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ZEEBRUGGE PORT EXTENSION SEDIMENT TRANSPORT MEASUREMENT ON AND OFF THE BELGIAN COAST BY MEANS OF TRACERS

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ABSTRACT

An extensive program of tracer experiments was carried out for calculating the sediment transport in the vicinity of the Port of Zeebrugge where extension operations are in progress.

Offshore radioactive bottom tracers were used for studying the sand transport along the beaches where erosion problems exist. On the beach itself fluorescent tracers were used. For the evaluation of the silting-up rate of the access channels to the harbour a series of radioactive bottom and suspension tracers were tracked in-situ. For determining the efficiency of future dumping grounds a combination of bottom tracers and suspension tracers was used.

In total, 18 experiments with radioactive tracers were carried out and 9 with fluorescent ones.

1. INTRODUCTION

For several decades, two major sedimentation processes have been at work along the eastern coast of Belgium. The first problem is the silting-up of a navigation channel, the "Pas van het Zand", a main approach artery to the expanding harbour of Zeebrugge. Being perpendicular to the coast, this artificially-dug channel finds itself in the longshore path of strong tidal currents.

The second sedimentary problem is the erosion of the beaches along the eastern coast. The reason for this process is sometimes coupled with the existance of the harbour at Zeebrugge, but this is not so straightforward scientifically.

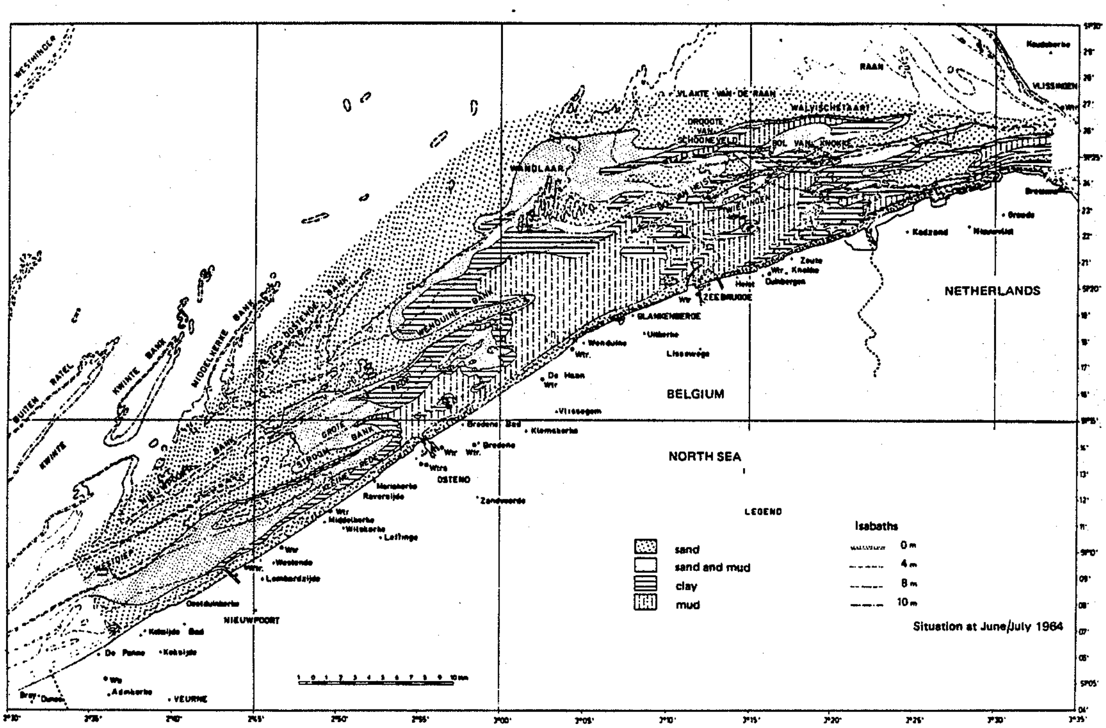


FIG. 1 – Lithological map of the North Sea bed (1964) drawn on the basis of natural radioactivity measurements.

For the port of Zeebrugge to stay competitive, the approach navigation channel must be deepened, and longer jetties must be built which can influence adjacent beaches. For the optimum length of extended jetties, the sedimentation rate for both an enlarged and deepened channel must be known, as well as the degree and rate of influence such constructions will have on the present behaviour of the east coast. For the calculation of these trends, a comprehensive and exact "know-how" of the actual phenomena must be compiled.

When in 1964 the lithological map of the Belgian coastal area was drawn, based on natural radioactivity readings, a large muddy area was revealed offshore (fig. 1). (Bastin A. 1973 and 1974) The extension to the port of Zeebrugge, including the approach channel, lay within these mudflats.

Measurement, as well as computation of the sediment transport over such an area, subject as it is to the combined actions of waves and fluctuating tidal currents, is extremely difficult. Most transportation takes place during the irregularity of storms and moreover, the majority of formulae to predict transport are, at present, only applicable to sandy material.

For silty or muddy sediments, the only way to collect both qualitative and quantitative data on the real sediment transport is to use tracers. Within tracer technology, the radioactive types are by far the most attractive since techniques and calculation methods are the most advanced. These were therefore selected for the determination of the sediment transport load at sea.

On the beaches however, where health hazard regulations are more restrictive, fluorescent tracers were employed.

In total, 18 experiments with radioactive tracers were carried out and 9 with fluorescent ones (fig. 2).

2. THE METHOD OF RADIOACTIVE TRACERS

2.1. General description

There is a lot of documentation available on tracer techniques. A good synthesis can be found in the report of a panel meeting that discussed the use of tracers, organised by the International Atomic Energy Agency in 1971 (I.A.E.A. report - 1973). The essentials of this report can be summarized as follows :

At a certain place termed the injection point, marked particles with an initial activity A are injected at a time t on the sea-bottom. These particles must duplicate the behaviour pattern of local sediments, and have a selected and known particle-size distribution. At a time t_s after the injection, a plume of marked sediments is formed on the sea-bottom which can be detected and measured.

