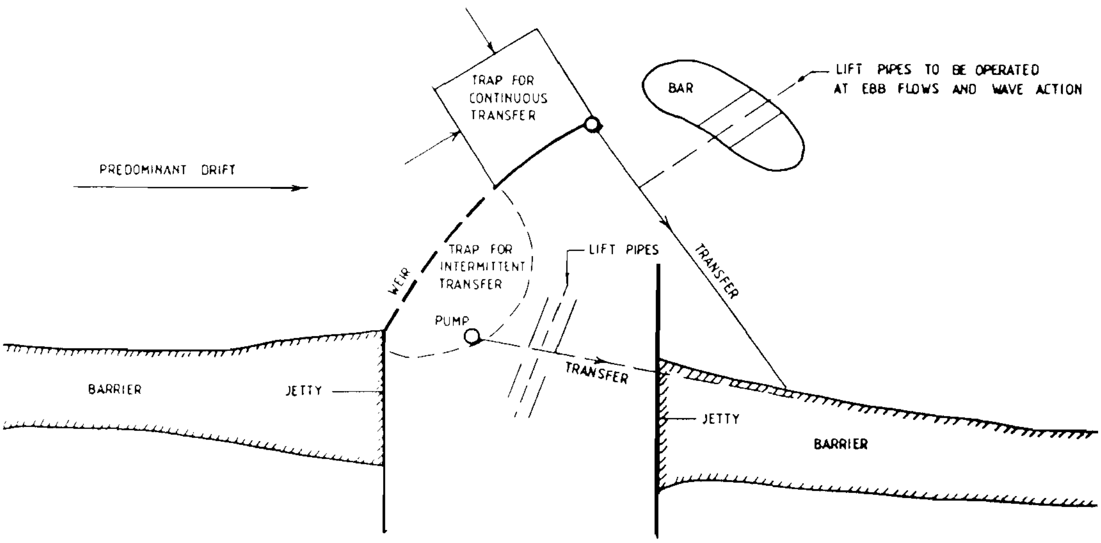

Figure 8. Case four: Stabilization of dredged protected channel for navigation and bypassing.

lift. One may say that a lift system puts more "brain" in the entire stability operation scheme.

Advantages Associated with the Use of Fluidization for Bypassing

Critical requirements for all sand bypassing systems are the abilities to catch and store large quantities of sand and put the stored sand in the bypassing pump intake. Storm storage capacity is necessitated by the episodicity of littoral transport. SEYMOUR and CASTEL (1985) found that on the California coast "almost half of the gross transport occurring during 10% of the time," with the "maximum transport occurring in a single day each year produced between ten times and 600 times the mean daily transport." They concluded that "it is probably reasonable to assume that a comparable level of episodicity occurs in longshore transport on most of the other shorelines of the world. This implies a number of potentially significant corollaries. 1. Sediment bypass-systems must be designed to store very large storm surge inputs, if they are to operate at a constant rate close to the mean load. 2. Bypass systems without surge storage capability will probably require peak capacities on the order of 30 times the mean transport rate. . . ."

In Florida, for their St. Lucie Inlet sand transfer plant proposal, the Army Corps of Engineers (USACE, 1986) proposed a 30,000 cubic meter sump (trap) in rock (with 25,000 cubic meter above it in sand) and a 120 cubic meter per hour pumping capacity for an inlet having a 210,000 cubic meter net annual littoral drift. If one divides the net littoral drift by the number of hours in a year the average hourly drift rate (a value rarely realized) is 25 cubic meters. Pump size chosen was five times this rate and the 30,000 cubic meter reservoir size is more than 1200 times it. These selections were based on computer simulation and optimization of plant cost, operating hours and peak wave energy records.

It is clear that storage capacity is required if one is to catch and hold large storm surges and pump them away over longer time periods using reasonably sized pumps and piping. Fluidization efficiency of the system design must not be impaired by an excessive amount of stored material. Once captured, it is necessary to bring the stored material into contact with the bypassing pump intake. This can be accomplished either by moving the sand to the intake, or moving the intake to the sand. Common methods of accomplishing the latter are floating dredges and fixed base boom mounted intakes.

A disadvantage of floating dredges in this case is that they are limited as to the size of waves in which they can operate. Because most sand bypassing pumps are small and most inlets are relatively shallow, the size of the barges on which they are mounted is limited. Most Florida bypassing dredges, for example, have to cease operations for waves less than 1 meter. This can represent a sizeable percentage of total time, and the lack of freeboard drastically limits their ability to work offshore on bars and deltas. Furthermore, floating dredges are connected to fixed distribution piping systems with floating pipelines having the same wave height limitations.

Fixed-based boom-systems have similar limitations to avoid wave damage and are further limited by reach. For instance, Florida's South Lake Worth Inlet, located on the upbeach jetty, has seen the beach grow beyond its reach, due to periods of inoperation, severely limiting the amount of sand coming to it for hydraulic bypassing. Because of wave height limitations, most bypassing traps have been located in the throat of inlets or in bays inside the inlet.

