CHAPTER ONE HUNDRED THIRTY SEVEN

Study of the Evolution of Dredged Material Discharges by Means of Radioactive Tracers

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Abstract

The choice of a dumping area for dredged materials must be carried out taking into account the general movement of sediments in order to evaluate the risk they represent for the zone itself, the harbour-works and the coastal area.

The use of radioactive tracers allows to study, in situ, transfer properties under tidal currents of fine sediments resuspended during the release, the distribution over the sea-bed of coarse particles and their future evolution due to currents and waves.

In this way, parameters such as transport axis, mean velocity, dispersion, dilution and bed-load transport rates are determined.

Four experiments which took place at OCTEVILLE, ANTIFER (FRANCE), SINGAPORE and ZEEBRUGGE (BELGIUM) during the ten past years illustrate the method.

I - Introduction

The construction or enlargement of a harbour and its access channel and future keep up need voluminous and expensive dredging work. In France, keep up itself represent per year, 40 million cubic meters of dredged materials at a total cost of 600 M.F. (about 70 millions U.S. dollars).

These operations modify the sedimentologic equilibrium of the environment and generate an increase of turbidity because of fine sediments removal. Besides, the discharge of dredged spoils on a dumping area next to the dredging site rise this problem of an eventual return of silt sediments to the harbour or the littoral and thus induce silting and pollution leading to additional tasks which may be avoided.

In order to forecast the effects of such discharges on the environment a good knowledge of sediments behaviour concerning both suspension and bed-load transport, is necessary. Yet up to now, the wide range of parameters, the complexity of liquid-solids interactions and the more or less cohesive nature of bed materials make almost impossible pure

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theoretical calculations and hydraulic model simulations. Thus, to be reliable such models must at least be calibrated by measures in nature, carried out on the future dumping area and for conveniently choosen and well known hydrological conditions.

Such in situ measures are possible thanks to RADIOACTIVE TRACERS. The technology, developed and improved throughout almost 250 experiments during the last 30 years has give rise to numerous publications (A. Caillot, 1970; G. Courtois, 1970; F. Tola, 1982). Only the principal features will be therefore recalled, the purpose of the present paper being mainly to illustrate the method by typical examples.

2. Methodology

A small quantity of labelled particles representative of natural sediments (similar granulometric distribution and hydrodynamic properties) is introduced in the medium, either directly or mixed to some hundreds of tons of dredged materials contained in a hopper (Fig. 1).

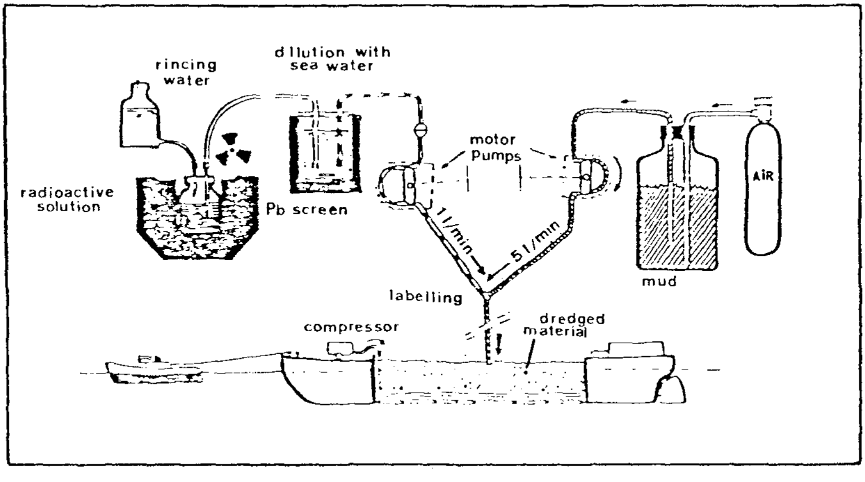

Figure 1 - Labelling and Injection of Silt Sediments.

The transport of radioactivity is used to determine sediments movement in the course of time. Material carried away in suspension is measured by means of vertical arrays of radiation probes attached to two tracking vessels which perform longitudinal and transversal detection of the plume. For bed measures, a single probe is fixed on a sledge which is then towed over the bed (Fig. 2). A location device allows regular plot of fix on a 1/5000 scale chart.

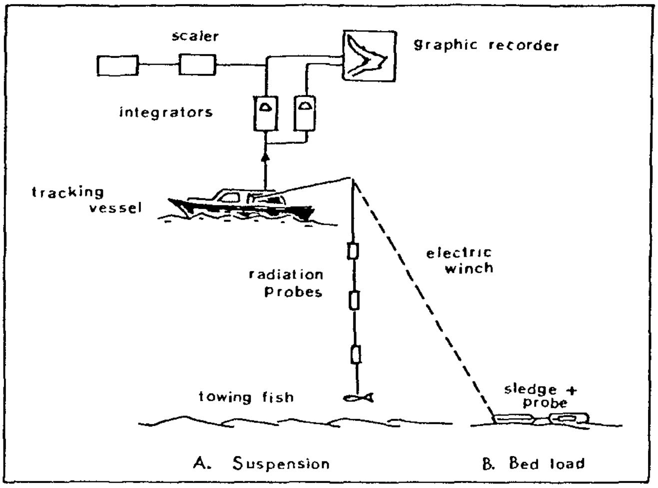

Figure 2 - Detection Equipment of Tracking Vessels.

When studying dredged material discharges we are interested on the following points:

- behaviour of fine sediments (silt and very fine sand) carried away in suspension,
- distribution of sand particles over the sea-bed,
- disposal efficiency,
- future evolution of deposited materials.

Sediments in suspension are followed during 3 to 4 hours. We proceed to bed detection 18 to 24 hours after release takes place in order to allow mixing of the radioactive tracer to natural sediments.