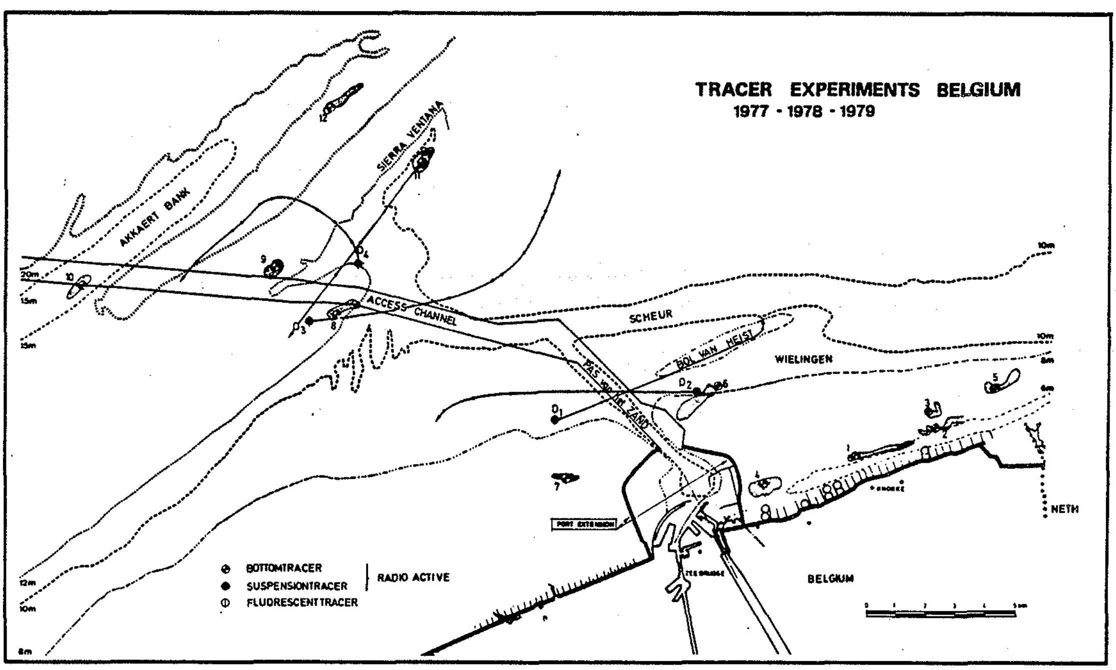


FIG. 2

This plume can be described as a net of lines of equal activity which describe the transport direction taken over a time (t_S - t). By following the evolution it is possible to make time-space relationships between the local hydraulics and the resulting sediment transport. The data obtained can be transformed into :

a) qualitative results :

- the paths followed by the sediments.
- the orientation of the resulting sediment transport.

b) quantitative results :

- transport velocity.
- transport quantity.
- erosion depth or accumulation thickness.
- critical grain size of the sediment to enter suspension.

2.2. The measurable parameters

The bottom transport through a given cross-section along a certain transport direction is equal to :

$$Q = \rho . Lt . Vm . Em$$

$$(Kg/day) = (Kg/m^3) . (m) . (m/day) . (m)$$

where ρ = volumetric weight of the sediment
Lt = mean width of the transport layer
Vm = mean transport velocity
Em = mean thickness of the transport layer

The thickness of the transported layer Em is the mean value between the distance to the sea-bed and that of the deepest-buried radioactive particles. The measurable parameters are Vm and Em, for a constant Lt of 1 m.

2.2.1. Method for determination of "E"

The following method is the principle of the "count-rate balance". For mathematical elaboration, we refer to the thesis of G. Sauzay (1967). This is an amelioration of the spatial integration method.

All particles are assumed either to lay on the bottom surface itself or to be mixed within a thin or thick bottom layer. The greater the mixed thickness, the greater the absorption and diffusion of radiation from the tracer particles. Consequently, the detector on top of a thick layer will receive less gamma rays.

A relationship exists between the number of counts "N" received by the detector, the initial injected radioactivity "A" and the burrowing depth E.

$$\frac{1}{\beta} . \frac{\alpha}{fo} . \frac{N}{A} . E . = 1 - e^{-E}$$

where α and fo are calibration coefficients of the detector probe used. For Zeebrugge :

α = 0,1555 cm^{-1}
fo = 50 . cps/uCi/m^2

and β is a function of the burrowing depth E. For small values of E, experience shows that β approximates to 1.15.

N is calculated using the field measurements. For each point in the plume that emits radioactive rays, there is a net count-rate n (corrected to the background of the natural radioactivity), which is a function of the amount of tracer immediately underneath the detector and of the amount at the depth of the buried point. Integrating these count rates for the whole radioactive plume gives :

$$N = \iint n ds$$

The calculation of N allows the solution of equation (1) and thus the determination of E.

2.2.2. Calculation of the transport velocity V

For visualisation of the radioactive plume, iso-count lines can be drawn (fig. 3).

A count distribution diagram, where the X-axis represents the mean transport direction, is used to isolate the gravitation point G (fig. 4). The change in time and space of this gravitation point gives the mean transport velocity Vm (fig. 5).

$$Vm = \frac{\Delta x G}{\Delta t}$$

2.2.3. The choice of the tracer

The lifetime of the radioactive source must exceed the duration of the experiment, but not by so much as to contaminate the area unnecessarily.

The information received by the detector must be proportional to the mass of the tracer in order to obtain qualitative results : the marking operation must label in bulk.

The user has several radioisotopes available so that the most suitable can be selected for the particular mechanism to be investigated. For tracking the bottom transport of the sand in the vicinity of Zeebrugge, the isotope Iridium 192 was chosen.

This isotope has a half-life of 74 days and a mean energy of 0,34 Mev.

The mass and the activity of the tracer must be minimal, not just for convenience and obvious radiation dangers, but also because a small quantity of tracer is more easily spread through the moving sediment layer. The quantity must be sufficient however to generate enough radioactive pulses back to the detector, and to be statistically representative of the transport. This optimal quantity can be calculated.

For the bottom-tracer experiments in the vicinity of Zeebrugge, the quantities ranged from 460 g to 920 g with activities from 0.45 Ci to 1.20 Ci.

2.3. Detection method

The detection unit, fixed to a sledge, consists of a probe with a gamma scintillation counter. The probe itself is a Na I (Tl) crystal with coupled photomultiplier. Both the sledge and the probe are connected to the survey boat by means of an electric carrier cable.

For producing the tracer particles, Iridium is melted in a special glass, milled to the desired grain size and then activated in the reactor.

3. THE INVESTIGATION

3.1. East Coast - the Appelzak trench

3.1.1. The problem

Along the east coast of Belgium, between the harbour at Zeebrugge and the Dutch frontier, beach erosion occurs on a significant scale. More extension on this problem is given by Roovers et al. (1981).

The following phenomeneon is observed : beach material is transported offshore by wave action into a trench, called "The Appelzak", just off the coast, from which it is carried away by relatively strong tidal currents (1.50 m/s at spring tide).

The bottom sediments of this natural channel are very heterogeneous, consisting of mud, sand, and a mixture of both. The aim of this investigation was to trace, both in quantity and direction, the movement of the beach sand once inside the Appelzak, and its course over the heterogeneous bottom. Such knowledge was essential in evaluating correct measures for future coastal protection.

The experiments took place from October 1977 until January 1978. Five injections (points 1 to 5, fig. 2) were made with Iridium 192 labelled glass particles. Grain size distribution was specified between 160 and 315 microns (d_{50} = 225 μ) so as to reflect the physical characteristics of the local beach sand. This would give a tie-up with natural transport calculations. To control this comparative technique, and also for other extrapolation and interpretation purposes, the hydraulic and meteorological conditions during the experiments were fully and accurately registered.

3.1.2. Results

The results detected are first seen as iso-count lines. As an example, fig. 3, shows the evolution of the iso-count lines for each detector reading from trial point 1.