If rivers and onshore runoffs bring silt to channel traps on outgoing tides, environmentally-imposed shutdowns may limit their operations. Florida's Sebastian Inlet, for example, with an inner channel trap has been forced to provide an onshore sorting operation. Even with sorting it has been enjoined from placing the material back on the beach during the sixth month turtle laying season. Rare birds nesting in the sorting operations area have caused other three month limitations, allowing the system to operate for only three months each year.

Inlet channel traps are exposed only to that portion of littoral transport that enters the inlet and they only catch the part of the dirft that does not bypass or over-run the trap. Thus at best they only catch a small fraction of littoral transport. This inefficiency was acceptable when only navigation was considered. In modern erosion prevention management, those portions of littoral drift formerly allowed to be jetted offshore to form deltas and/or to form bars need to be redeposited on the beach.

Clearly, a bypassing system that will work outside "will provide a better interface with the littoral drift" (USACE, 1986) and allow increased bypassing efficiencies. Important criteria for such a system are that it must: (1) withstand direct wave attack; (2) operate in inclement weather; (3) not be hazardous to beach users; (4) offer minimum detraction from the natural beauty of the seashore; (5) not be ecologically degrading or detrimental; (6) not allow over-pumping, *i.e.* pumping at a rate exceeding the littoral transport rate (USACE, 1986). Fluidized sumps and transport systems appear to meet all of this criteria, each of which may be considered.

(1). **Direct Wave Attack.** The multitude of offshore drilling platforms, lighthouses and beach piers surviving storms are proof that vertical pile pumping platforms can be built that will withstand direct wave attacks. The horizontal fluidization pipes buried beneath the top of the sand are not exposed to direct wave attack.

(2). **Operation in Inclement Weather.** Such structures can continue to operate in storms. Since gravity flow down slope is used as the mode of transport of the sand to the pump, and gravity is not affected by weather, the system is not affected. Remote control and automation can remove the necessity for human presence during storms.

(3). **Non-Hazardous to Beach Users.** The sides of fluidization traps with slopes of the normal angle of sand repose will experience only a gradual increase of slope and will not be dangerous to swimmers or bathers.

(4). **Preservation of Natural Beauty.** The offshore pumping stations may be designed to look like antique lighthouses or similar, now revered by coast watchers.

(5). **Non-Ecologically or Biologically Degrading.** Fluidization does not cause turbidity like some other methods (COLLINS *et al.* 1987). Turbidity is adverse to bottom life. (Improvements in fishing and crabbing have been noted after installation of the Lake LaVista system in Florida.) (COLLINS, *et al.* 1987 a, b). If rock or reefs must be removed to provide sufficient capacity, non-explosive methods of rock cutting can be utilized and extra rock can be brought in to replace lost habitat.

(6). **Non-Overpumping.** Up and down-beach monitoring stations away from the inlet may be used to determine natural non-related erosion or accretion. Automatic safety shutdown can insure that overpumping does not occur. Pre-education of concerned citizens and publication of monitoring results can assuage overpumping concerns. It should be noted that any pump intake lowered into wet sand gradually will create an inverted cone-shaped sump of $\sim \pi R^2H/3$ volume (R = radius, H = depth). The chief additional benefits of fluidization pipes are to extend the cone horizontally to create larger storage capacity and to fluidize the sand in the trap so that it can flow to the pump intake. Fluidization allows the use of outside traps that can catch and bypass a majority of the littoral drift, representing important improvements over existing systems. Figure 9 illustrates a three-finger fluidized-sand bypassing-sump (trap) delivering the sand to a central bypassing-pump intake.

CONCLUSIONS

(1). Inlet channels shoal at various degrees depending upon the material transfer to the entrance by littoral drift and bottom creep, in relation to the tidal flow which is proportional to tidal prism. The material may deposit in the channel itself and/or in ocean and bay deltas, or be jetted offshore by outgoing tides.

(2). For inlet navigation it was always desirable to prevent the deposition of the material in shoals and deltas. For erosion protection it has become necessary to place the arriving material back on the nearby beaches.

(3). Consistently-operating and efficient fixed sand-bypassing systems, taking the material around the inlet and placing it back on the beach, offer the promise of great stability (low variation in channel depth and beach width).