5 to 9 Ci of gold 198 (half life 2.7 days, γ energy of 410 keV) are sufficient to label 1 kg of silt sediments or 0.5 to 1 kg of crushed glass simulating sand particles.

Information collected during this type of experiment is completed by measures carried out from point injections of small quantities of labelled materials in several points of the site and for different hydrological conditions. A clear scheme of the general movement of dredged spoils is thus obtained.

In order to study transfer properties of a silt suspension, sediments are labelled with gold 198 as previously. The following parameters are determined:

- trajectory of the center of gravity,
- mean transport velocity,

- vertical concentration profiles,
- horizontal dispersion (which may be represented by the longitudinal and transversal standard deviations σ_x and σ_y),
- dilution, that is maximum concentration in function of time,
- particles sedimentation, when it takes place.

To study the evolution of deposited materials we use glass labelled with iridium 192 (half life 74 days, γ complex spectrum of energy 296 to 885 keV), allowing experiments lasting 5 to 6 months and thus increasing considerably the amount of data obtained. Only 0.5 to 1 Ci of iridium 192 is sufficient to label 0.25 to 1 kg of glass, per point; that is ten times less than the maximum activity permitted (G. Courtois, R. Hours, 1964). Such low quantities allow easy preparation, transport and manipulation of radioactive products as well as a rapid integration of the tracer to natural sediments.

Qualitative and semi quantitative informations are obtained, such as:
- main transport axis and, eventually, secondary ones,
- mean velocity of particles gravity center,
- dispersion parameters, dimensions of the spot,
- tidal currents and waves effects (bed-load transport, saltation, resuspension),
- burying (sedimentation), mostly during slack water,
- presence of morphological factors (sand banks, deeps, channels) which will either act as a trap of particles or canalize them in a privileged direction.

Lastly, the mean transport thickness is determined thanks to the "total count rate balance" method (G. Sauzay, 1968), thus allowing to quantify the entrainment rate.

Radioactive tracers experiments are completed by intensive hydraulic and meteorological measurements such as currents and wind direction and intensity, waves height, period and direction and tides amplitude. In this way, data concerning sedimentary movements can be linked to local conditions.

3. Illustration of the Method by S.A.R. Main Studies

Four experiments which made use of radioactive tracers techniques and took place respectively at OCTEVILLE, ANTIFER (FRANCE), SINGAPORE and ZEEBRUGGE (BELGIUM), have been selected to illustrate the method. Their detailed description is available in a recent publication (F. Tola, 1984) from which we reproduce the most striking features.

3.1 - Evolution of dredged material discharges off OCTEVILLE

Dredged materials resulting from the upkeep of LE HAVRE harbour are discharged off OCTEVILLE at a depth of 14 m. They are mainly composed of silt sediments ($<$ 40 µm) and fine sands (60 to 350 µm), unproperly incorporated to sedimentologic equilibrium, recirculation of which may affect the coastal environment and ANTIFER oil installations located 15 km N.N.E of the dumping area. On request of LE HAVRE authorities, several radioactive tracers experiments were carried out in order to appraise the real risks:

1°) <u>Transport in suspension and sea-bed distribution of dredged spoils discharges</u>

70 tons of dredged material contained in a hopper at an initial concentration of 150 g/l (73% silt, 27% fine sand) were discharged during a spring tide flood. Fine particles, mainly silt sediments less than 40 μm, form a suspension subject to dispersion due to turbulence, swell and velocity gradients, conveyed Northwards towards ANTIFER and covering almost 7 km in 3 h without settling (Fig. 3). By that time the cloud is spread over an elliptical surface 1 km and 250 m main axis (± 26), with uniform vertical concentration profiles less than 16 g/l.

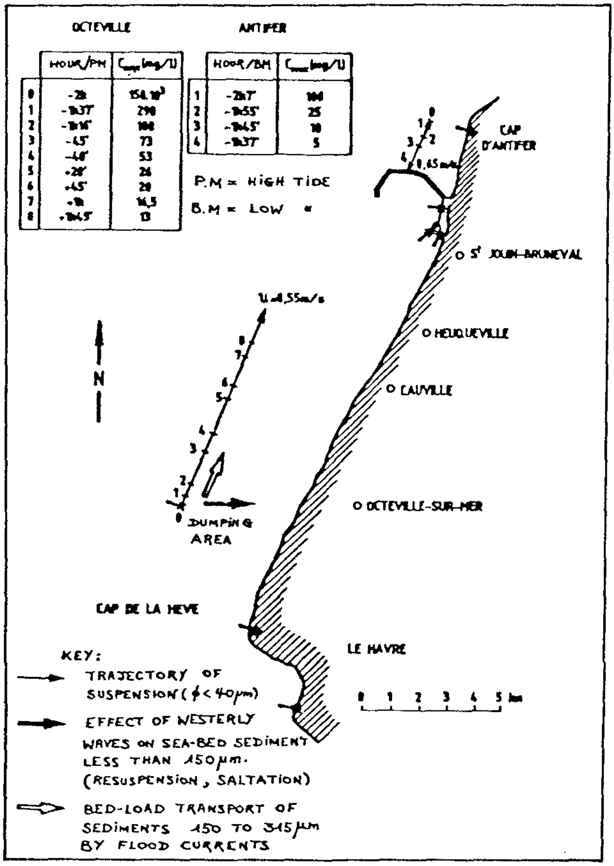

Figure 3. Sedimentary Movements at OCTEVILLE and ANTIFER

However, materials discharged off OCTEVILLE may be highly concentrated and therefore have an initial rigidity which will oppose to dilution when released. Mud with a rigidity greater than some N/m^2 would settle next to the point of immersion.