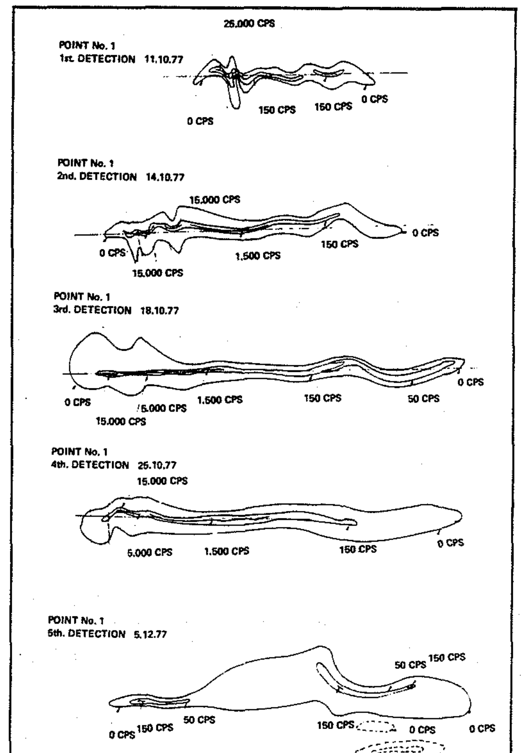


FIG. 3 - EXAMPLE OF ISOCOUNTLINES FOR POINT 1

FIG. 3

These graphical representations give an overall picture of how the radioactive plume disperses with time, and are very useful for qualitative interpretation.

Yet more data is assimilated by analyzing count distribution diagrams. Fig. 4 exemplifies such output for trial point 1. For each of these count distribution diagrams, the gravitation point G can be calculated, as well as the shifting velocity of that gravitational centre with time. The shifting velocities encountered at trial points 1 to 7 are given in fig. 5. The displacement of the centre of gravity in space for the same points is depicted in fig. 6. The mean transport direction can then be calculated.

Given these changes in time and space of the gravitational centre the mean transport velocity Vm can be calculated. Consequently, by application of the principle of count-rate balance as described in 2.2.1, the mean thickness of the transported layer Em can be determined.

This is a very critical stage in all tracer experiments, where the experience of the investigator counts the most.

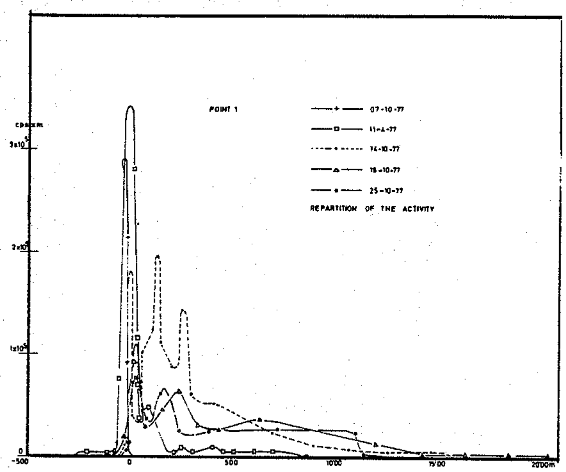


FIG. 4

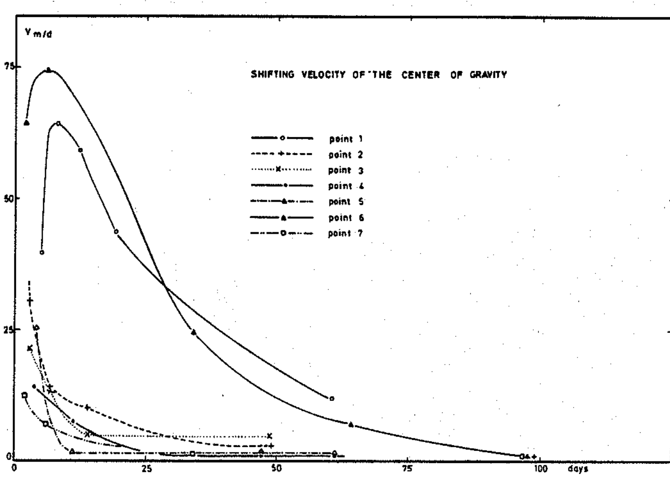


FIG. 5

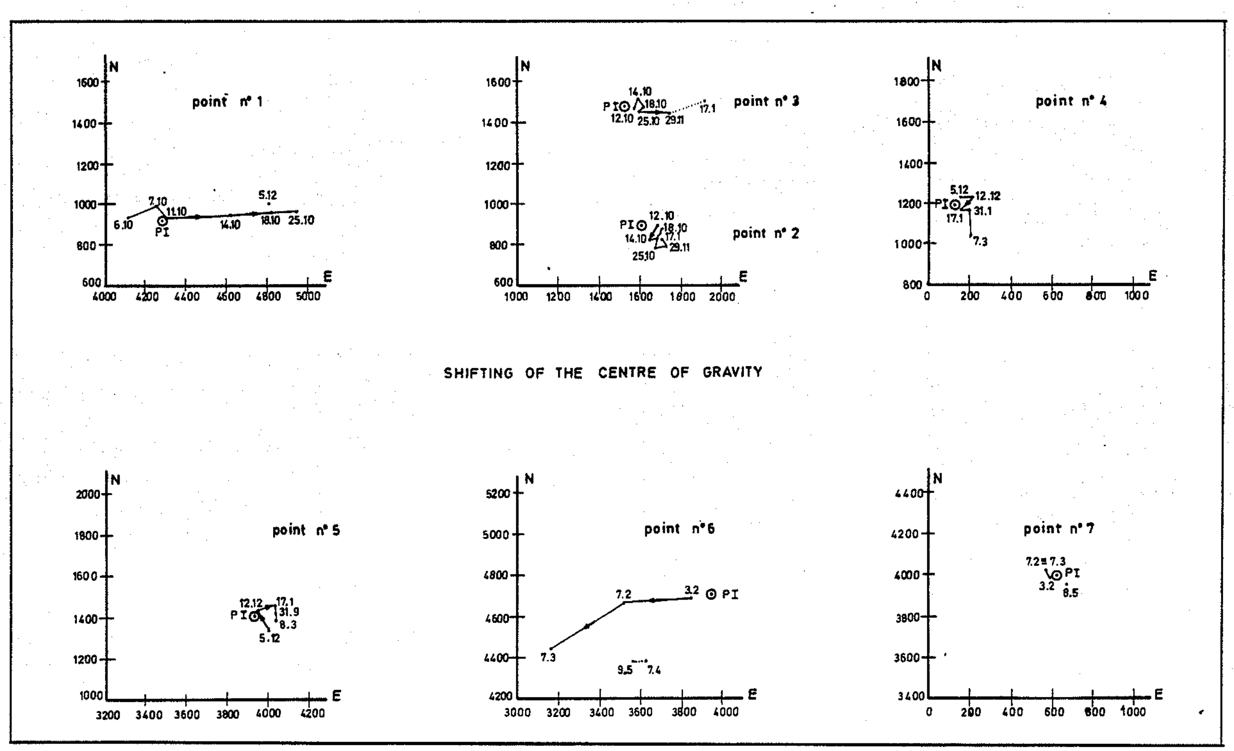


FIG. 6

Indeed, even with all the data of the trial recordings and the simultaneous back-up of hydraulic and meteorological conditions, a competent interpretation and synthesis are vital. One must, above all, identify that data period wherein all injected source material is still present, dispersed, and active in the bottom layer, and has, as yet, in the absence of storm wave conditions, remained undiffused. At that moment the relative drop in detected activity is proportional to the burrowing depth. In table 1 the detected activity as a percentage of the initial velocity is given for the successive readings made from the 7 trial start-points.