(4). Existing bypassing systems are less efficient when their traps are located inside the inlet, where they are not exposed to sizable portions of the drifting material. Much of the drift

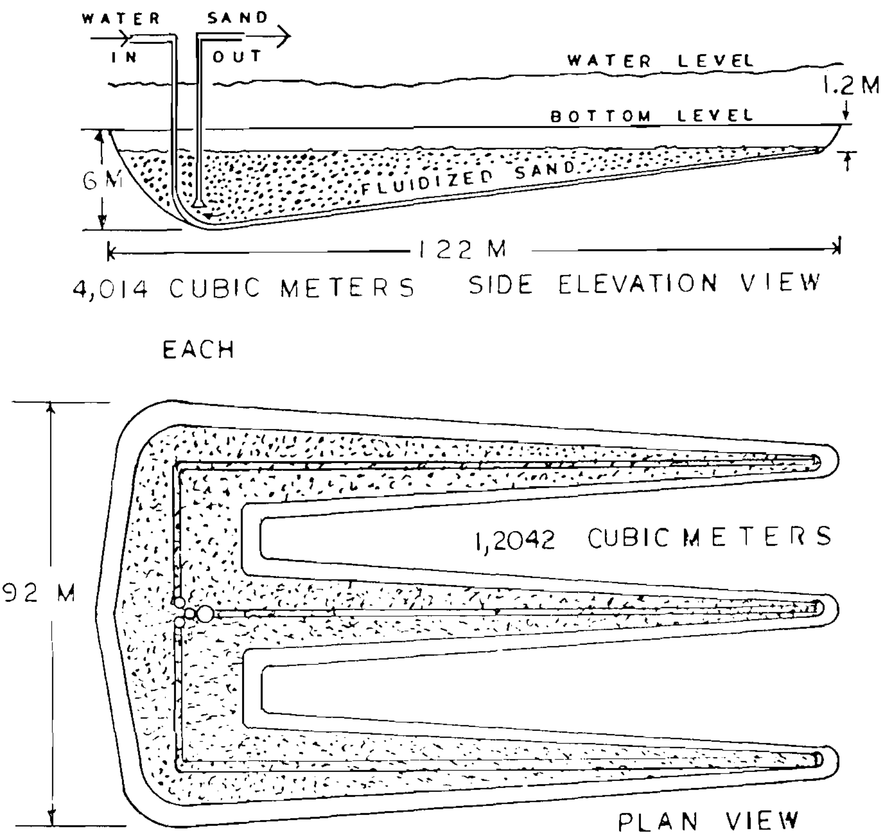

Figure 9. Three finger fluidized sand bypassing sump and delivery to pump system. Note, fingers can be curved to fit around obstructions, expanded or contracted in size, and arranged in numerous combinations shown during pumpout cycle.

may be lost to the offshore bottom instead of being bypassed to down drift beaches.

(5). Sub-bottom hydraulic pressure modulation methods—*lift* and *fluidization* offer important benefits for sand bypassing. Lift can be used to increase bed load transport and thereby direct materials usually deposited in part in shoals and deltas, into traps; and from there they can be bypassed to beaches. Fluidization can be used to create large all-weather offshore traps and to cause the trapped material to flow to central fixed by-passing-pump intakes even during and after inclement weather.

(6). Lift/Fluidization bypassing plants, in addition to being much more effective, will be more cost-effective than conventional sand bypassing systems. A recent study by a Florida company (1988) on various methods of bypassing clearly demonstrated the higher efficiency of the proposed method compared to all other existing procedures. This includes a higher cost-efficiency. The unit price for transfer is only about half plus-minus a variance of the costs for conventional methods. At the same time transfer capacities are increased due to the larger trap capacities. This, of course, is a definitive advantage to the downdrift beaches and their maintenance. More of the drift to the inlet is captured and used for better purpose than being diverted towards the ocean and flushed by ebb-currents into deeper waters or carried by flood currents into the bay or lagoon and deposited where it is not wanted.

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□ RESUMEN □

Este articulo revisa brevemente los procedimientos existentes y métodos para la estabilización de canales y los sistemas de by-pass. El objetivo en todos los casos es alcanzar una estabilidad ininterrumpida y similar a lo largo de todo el canal y un sistema de by-pass fiable, continuo y económico que retenga la parte más importante del transporte longitudinal de material. Se ha demostrado que la modulación de las presiones hidráulicas bajo el fondo de la bocana incrementa el transporte por carga de fondo, creando mayores trampas de arena en el lado del mar y transportando arena por fluidificación hacia las bombas de by-pass—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ ZUSAMMENFASSUNG: □

Dieser Artikel gibt einen kurzen Überblick über bereits vorhandene Verfahren und Methoden zur Stabilisierung und Umleitung von Rinnen. Das Ziel ist jeweils, eine ebenmäßige, ununterbrochene Stabilität der Rinne in ihrer gesamten Länge zu erreichen, sowie eine zuverlässige, kontinuierliche und wirtschaftliche Ableitung, die einen wesentlichen Teil des mit der Strömung verfrachteten Materials festhält. Es wird gezeigt, wie die Steuerung des Einlasses von Unterwasserdruck den Transport der Bodenfracht erhöht, größere Sedimentfallen küstenfern erzeugt und Sand ableitenden Pumpen zuführt.—*Helmut Brückner, Geographisches Institut, Universität Düsseldorf, F.R.G.*