Detection performed 18 h later shows that sand particles are superficially distributed over the sea-bed, up to 1 km N.N.E, the distance covered before settling depending on the grain size (Fig. 4):

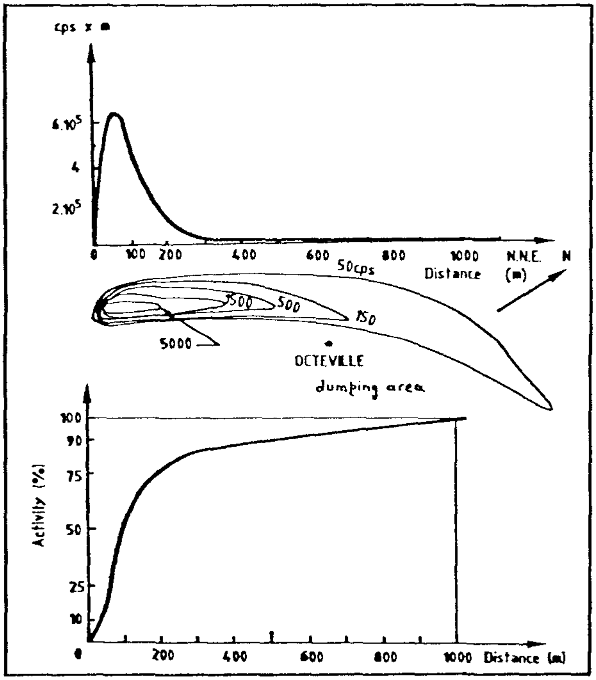

Figure 4. Distribution of Sand Particles over the Sea-bed 18 h after Immersion: Lines of Equal Concentration and Transport Diagrams.

- 50% of sand particles ($\phi > 105\ \mu m$) lay at less than 100 m from the point of immersion, - 75% of them ($\phi < 80\ \mu m$), at less than 200 m,

- only particles less than 80 µm settle at more than 200 µm and reach the limits of the spot (1000 m). Mean fall velocity corresponding to $d_{50} = 105\mu m$ is 0.7 cm/s, while it is found to be equal to 1.1 cm/s in calm water.

2°) Evolution of deposited materials

Two injections of glass particles labelled with iridium 192 were performed next to OCTEVILLE dumping area and a third one in front of CAUVILLE. In the first case the granulometric distribution of the tracer is close to that of dredged materials (80 to 315 μm), while in the last one it is close to that of natural sea-beds sediments (170 to 1000 μm).

Compared to sea-bed sediments which are rather motionless, dredged materials seem quite movable under the same hydrological actions (Fig. 3):

- W to N.W. waves (H_s = 2 to 4.5 m) developed during storm periods ensure resuspension of fine particles which are then conveyed and dispersed in the coastal direction. 70% of sand ($\phi < 150$ μm) cover in this way more than 500 m in 3 1/2 months;

- spring tide currents disperse particles less than 350 μm in a N.N.E. direction (flood predominance);

- by calm weather, N.W. waves disperse sand particles towards the coast (S.E.).

3.2 - Evolution of ANTIFER dredging material discharges

About 30 million cubic meters of dredged materials derived from the construction of ANTIFER oil terminal installations are discharged 2.5 to 6 km North, at a depth of 17 to 22 m.

According to their nature, initial concentration and intensity of currents, which during spring tides may exceed 2 m/s in flood and 1.4 m/s in ebb, sediments will either deposit where release takes place or, on the contrary, be conveyed in suspension, bed-load or saltation. Transport in a Southwards direction would lead to the silting up of the channel access and the harbour-works as well as pollution of the coastal area.

Radioactive tracers experiments allowed to estimate the risk of recirculation of sand spoils.

1°) Transport in suspension and sea-bed distribution of sandy material discharges

About 100 tons of sediments (10% silt and 90% 50 to 550 μm sand) were released from a hopper dredger, off Cape of ANTIFER, by maximum spring ebb currents, since such hydraulic conditions exhibit a high risk for the harbour-works.

The tracer, representative of fine sand 50 to 350 μm, was followed in suspension immediately after release took place and its distribution over the sea-bed measured 18 h later.

Only sand particles less than 125 μm, which represent 15% of the total mass, is carried away in suspension. But contrarily to silt sediments, they will cover at the most 1600 m before settling (Fig. 3), since 40 min after immersion takes place there is no tracer in suspension at detectable concentrations (4 mg/l).

Thus, within 40 min time, the almost entire mass of sand spoils is distributed over the sea-bed up to 1600 m S.S.W. from the immersion point. 18 h later, that is after two floods the following evolution is observed (Fig. 5):

- only 30% of the total mass still remains on the sea-bed: sand particles less than 200 μm (critical entrainment velocity $u_* \leq 1.25$ cm/s) have been resuspended by flood currents, transported N.N.E. and dispersed beyond the limits of the spot at non detectable concentrations,

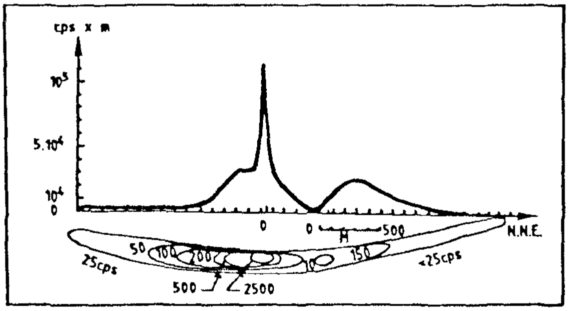

Figure 5. Distribution of Sand Particles over the Sea-Bed 18 h after Immersion at ANTIFER.

- sediments lying on the bed are distributed along a S.S.W.-N.N.E. axis, 1/3 of them are still up to 1600 m S.S.W. from the point of immersin while the remaining 2/3 were retrieved up to 1800 m N.N.E.

On the whole, flood currents have entrained 90% of dredged materials N.N.E. (70% at more than 1800 m), that is, a transport ten times greater in regards to ebb.

2°) Evolution of deposited materials

Two immersions of glass particles labelled with iridium 192 were performed at a depth of 20 m and the tracer followed during 113 days. These experiments confirmed previous results, mainly, flood predominance next to ANTIFER dumping area.