In table 3 all quantitative data from all radioactive bottom-tracer experiments is summarized. For the 5 locations close to the east coast, computed data was also available so that comparison was possible. Between theoretical calculations and in-situ measurements there are some descrepancies. As regards the discharges, although the mass-flow rates were largely similar, their orientations were frequently of opposite sense. This happened because the error percentage for the transport formula can be such as to occasion a change of sign. The true direction always came from the tracer path, which need not be doubted.

Immersion Point	1st Detection	2nd Detection	3rd Detection	4th Detection	5th Detection	6th Detection
1	3	70	100	70	70 storm	5
2	29	72	94	64 storm	22	16
3	26	59	> 62	100 storm	74	44
4	14	83 storm	88	78	61	
5	45	45 storm	21	• 23	27	
6	60	100	60	25	4	
7	3	7	89		20	

TABLE 1 : Detected activity as a percentage of initial activity

The small percentages of the initial detections are due to the fact that such a small mass of tracer needs 2 days before dispersion over a relatively large area takes place.

The transported layer thickness Em for the seven drop-points is given in table 2.

Immersion Point	No. of days after imm.	N x 100 / A x fo	Em cm
1	19	70	7
2	14	64	8
3	49	74	6
4	61	78	5
5	–	–	–
6	34	80	8
7	34	89	3

TABLE 2 : Transported layer thickness Em

At point 5 the dispersion was never big enough to give a good detection. Integration between successive detections was therefore unsatisfactory and a part of the information was in that way lost.

3.1.3. Remarks

Drop-point 1

- This bottom transport appears to be especially influenced by flood-tide currents.
- The totality of the tracer-shift relative to the injection points is to the east.
- The transport rate is relatively high.
- Storm-waves cause pore-pressure build-up in the bed layer, allowing a proportion of the tracer to escape in suspension.

Drop-point 2

- Flood-tide currents are also prevalent in the dispersion of the tracer, but this is less conclusive than for point 1.
- The transport path is more complex and follows a zigzag pattern. In stormy weather the resultant transport is onshore. The bottom transport is then strongly influenced by wave action.

Drop-point 3

This location was little affected by wave action. Here also the transport is more haphazard than at drop-point 1. The resultant transport is still to the east.

RADIOACTIVE TRACER EXPERIMENTS					CALCULATIONS	
Point	Layer Thickness (cm)	Velocity (m/d)	Direction (°)	Discharge ($m^3/m/d$)	Discharge ($m^3/m/d$)	Direction (°)
1	7	35	75	2,5 ± 1,1	0,960 ± 0,404 0,630 ± 0,417	242 260
2	8	6	185	0,5 ± 0,1	0,459 ± 0,422 0,614 ± 0,447	269 268
3	6	2	75	0,1 ± 0,03	0,231 ± 0,417 0,076 ± 0,393	266 258
4	5	1	160	0,05 ± 0,01	0,135 ± 0,408 0,201 ± 0,386	153 156
5		negligible			0,069 ± 0,393	250
6	8	22	232	1,8 ± 0,4		117
7	3	1,4	275	0,04 ± 0,03		25
8	4	2,2	41↔221	negligible		
9		negligible				
10		0,8	50↔230	negligible		
11	2-3	0,7	20-60	0,002		
12	2-3	0,7		0,002		

TABLE 3 : Quantitative data of all radioactive bottom tracer experiments

Drop-point 4

Due to the shallow water depth the tracer at this point is strongly affected by wave action. The resulting transport is towards the coast, mostly generated by waves. The action of the tidal currents balances itself out.

Drop-point 5

Here a number of small transports occured which appeared equal in both directions, giving a zero resultant. During rough weather some of the tracer went into suspension.

Considering wave action in general it can be said that all points experienced some effects but not necessarily in the same magnitude.

By comparing the radioactivity detected after a storm with the cumulative grain size distribution it is possible to deduce what fraction went into suspension due to storm wave action. Table 4 gives the relevant data.

Point	% brought into suspension	H_s (m)	Ø tracer particles brought into suspension by storm wave action
1	95	3,2	$< 300\ \mu$
2	84	5,5	$< 250\ \mu$
3	56	5,5	$< 220\ \mu$
4	40	5,5	$< 220\ \mu$
5	–	–	–
6	75	–	$< 250\ \mu$
7	80	–	$< 250\ \mu$

TABLE 4 : Percentage and grain size brought into suspension by storm wave action

3.1.4. Conclusions for the Appelzak trench

On both sides of the Appelzak trench the bottom transport caused by the tidal currents is small. At the western end (drop-point 4) there is a transport towards the coast due to wave action (0.05 $m^3/m/$day).

In the centre of the Appelzak, midway along the trench, the resulting transport is very large and flood-orientated (2.5 m^3/m/day). Wave action is also a cause of intense pressure build-up in the bottom layer, allowing a proportion of sediments to be transported in suspension.

Points 2 and 3 contrast in behaviour. Point 3 is little affected by waves and bottom transport is predominantly flood-orientated (0.1 m^3/m/day). Point 2 has a transport towards the coast (0.5 m^3/m/day) and is strongly influenced by wave action.

3.2. East Coast - the beach

3.2.1. The problem

In the preceeding chapter the processes were analysed which interact offshore on the beach sand, once it has been carried away from the beach by transverse transport. In order to study the possible repercussions on the beaches themselves from the harbour enlargement, the sand transport processes on the beach under T_0 conditions have to be known for the calibration of the extrapolation calculations and the physical models. For more on this problem, see Roovers et al. (1981).

The use of tracers is a way of getting some of this information. Radioactive tracers however are excluded on the beach. Next to radioactive tracers the fluorescent ones satisfy most the requirements of a good tracer study. To allow calculations of the sediment transport on the beach in m^3/m/day the following parameters must be measured.

1. The ratio detected tracer to the injected quantity.
2. The thickness of the layer in which the tracer is mixed.
3. The quantity of tracer shifted with regard to the quantity measured at the injection point.

For the greater part these requirements are the same as for the use of radioactive tracers over the sea bed. Methods and measuring systems were worked out, giving nigh-on identical results but characteristic of a beach environment.

3.2.2. Measuring systems

On the beaches east of Zeebrugge, the following systems were used. For each experiment 35 kg of fluorescent sand, equivalent to the characteristic d_{50} (220 μ) of the beach sand was injected. The injection took place as shown in the following figure.

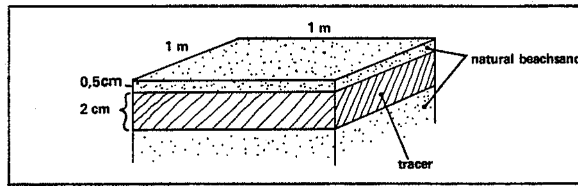


Fig. 7 - Fluorescent tracer disposal on the beach

Experiments were executed on the beaches at Heist, Albert, Het Zoute and Lekkerbek (fig. 2). For each beach two injections were simultaneously made, one on the lower beach (± Z + 2,2 m) with red sand and one on the higher beach (± Z + 3,2 m) with green sand. After dispersion the following detection was made :

1. Measuring the dispersion by sampling the beach sand with the fluorescent tracer particles and detailed analysis in the laboratory (only for the first experiment).
2. Small cores (10 - 20 cm) for determining the thickness of the transport layer.
3. Measuring the dispersion of the tracers by systematic polaroïd photography with U.V. film.
4. Continuous measuring of the dispersion with a photomultiplier.