Therefore, sand spoils released at more than 2.5 km North from ANTIFER oil installations represent a fairly low danger for the harbourworks.

3.3 - Study of transfer properties of a suspension of silt sediments at SINGAPORE

At SINGAPORE, ground levelling and littoral extension for urbanization purposes lead to sea disposal of some million cubic meters of silt sediments near the shore. CHANGI airport was built in this way over a site of 660 ha constituting an artificial beach 12 km long. Actually, 15 million m^3 of materials coming from the interior (LOYANG and TAMPINES) are discharged through a pipeline 750 m off BEDOK (Fig. 6). Such procedure will undoubtedly increase the turbidity of the surrounding areas and could create potential danger to the environment. Besides, transfer and settling of fine particles during a west going tide may pollute recreational areas and generate considerable siltation in the port.

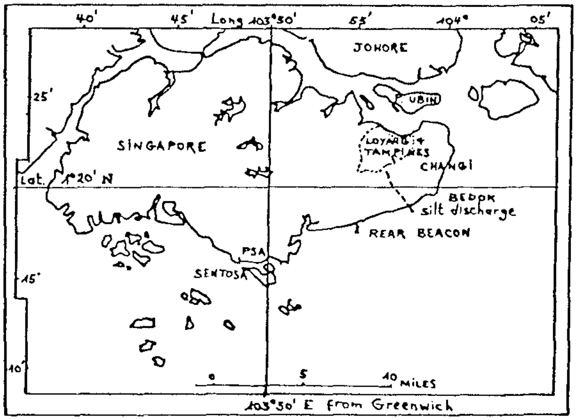

Figure 6. General Map of SINGAPORE

On request of P.S.A. authorities and A.I.E.A. financial support radioactive tracers experiments were carried out in order to study the behaviour of silt sediments in suspension and determine the risk they represent for the coastal area and the harbour-works. Thus, two punctual and instantaneous injections of mud labelled with gold 198, at an initial concentration of 18 g/l, were performed off BEDOK during a west going tide (lasting 16 h, with velocities 0.4 to 0.5 m/s). The cloud so formed was followed during 3 1/2 h over a distance of 6.5 km, by that time dilution being of a 2.5×10^{-6} factor.

These experiments were completed by local velocity measures and float-tracking. They allowed to determine the trajectory and mean transport velocity of sediments, dispersion parameters and dilution (Fig. 7).

For fully established tidal conditions, a lowly concentrated suspension of silt sediments ($\phi < 40\,\mu m$) has very similar transfer properties as fluid particles. They are conveyed by currents over large distances with negligible retard and without settling, while turbulence effects ensure uniformity of vertical concentration profiles over a depth of 10 m within 30 min.

Below a critical threshold, depending on sediments physico-chemical properties and concentration, the energy of turbulence is no longer sufficient to maintain particles in suspension and sedimentation takes place. Indeed, this mainly occurs at the oncoming of tide turn since then velocities decrease and vanish.

Results derived from radioactive tracers experiments were extrapolated to a continuous discharge of silt sediments during ebb and lasting at least 9 hours (Fig. 8):
The plume would reach the shore and the harbours entry respectively 4 1/2 and 9 hours after the beginning of injection, followed by siltation during slack water.

It follows a double risk:

- pollution of the sea-shore by mud particles,
- silting-up of harbour works during slack water.

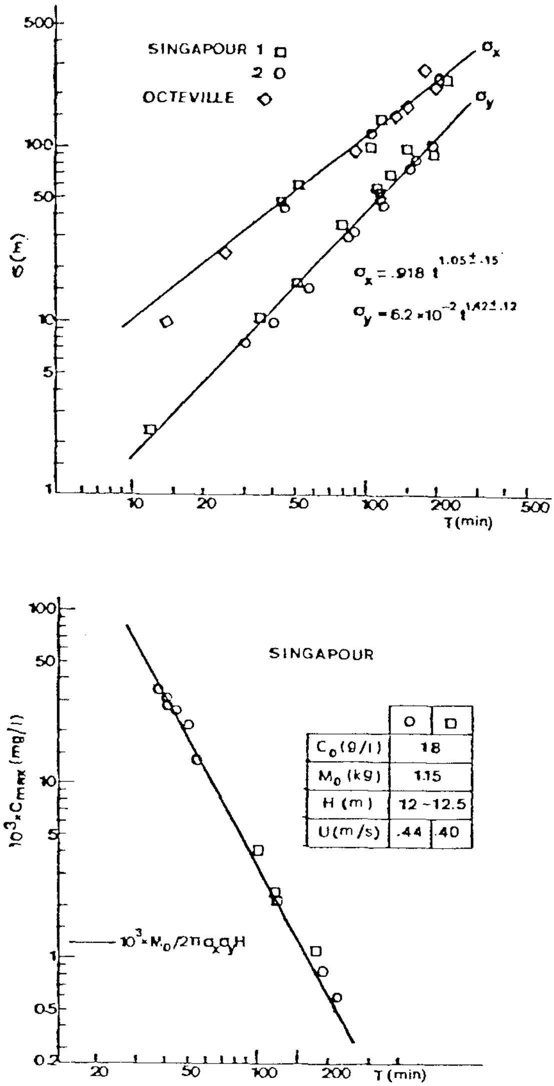

Figure 7. Evolution of Horizontal Dispersion Parameters and Maximum Concentration of a silt Sediment Suspension (ϕ < 40 µm).

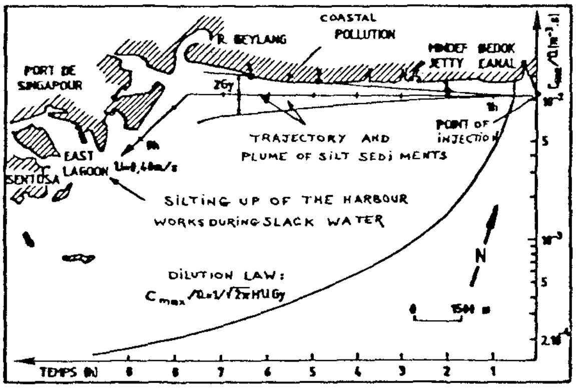

Figure 8. Trajectory, Mean Velocity, Dispersion and Dilution of a Continuous Release of Silt Sediments off BEDOK (SINGAPORE).

3.4 - Sedimentary movements along the Belgian littoral

In 1974, the Belgian government planned to equip ZEEBRUGGE with a modern harbour and a new channel allowing access of greater ships. In order to limit its effects on littoral sedimentologic equilibrium, this task was carried out considering results of a wide research program including radioactive tracers measures. On the whole, 17 injections were decided by HAECON N.V - GHENT both for optimization of dredging operations as well as studying the behaviour of fine sediments resuspended during the discharge and the evolution of spoil disposals (Fig. 9).

1°) Dredging disposals at SIERRA VENTANA

In order to forecast the risk of siltation of the future channel because of recirculation of dumped spoils, labelled sediments (60% silt and 40% glass particles simulating sand) previously mixed to 2250 tons of dredged materials of density 1.49 were discharged from a suction hopper dredger during a spring tide ebb. Sediments carried away in suspension were followed during almost 3 1/2 h, while distribution of deposited materials was measured 24 h later.

Silt sediments and a fraction of fine sands (33%) form a lowly concentrated suspension convected and dispersed southwards towards the future channel (Fig. 9, point D5). Sand particles will most probably deposit before reaching it, contrarily to silt sediments which covered 7 km in 3 h with a mean velocity of 0.6 m/s. The experience was unable to put forward their sedimentation. However, this seems rather unlikely, at least during spring tides, given the absence of slack in the area concerned and the intensity of currents which may reach 1.5 m/s. Thus, silt sediments will be carried away by flood currents and dispersed Northwards. Further experiments (D3-4) confirmed such presumptions.

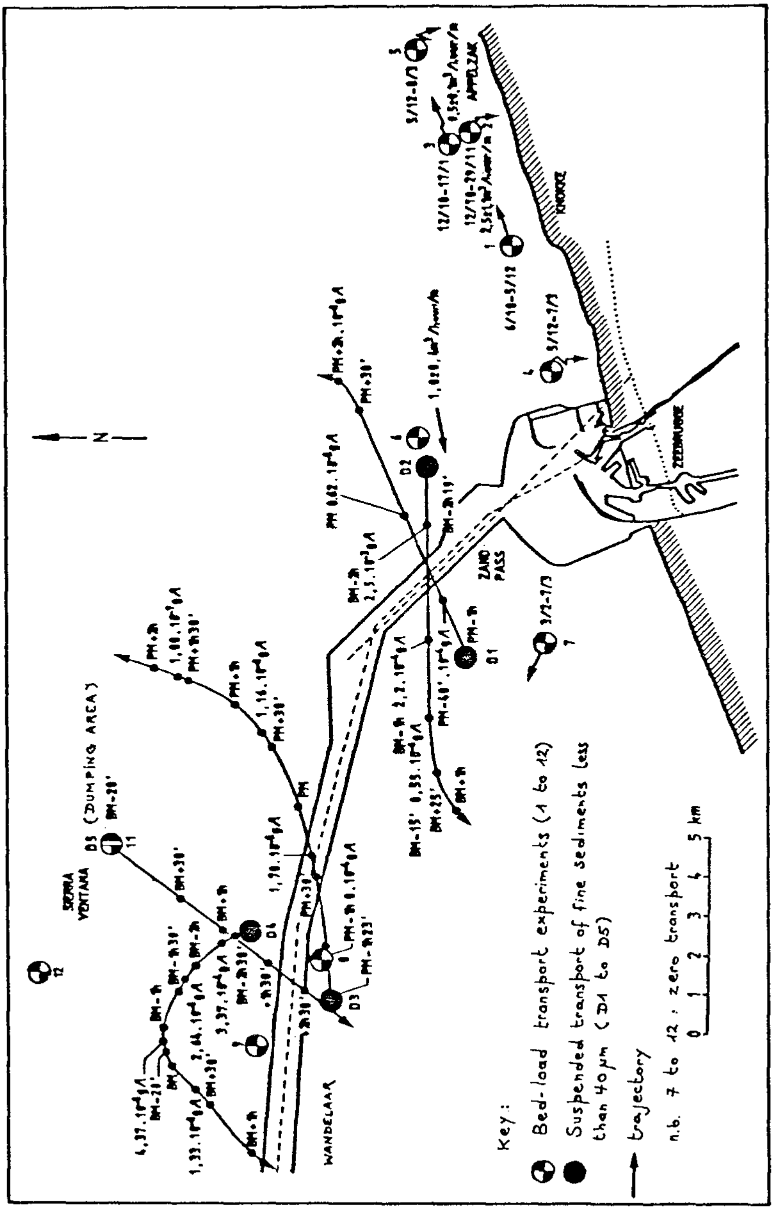

Figure 9. Radioactive Tracers Studies of Sedimentary Movements at ZEEBRUGGE.

About 27% of dumped spoils, that is, 67% of sands settle at less than 1000 m from the point of immersion and over 400 m width (Fig. 10) without any further evolution, sediments being almost unsensitive to currents and waves even during storms (H_s = 5.5 m).