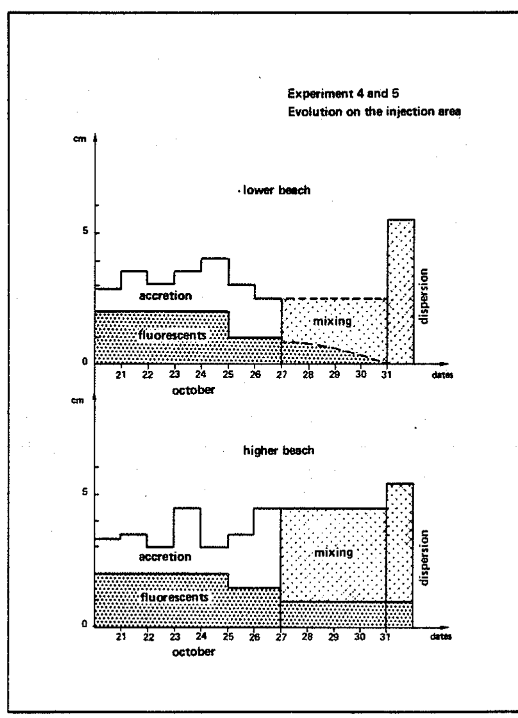


Fig. 8 - Example of the evolution of the moving layer

3.2.3. *Results and discussion*

Just as for the radioactive tracers iso-count-lines were drawn after each detection, to give qualitative information on the dispersion. Count distribution diagrams were made and in addition, by taking small cores, the thickness of the moving layer was fixed.

Fig. 8 shows an example of the phases observed when tracking the moving layer on the injection points. Put together one can describe the sequence to dispersion.

In table 5 all quantitative data from all fluorescent tracer experiments on the east coast beach is summarized. As qualitative side information it must be remarked that on all the beaches, Heist, Albertstrand, Het Zoute, the same transport directions were found, namely to the east (towards the Dutch border).

These two cases are :

a) Beach at Heist - 1 km east of Zeebrugge
   Date : 10.01.78 Wind direction : WZW
   Hs : 1,20 m
   Tm : 3 sec.
   Kr : 0,08
   φb : 4°
   Width of breaker zone : 235 m
   CERC formula : S : 3,63 m^3/day
   Tracers : S : 7,05 m^3/day

b) Beach at Lekkerbek - Het Zoute at 6 km east of Zeebrugge
   Date : 25.10.77 Wind direction : ZW-NW
   Hs : 0,33 m
   Tm : 3 sec.
   Kr : 0,15
   φb : 6°
   Width of breaker zone : 220 m
   CERC formula : S : 1,44 m^3/day
   Tracers : S : 3,67 m^3/day

FLUORESCENT TRACERS EXPERIMENTS								CALCULATIONS
Beach	Data	Meteor. Hs m	Meteor. BF	Section (m)	Thickness (cm)	Velocity (m/d)	Discharge m^3/d section	Discharge m^3/d section
Heist 1	10/01/78	1,20	4 - 6 WZW	235	3	1	7,05	3,63
Heist 2	10/01/78	1,20	4 - 6 WZW	303,1	1	9,09	27,55	
Heist 2	11/01/78	0,90	5 - 6 WZW	270,7	4	1	10,83	
Albert	13/09/77 03/10/77	0,30	3 - 4 NW	206,7	2	0,88	3,64	
Lekkerbek	13/10/77	0,28	2 - 3 ZE	172,9	2	1	3,50	
Lekkerbek	25/10/77	0,33	3 ZW- NW	220	1,6	1,04	3,67	1,44
Lekkerbek	02/11/77	0,78	4 - 6 WZW	244,9	5	2	24,49	

TABLE 5

At 2 points, for which complete data sets of ambient measurements were available, results were compared with calculations. These calculations were made by means of the CERC formula (Coastal Engineering Research Council) :

$S = 0{,}014 \cdot Ho^2 \cdot Co \cdot Kr^2 \cdot \sin \varphi b \cdot \cos \varphi b$

for which :

Ho (m) : wave height in deep water
Co (m/s) : propagation velocity of the waves in deep water
Kr : coefficient of refraction
φb (°) : angle of wave incidence in the breaker zone

From these two cases it would seen that the CERC formula (which calculates a longshore transport independent of beach slope and grain diameter) only gives an approximation of the transport in the breaker zone. For a better evaluation one should compare more cases and measurements during bad weather to check higher-bound data.

From the fluorescent tracer experiments it would appear that during fine weather conditions the beach will change very little. Although the sand transport on the beach is not correlated systematically with hydro-meteorological data during these conditions the mean transport velocity was 1,5 m/day with a thickness of 2-3 cm, equivalent to 0,045 m^3/day. For a beach where the lower beach is about 250 m wide this transport is roughly 11,25 m^3/day.

It is obvious that during fine weather conditions the longshore transport is obstructed by the groynes. This small effect certainly does not justify their construction because the loss of beach sand was insignificant both through longshore and transverse transport. It is also obvious that this loss occurs during bad weather conditions. But the tracer experiments showed clearly that on the lower beach the transverse transport towards the Appelzak trench is encouraged by the groynes. Already during small storm weather (Beaufort 6) the tracer patches were dispersed and emptied along the groynes. This phenomenon was already observed by Bastin (1964 a and b and 1974) during fluorescent tracer experiments on the Belgian beaches in 1962 and 1965-1966. The latter carried out during a full year, with every week an injection of 10 kg tracer, being made at the same point gave, on the lower beach of Albertstrand and Heist, a longshore transport of 150.000 ton (about 86.000 m^3) but in the opposite direction, thus towards Zeebrugge. These experiments had the advantage of being subject to all sorts of weather conditions over a full year which was not possible with experiments described, but these also did not give information on transverse transport.

The difference in direction of the resulting transport made on certain beach sections during observations in the sixties and those made in the seventies would suggest that something has changed in-between. On close examination of the evolution of the morphological maps, the unpronounced formation of a flood channel off Zeebrugge-Heist in the early seventies is possibly responsible for this phenomenon.

3.2.4. Conclusions for the east coast beaches

Qualitatively, one concludes that :
All measured transport was in an easterly direction. During fine weather conditions there is very little longshore transport; this longshore transport is obstructed by the groynes.

During bad weather conditions a transverse transport exists from the beach towards the Appelzak trench. The groynes accentuates this action on the lower beach.

Quantitative results gave during fine weather ($<$ 5 BF and Hs $<$ 1.00 m) a transport of about 0,045 m^3/m/day. During bad weather the tracer was dispersed and transport velocities and rates could not be determined. Most significant beach transport and erosion happens during bad weather, just when the fluorescent tracer experiments were difficult to interpret. In this way they did not fullfill totally their objectives like radioactive tracers do.

3.3. The access channels

3.3.1 The problem

As described in the introduction and showed in fig. 1 a mud area exists in front of Zeebrugge.

The access channel to Zeebrugge, the "Pas van het Zand", is dredged through this mud area. An additional difficulty is that tidal currents are parallel to the coast, thus transverse to the channel.

So dredging of this channel is a continuons battle against a high rate of siltation. This silting -up by bottom transport and by suspension fallout is evaluated w.r.t. T_O (zerotime) conditions in order to extrapolate calculations for future maintance dredging at greater depths.

Further offshore the "Pas van het Zand" joins "the Scheur", the main approach channel for the harbours on the Scheldt, Antwerpen and Gent. The siltation problems for this main approach channel are smaller because the muddy composition of the sediments is less and because the channel direction lies more parallel to that of the tidal currents. However at some periods of the tide transverse currents develop. Moreover the access channel has to be dredged across the sandbank "The Akkaertbank".

As shown in fig. 2 a series of tracer experiments where made on both sides of the channel to evaluate the importance of flood and ebb actions. Numbers 6 to 10 are the five bottom tracer experiments and D1 to D4 are the four suspension tracer experiments. The trials 6 and 7 took place in the same period as those made for the Appelzak problem from October 1977 until January 1978. All the other experiments took place between October 1978 and May 1979.

3.3.2. Results and discussion

a) The bottom tracer experiments

As for the Appelzak isocount lines were drawn, the distribution of the activity for each point after each detection was plotted, the shifting of the centre of gravity with time was calculated as well as the displacement of this centre of gravity in space.

In figs. 5 and 6 these last two calculation results are presented for points 6 and 7, together with the

Appelzak results. For points 8, 9 and 10 results are shown in figs. 9 and 10.

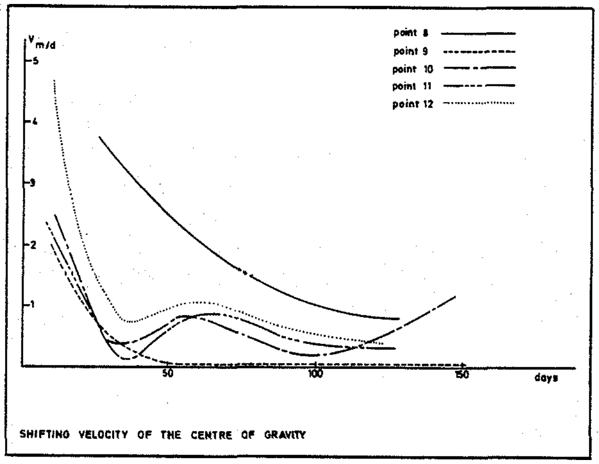


FIG. 9

calculations for muddy areas. Indeed the directional accuracy of the tracer experiments over a period of sometimes more than 3 months, inclusive of storms, has been very reliable.

b) The suspension tracer experiments

For the study of the behaviour of the suspension load around the access channels, the local mud was labelled with the radioactive isotope Gold 198 which has a half life of 2,8 days. A quantity of about 1,4 kg with a total activity of 9 Ci is brought into suspension and can be followed for about 6 hours over an average distance of 8 kilometres.

The system of labelling a mud with gold 198 is shown in fig. 11. Special experiments (Bougault 1970) proved that it was possible to fix the gold and thus isotope 198, on the mud particles of a suspension by a oxydo-reduction reaction. The gold

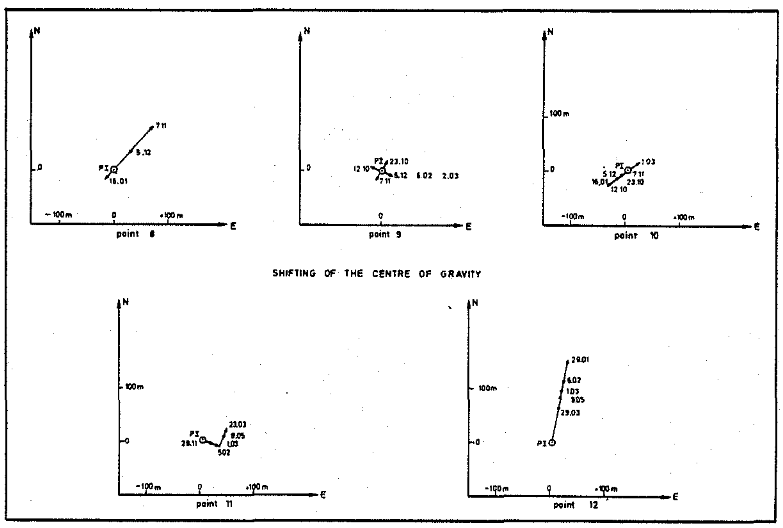


FIG. 10

All data of the bottom tracer experiments in the vicinity of the access channels is also summarized in table 3.

The most important remark to make is that only point 6 shows an important net transport. For the other points the transport is rather small and resultants are not very pronounced.

The big difference between the dispersion of bottom sediments at point 6 and 7, although the direction is the same, is a clear indication that the channel of the Pas van het Zand functions as a sediment trap. As experienced with the Appelzak the calculated transport directions at these two points were not identical to the observed ones. These deductions raise serious doubts on the value of transport

initially in solution in the form of acide aurichlorhydrique is, once the contact with the particles, transformed into metallic gold.

The detection of the radioactive cloud is achieved by towing inmersed detectors at different depths as shown in fig 12.

There are three main transport mechanisms active in the transport of suspended sediments :

- advection (currents)
- dispersion (turbulences)
- decantation (specific weight and volume of particles)

When the radio-active suspension-tracer is injected (1kg) into the sea (1 m below sea - level) at an initial concentration of 20 g/l, first a quick dilution occurs to tracer-concentrations of about 0,1 g/l (within a few minutes).

Advection transports the tracer cloud at a speed U, which is approximatly the same as the water velocity.

Decantation is supposed to be constant throughout, this can be assumed when the mud-flocs are formed during slack water. When tidal currents are active, flocs disintegrate and tend to become homogeneous.

FIG. 11

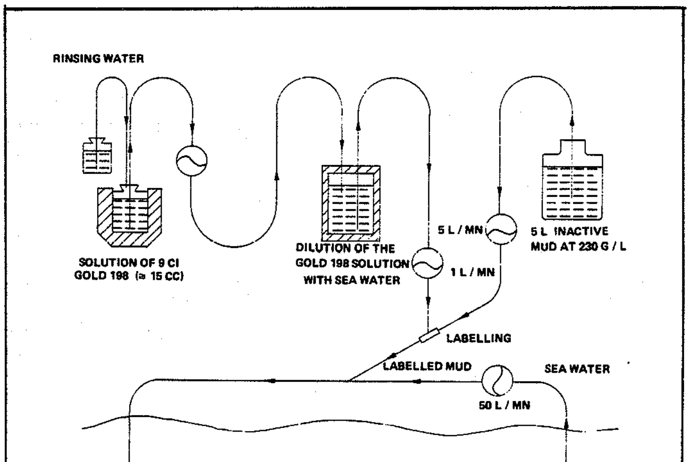
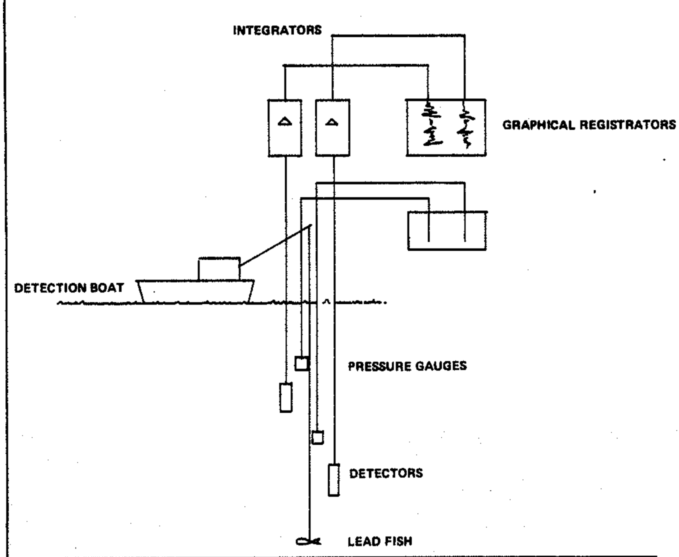


DIAGRAM OF A MUD LABELING WITH GOLD 198

FIG. 12



PRINCIPLE OF DETECTION

Dispersion causes the cloud to expand in three dimensions. The spatial variation of the activity within the elliptic suspension-tracer cloud (measured along the longitudinal and transversal axes) can easily be adjusted to a normal distribution.