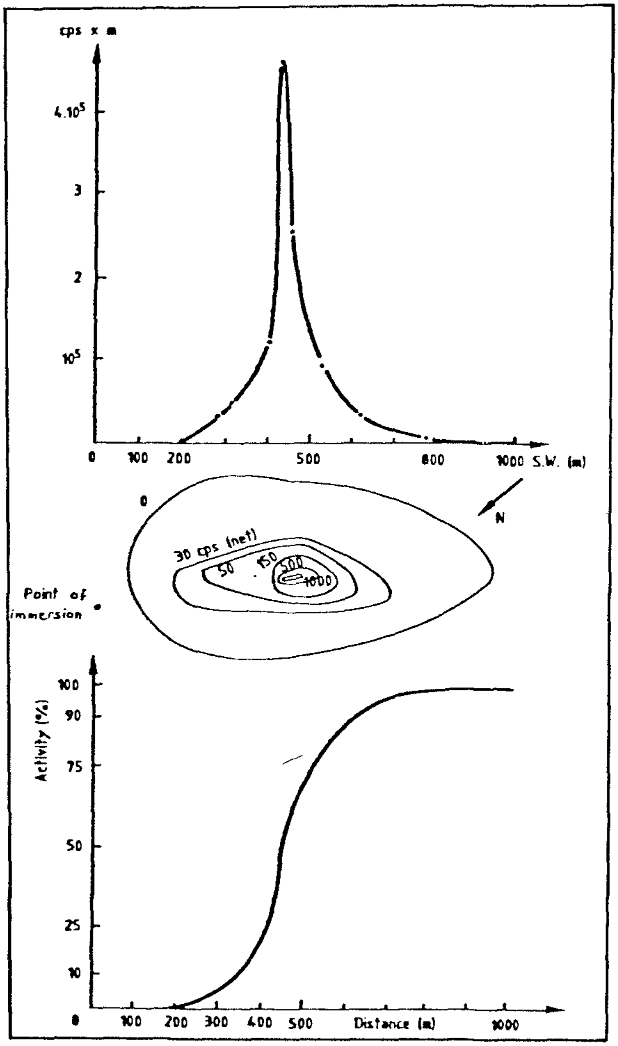

Figure 10. Sea-bed Distribution of Dumped Spoils at SIERRA VENTANA 24 h after Release Takes Place.

2°) General movement of sea-bed materials off ZEEBRUGGE

12 immersions of glass labelled with iridium 192 were carried out in different points from 5 to 18 m depth, and the tracer followed for a period of 4 months during which violent storms alternated with spring tides.

These experiments allowed to study the behaviour of sea-bed sediment of 160 to 315 µm mean diameter and quantify their transport (Fig. 9, points 1 to 12). Their movement is not identical in every point nor occasionated by the same hydraulic actions:

- near the littoral and by less than 5 m depth (points 2 and 4), swell effects (H_s = 5.5 m) ensure resuspension, dispersion and transport towards the coast of sediments less than 250 µm,

- between 5 and 10 m depth, added to wave effects during storms as previously, spring tide currents give rise to a rapid but superficial bed-transport: respectively 35 and 22 m/day with a mean transport thickness of 7 to 8 cm in points 1 and 6 (Fig. 11). The resulting movement is oblique relative to the coast-line. At APPELZAK (points 1 and 3), there is flood predominance with a net transport Eastwards of 0.5 to 2.5 m^3/day/m. Next to the ZAND PASS (points 6 and 7), there is ebb predominance, with a net transport of 1.8 m^3/day/m towards the channel east from it,

- beyond 15 m depth (points 8 to 12), sand particles are unaffected by waves but dispersed along a S.W.-N.E. axis, by alternate effects of flood and ebb currents, although the resulting transport is negligible (less than 2 x 10^{-3} m^3/day/m). Resuspension is not significant, excepted North from the future channel (point 9) where spring tide currents give rise to resuspension of sediments less than 300 µm including 30% of cohesive materials (ϕ < 40 µm). The corresponding critical entrainment velocity is equal to 1.4 cm/s.