From the longitudinal and transversal records of the activity in suspension it is possible to deduce the advection (normal distribution), and the maximum activity.

Dispersion - coefficients, D, are then calculated by :

$$2 D_i = \frac{d\sigma i^2}{dt}$$

i = x (longtitudinal)
y (transversal)

D_i = dispersion coefficient

σi = standard-deviation

On fig. 13 the evolution of the maximum concentration within the suspension-tracer cloud is drawn as a function of elapsed time (from the time of injection).

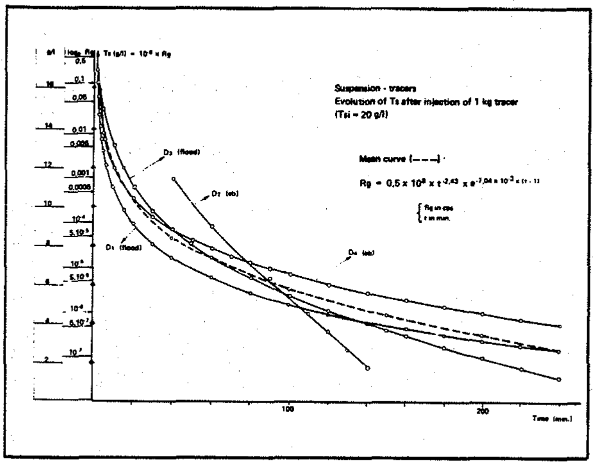


FIG. 13

The quantity of suspension-matter at any one moment can be obtained from :

$$M(t) = M_O . \exp - \frac{\overline{w}}{H.\varphi} . (t - to)$$

t = time

t_O = time of injection

$\overline{w}$ = sinking speed of suspension particles

H = water depth

M_O = total mass of suspension-tracer

φ = dimensionless function in Rouse's theory

$$\varphi = \int_{a/H}^{1} \left[\frac{a/H}{(1-a/H)} . \frac{(1-Z')}{Z'} \right]^{\frac{\overline{w}}{k.u^*}} dz'$$

$z' = \frac{z}{H}$ reduced height above sea-bed

a = height of first detector (~ 5 m) above sea-bed

k = von Karman constant

u^* = shear-stress velocity

By using radio-active tracers with a long half life relative to the duration of the experiment, it is possible to correlate measured activity to concentration.

Variation of M with respect to time give decantation rate :

$$\theta = \frac{1}{M.} \left| \frac{dM.}{dt} \right|$$

From the results observed, one can conclude that decantation mainly occurs during slack water :

Point	Decantation-rate (g/sec. - ton suspension)
D1	40
D2	550
D3	235
D4	100

3.3.3. Application of the results

For the access channels the question is to determine the silting up rate. This silting up is caused by three processes :

a) the bottom transport
b) the suspension transport
c) the evolution of the slopes

From the bottom transport we have figures of the sand build-up. From the settling caused by suspension transport we have additional data. The evolution of the slopes can be deduced by determining the equilibrium slope for both sides.

As the evaluation of the silting-up rate of the Pas van het Zand is very important for assessing the maintenance dredging, it was determined using three different methods :

a) Empirically by examining the relationship between dredged quantities and channel evolution in the past.
b) by mean of tracers
c) mathematical

The comparison of these three methods will be the subject of a special article.

To allow the comparison between the three methods it was decided to use the tracer values only for that area where they were registered and not to go too far with extrapolations. So a short section of 2 km of the Pas van 't Zand was chosen in the vicinity of where experiments 6, 7, D1 and D2 took place.

For the evaluation by tracers the following base data were used :

a) for the bottom transport

- for trial point 6 :
  - . composition :
    35 % sand (> 40 μ)
    65 % silt (< 40 μ)
  - . consistency :
    Ts : 500 to 750 g/l
    Ysat : 1.3 to 1.48 t/m³
  - . average discharge :
    qs : 1.8 m³/m/day
- for trial point 7 :
  - . composition :
    30 % sand (> 40 μ)
    70 % silt (< 40 μ)
  - . consistency :
    Ts : 650 to 760 g/l
    Ysat : 1.42 to 1.48 t/m³
  - . average discharge :
    qs : 0.04 m³/m/day

b) for the suspension transport

- for trial D1 :
  Decantation during turning of flood = 40 g/s/ton.
- for trial D2 :
  Decantation during turning of ebb = 550 g/s/ton suspension. The mean suspension load was evaluated during special marine surveys and taken at 0.100 g/l during 6 summer months and 0.250 g/l during 6 winter months.

c) for the slope evolution

The equilibrium slopes are :
East slope : 1/45
West slope : 1/20

It is assumed that this equilibrium is reached after one year. Sedimentation resulting from slope evolution is shown as in table 6.

deepening from - to	E-slope	W-slope	Total
10,5 m 11 m	157.500 m³	70.000 m³	227.500 m³
11,0 m 12 m	363.000 m³	160.000 m³	523.000 m³
12,0 m 13 m	500.000 m³	200.000 m³	700.000 m³
13,0 m 14 m	600.000 m³	240.000 m³	840.000 m³
14,0 m 15 m	700.000 m³	280.000 m³	980.000 m³

Table 6 - Sedimentation due to slope evolution

The mean density of these sediments :
Ysat = 1.34 t/m³
The mean composition is : 40 % sand (> 40 μ)
60 % silt (< 40 μ)

The sedimentation in this 2 km section of the Pas van het Zand for T_O condition evaluated by these three processes and on the basis of the T_O tide-current pattern as shown in table 7.

For the extrapolation to the conditions after port extension the values of the current velocities of the hydraulic tidal model. (Waterbouwkundig Laboratorium, Antwerp, Belgium), were used.

Channel dimension		Sedimentation (channel 2000 m length)					
		first year			following year		
bottom width	depth (m)	annual sedimention (m³)	composition (% slib)	density γ sat (t/m³)	annual sedimentation (m³)	composition (% slib)	density γ sat (t/m³)
300	10,5	4.443.000	88	1,33	4.443.000	88	1,34
300	11,0	4.914.500	87	1,33	4.687.000	87	1,32
300	12,0	5.766.900	85	1,32	5.243.900	86	1,31
300	13,0	6.531.300	84	1,32	5.831.300	85	1,30
300	14,0	7.234.700	85	1,31	6.394.700	87	1,30
300	15,0	8.077.500	86	1,31	7.097.500	89	1,29

TABLE 7 - Evaluation of sedimentation in a 2 km section of the Pas van het Zand with respect to the T_O condition

In the studied area the mean current velocities are increased with 60 % due to the extension.