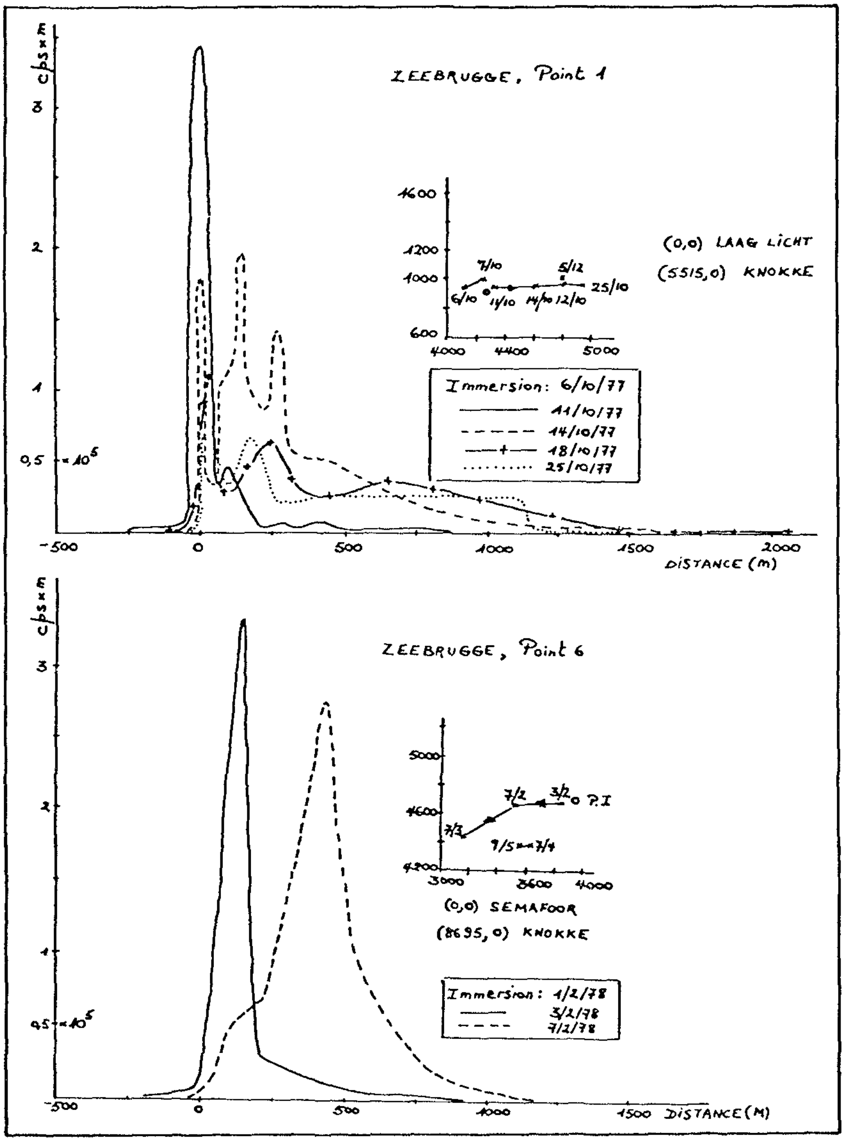

Figure 11. Evolution of Transport Diagrams and Gravity Center. ZEEBRUGGE, Points 1 and 6.

Main quantitative results are summarized on the following table:

Bed-load Transport and Resuspension of Fine Sands off ZEEBRUGGE

Measure Point (see figure 9)	1	2	3	4	6	7
Tracer grain size (μm)	160-315					
Period of observation before resuspension (days)	19	14	49	61	34	34
Mean transport thickness (cm)	7	8	6	5	8	3
Mean transport velocity (m/day)	35	6	2	1	22	1.4
Entrainment rate (m^3/day/m)	2.5 ± 1.1	0.5 ± 0.1	0.1 ± 0.03	0.05 ± 0.01	1.8 ± 0.4	0.04 ± 0.03
Transport direction	E	S	E	S	W.SW	W.SW
% of sediments resuspended by waves	95	84	56	40	75	80
Waves magnitude H_s (m)	3.2	5.5				
Maximum grain size of particles resuspended (μm)	300	250	220	220	250	250
Depth (m)	5	5	5	5	9	5 to 6

3°) Transport of silt sediments in suspension

Four punctual and instantaneous immersions of mud labelled with gold 198, at an initial concentration of 20 g/l, were performed on both sides of the ZAND PASS and the futur channel for flood and ebb spring tide conditions (Fig. 9, points D1 to D4).

The suspension so formed was tracked over a distance of 7 to 10 km within 3 h preceding tide reversal, during which there is no significant sedimentation. Besides a dilution of a 10^5 factor a few minutes after injection, spring tide currents 0.5 to 1.5 m/s are sufficient to maintain sediments in suspension at concentrations close to natural turbitidy and transport them over large distances.

Yet, next to the ZAND, and more generally, close to the coast, tide turn is accompanied by slack water which may last almost 1 h during which sedimentation takes place. Even if the possibility of resuspension must not be set aside, there is still a risk of silting up of the channel. On the contrary, at WANDELAAR or more generally, as we go away from the coast, slack water is less pronounced and the risk of siltation slighter.

Sediments transport is accompanied of vertical diffusion and horizontal dispersion. As it was the case at SINGAPORE, vertical concentration profiles become rapidly uniform after what,for constant depths and permanent current conditions, maximum concentration evolution follows the classical two-dimensional law:

$C_{max} = M_o/2\pi\sigma_x\sigma_y$ (Figs. 7 and 12).

Horizontal dispersion is represented by standard deviations σ_x and σ_y of longitudinal and transversal activity profiles(Fig.13a and b). These parameters are found to be independent from the depth of the point of measure and not only functions of time, but also of velocity, acceleration and their time and space variations.

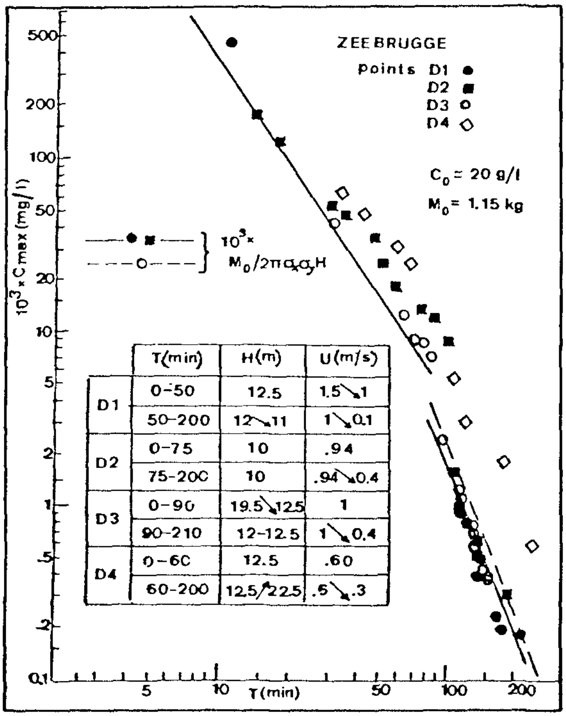

Figure 12. Dilution of a Suspension of Silt Sediments off ZEEBRUGGE.

A comparison of results from different experiments is given in figure 14. Since hydraulic conditions vary from one experiment to another, so does dispersion parameters when expressed in function of time.

For permanent current conditions, values of σ_x and σ_y are well fitted by a power law:

$$\sigma_i = k_i \cdot t^{n_i} , \qquad i = x, y ,$$

where coefficients k_i and n_i are constant but differ according as i = x or y. This is the case for SINGAPORE and OCTEVILLE. Velocity variations will affect coefficients k_i and n_i, inducing an increase of exponent n_i and a decrease of k_i, as it is the case for ZEEBRUGGE experiments.

Lastly, horizontal dispersion seems to increase with currents intensity and velocity variations, being greater in points D1, D2 and D3 of ZEEBRUGGE then it is in point D4 or at SINGAPORE.

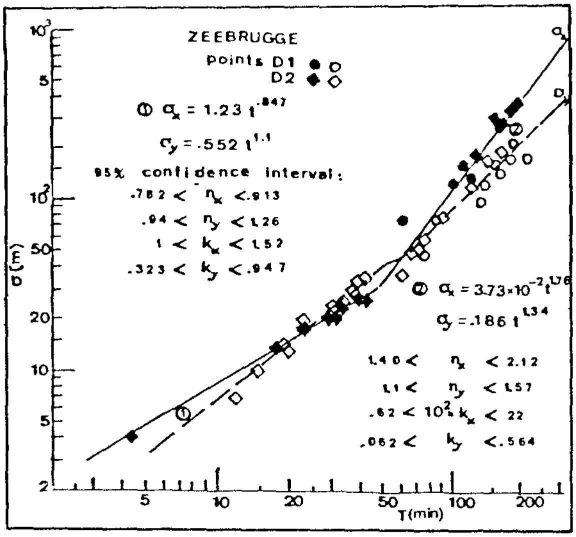

Figure 13a. Horizontal Dispersion Parameters of a Suspension of Silt Sediments off ZEEBRUGGE.

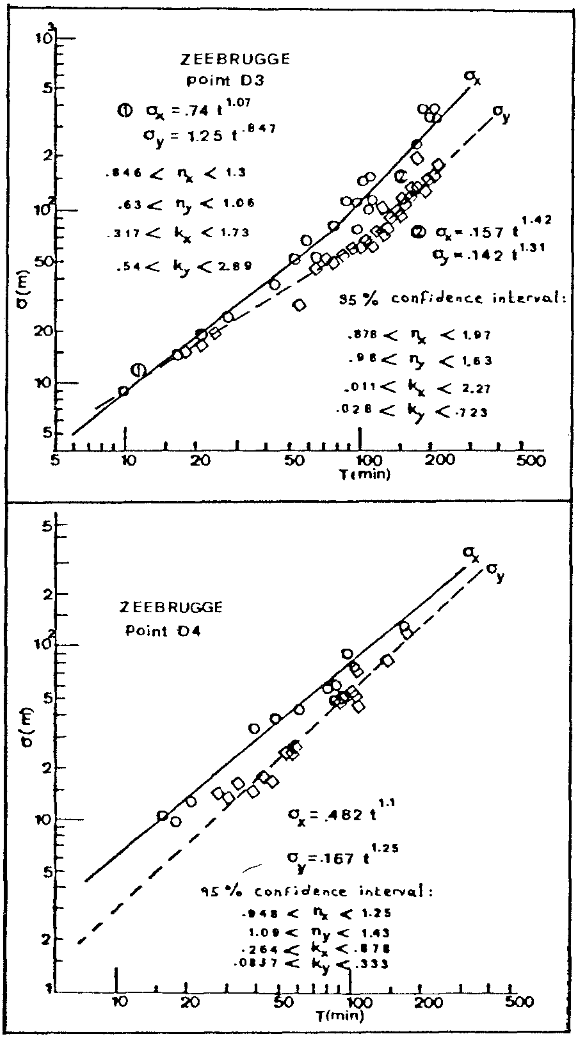

Figure 13b. Horizontal Dispersion Parameters of a Suspension of Silt Sediments off ZEEBRUGGE.

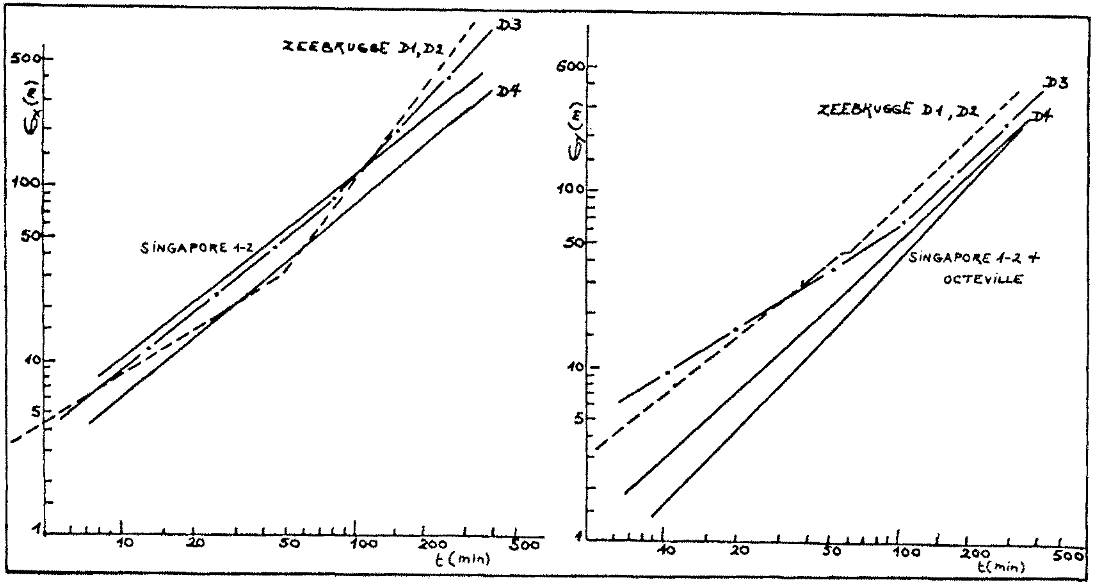

Figure 14. Horizontal Dispersion Parameters of a Silt Sediment Suspension. Comparison of Results.

4 - Conclusion

In the past, dredging operations and dumping conditions were mainly based on local habits and empirical experience. Nowadays, the necessity of practicing voluminous spoil discharges at least prices, yet limiting environmental pollution and the risk of recirculation of materials, requires quantitative evaluation of dredging efficiency. Experience shows that radioactive tracers are well suited for such a task. Besides, our present knowledge on dynamic properties of sediments is improved.

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