If one accepts that bottom transport is proportional to the fourth power of the mean current velocity, then the bottom transport can also be evaluated.

The suspension transport will also increase with the higher velocities due to increased erosive activity. In a parallel rheological study to the tracer experiments. (Malherbe et al. - 1982), the relation between shear stress velocities and suspension rate was established by means of 728 measured results. According to this study the increase of 60 % current velocity gives a mean increase in shear stress of 0.8233 N/m². This results in a mean suspension load of 0.126 g/l in summer conditions and 0.316 g/l in winter conditions. The three processes which influence the siltation rate of the channel after port extension are as follows :

a) bottom transport : 6.55 m³/m/day
b) suspension transport :
   - summer : Ts = 0.316 g/l
   - winter : Ts = 0.216 g/l

   Decantation : as in T_O conditions 40 g/s/ton suspension and 550 g/s/ton suspension.
c) slope evolution : as in T_O conditions.

The resulting siltation rates are shown in table 8.

As already mentioned the silting up rate was also assessed by two other methods, first empirically by relating dredged quantities to the channel evolution in the past and, secondly by the mathematical method.

These two methods cannot be explained in the confines of this paper. We only give here the graphical comparison (fig. 14) of the results of the three methods.

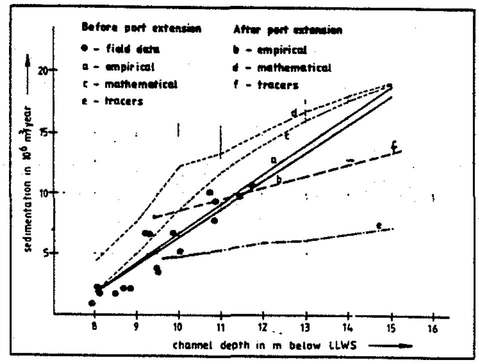


FIG. 14

As expected there are some discrepancies. Which one of these methods is the most exact cannot be said with certitude. There is some predisposition to think that the empirical approach is the most credible because it is based on measured quantities. However this is not so evident as it looks. Indeed the relationship between dredged quantities and in situ sedimentated quantities is not so clear in muddy areas like the Pas van het Zand. Whilst dredged quantities can be measured, the sedimented ones on the contrary are difficult to estimate as long as the build up of density in the mud in the channel is not exactly known.

Channel dimension		Sedimentation (channel 2000 m length)					
		first year			following year		
bottom width	depth (m)	annual sedimention (m³)	composition (% slib)	density γ sat (t/m³)	annual sedimentation (m³)	composition (% slib)	density γ sat (t/m³)
300	10,5	9.573.800	89	1,31	9.573.800	90	1,31
300	11,0	10.170.700	88	1,30	9.943.300	89	1,31
300	12,0	11.311.100	87	1,30	10.788.000	88	1,31
300	13,0	12.379.300	87	1,30	11.679.300	87	1,29
300	14,0	13.377.000	87	1,31	12.534.000	90	1,29
300	15,0	14.580.900	87	1,31	13.600.800	90	1,28

TABLE 8 - Evaluation of sedimentation in a 2 km section of the Pas van het Zand after port extension

Moreover as long as overflow of the fines of the dredged material is used, as the case in the Pas van het Zand, it is not possible to make a distinction between the resedimentated spoil and the natural sedimentation.

All by all the comparison of the three methods shows good correlation for the conditions after port extension, especially for the first attempted depth of 12,5 m.

Indeed results of yet another two formulae may differ more than the discussed transport ones. It might also be that all three are wrong. According to recent observations there are some indications that the whole net transport system off Zeebrugge being fundamentally changed by the extension works. In these new conditions silting-up rate evaluations may have to be recalculated by other methods.

3.4. The dumping sites

3.4.1. The problem

To deepen all access channel to the outerport of Zeebrugge, and the connecting channel to Antwerpen and Gent very large quantities have to be dredged. The future maintenance dredging of these channel will also deliver large quantities. The question was to find good dumping grounds for these enormous quantities which are not to far for transportation costs and yet far enough to prevent quick recycling.

3.4.2. Experiences and results

Two sites were chosen as trial area (fig 2 : points 11 and 12). For evaluating the dispersion rates of the dredged materials at these two tests-grounds, 2 bottom tracer injections and 1 suspension-tracer (point D5, same as 11) were released. The bottom tracer experiments 11 and 12 gave nearly the same results namely a small resultant transport of about 0.002 m^3 /m/day to the NE (table 3).

This is negligible and means that the bulk of the sandy part of the spoil stays on the dumping ground once it has reached the bottom. However the biggest part of the material to be dredged is a mixture of mud and muddy-sand. Point 12 is far enough from the access channels so that dispersion of this muddy material will not cause problems of recycling. But the transportation distance is rather large, as are costs.

For point 11 which was the most tracked dumping ground additional experiments were done for evaluating the dispersion of the muddy material. For this purpose 15 to 20 tons of authentic dredged material from a hopper dredge were labelled with gold 198 ; this was done like for the suspension tracer experiments but here the sandy part of the material was also labelled in a known proportion, namely 59 % of mud and 41 % of sand. The mixture was dumped on site 11 or D5 at the beginning of ebb tide. The aim of this control experiment was to obtain information :

- on the behaviour of the dumped material in suspension,
- the distribution of the seabed,
- the evolution in those days, following dumping.

After dumping the particles in suspension were carried in a south-westerly direction towards the channel with a speed of 0.6 m/s. The plume was followed over 7 km, tracing a path that crossed the access channel.

The spread on the bottom of the dumping site itself was in the form of an ellipse with a major axis of 1000 m and a minor axis of 400 m and an area of 300,000 m^3. The detected radioactivity on the site itself indicates that only about 27 % of the total dump material (sand and mud) reach the bottom, with little movement during the thereafter days. This confirms the observation made during the bottom tracer experiment no. 11. Thus a large portion of the fines and a part of the fine sand, don't reach the bottom during a dumping under ebb current, but are lost to recycling. The efficiency of the dumping ground on the Sierra Ventana (point 11) can be approximated at 30 % .

4. CONCLUSIONS

This tracer programme, one of the largest ever undertaken, illustrates, the diversity of tracers in the different sedimentological problems which can arise from new harbour constructions.

For these port extension works at Zeebrugge they were used to study the repercussions of the extension of the nearby east coast.

Offshore radioactive bottom tracers showed the path that sand particles take during their transport. Good qualitative and quantitative data of this transport was obtained.

On the beach fluorescent tracers gave qualitative and quantitative data but only during relatively good weather conditions. By changing from single injections to the method of semi-continuous injections it is possible to get more information during bad weather conditions when most erosion takes place.

For the evaluation of the silting-up rate of the access channels to Zeebrugge in T_O and after port extension conditions the combination of radioactive bottom tracers and radioactive suspension tracers gave comparable data to evaluations made by other methods, both empirical and mathematical.

For the study of the efficiency of the future dumping grounds for dredged material, once again the combination of bottom and suspension tracers proved to be extremely useful. The overriding value of the tracer studies is the fact that calllbratlon of calculations is indeed possible so that they become as credible for the principal of the works as for the mathematician.

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