Full scale mine burial experiment and comparison with models

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Abstract – **Buried sea mine remains a threat still unsolved in spite of new sonar development. Reliable predictions of where and under which conditions mines will bury are not yet available. Field experiments are required for a better understanding of the burial processes.**
This paper reports on a field experiment carried out between January and April 2004 in the Bay of Brest (France) in cooperation between French and German institutions on two sites. The conditions at the two sites differed through the mean water depths and the hydrodynamics conditions achieved. At Rascas, the sea bed is almost uniquely submitted to tidal and river current flows. Very limited mine burial was observed. The dynamics at the second site is driven by tides and ocean waves. A one week long storm and several swell events were experienced. They resulted in significant mine burial. The first part of the paper reports on the joined analysis of mine burial data, sediment data, sea bed observations and hydrodynamics measurements. In a second part, comparison is made between burial and the predictions of mine burial using various models.

I. INTRODUCTION

Sea mines were first used on a large scale during the First World War and resulted in severe damage to commercial and military shipping. Since that period, sea mine technology has become increasingly sophisticated. In spite of significant progress in countermeasures, the threat is still present. Mine burial into the sea floor is one of the main reasons for the continuing threat in spite of new sonar technology based on synthetic aperture or parametric transmission techniques, allowing both low-frequency and narrow-beam waves to penetrate into the sediment. Keeping ships away from burial risk areas remains the only secure way for navies to protect their vessels from the mine threat. Reliable predictions of where and under what conditions mines will or will not be buried are not yet available. Models exist, but they need further validation under different sediment and hydrodynamic conditions. Field experiments are required for a better understanding of the burial processes. They demand the simultaneous monitoring of mine burial and of the forcing environmental conditions, in addition to knowledge of sediment properties. Several field experiments have been carried out in recent years. The present paper reports on the field experiment carried out in France between January 27, 2004 and April 8, 2004, in cooperation between French and German specialized institutions, [1].

Two sites, with different experimental conditions, were chosen in the vicinity of Brest. The goal of the experiment was to observe the mine burial phenomena that occur in two different hydrodynamic environments and over time scales of one hour to a few months. Besides visual observations, mine burial was continuously recorded using Burial Recording Mines (BRM), while tides, currents and waves were continuously measured using current-meters and pressure sensors mounted on tripods laid out in the vicinity of dummy mines. The results are complemented by an analysis of sediment core samples taken at different times during the experiments and by three sonar observations of the sea bed and of the equipment laid out.

The results of the experiments were compared with the predictions of mine burial models; a model of momentary liquefaction by the action of waves, and a wave scour model.

II. DESCRIPTION OF MINE BURIAL EXPERIMENTS

A *Site characteristics and equipment deployed*

The first site, Rascas, is located within the Bay of Brest. It is well protected against open ocean waves. Flow is mainly caused by a tidal current (up to 0.45 m/s) combined with river outflow. Water depths vary with the tide from 32 to 38 m. The second site, Bertheaume is outside the Bay of Brest, well exposed to North Atlantic waves propagating from the West and South-West. Flow over the bed is mainly caused by waves. Water depths range between 17 and 23 m, with the tide driving currents up to 0.35 m/s at 1 m above the bed.

The duration of the experiment was shorter at Rascas than at Bertheaume. Equipment was deployed at Rascas from January 28, 2004 to March 11, 2004, whereas the experiment at Bertheaume ran from January 27, 2004 to April 8, 2004. Intense sediment transport and significant mine burial were observed at Bertheaume during the experiment, while very few changes were noticed at Rascas. Because of this, the experiment at Rascas was not prolonged.

Three different mine-like objects were deployed on each site: two dummy mines with the shape and the weight of Rockan and Manta mines and a Burial Recording Mine (BRM) “Fig.8”.The BRM has a cylindrical shape with two different ends, a tapered end and a conical end. The length and diameter are 1.70 m and 0.47 m, respectively. Its weight is about 500 kg in air. A BRM has the capability of monitoring the state of burial of the mine casing using optical sensors.

Time series of flow properties were measured using current-meters of different types, mounted on tripods placed at a distance of about 10m from the mines. Due to limited power supply autonomy and insufficient recording capacity, the current-meters were changed during the experiment. Two different types of current-meters, Aquadopp and Vector, both produced by Nortek A/S, were deployed. One Aquadopp was used at Rascas. It measured 15-minute averages of bottom current and pressure. Mean water depth variations were deduced from pressure. Two Vectors and one Aquadopp were used successively at Bertheaume. In addition to measuring the three components of mean velocity, temperature and pressure (tide), both instruments also recorded pressure and velocity at 2 Hz in 20 minute records. The recordings were stored every 1 hour for the Vector and every 6 hours for the Aquadopp. The wave properties, including frequency spectra of bottom pressure and velocity, were determined from these high-frequency records. The bottom wave agitation velocity, $U_{b,r}$ (defined as the square root of twice the bottom velocity variance) and the corresponding bottom orbital displacement, $a_{b,r}$, were also determined. In the case of monochromatic waves, these parameters are the amplitudes of the wave-induced velocity and displacement at the bottom, respectively. Further, the significant wave height, H_s, was determined using linear wave theory [3] applied to the low frequency (less than 0.15 Hz) part of the bottom pressure spectrum.

All equipment was deployed and recovered by divers. Divers also reported on the mine burial, taking photographs of the mines, and sampled sediment cores nearby. These operations were repeated six times over the period. Diving operations where carried out when the sea was calm. Hence, the photographs do not show the field during active sediment transport conditions. However, they enable the BRM data to be verified and account for general variations in sediment deposition and erosion in the vicinity of the mines.

Significant changes in the sediment cover were observed during the experiment. They are described in the next sections.

B. *Sonar observations*

Three sonar data acquisitions were performed at Bertheaume during the experiment. The first sonar images were taken the day after the equipment was laid out, using a Reson sonar mounted on a ROV (Remote Operational Vehicle). Two distinct areas were distinguished on the pictures, one rippled area and another flat bed area “Fig. 1”.
Observations by divers revealed that ripples occurred over coarse sand whereas the flat sea bed area consisted of finer sand. The location of the BRM was identified in the image at some distance from the ripple field.

Fig. 1: Image from the RESON sonar

Observations by divers revealed that ripples occurred over coarse sand whereas the flat sea bed area consisted of finer sand. The location of the BRM was identified in the image at some distance from the ripple field.
The two other sonar acquisitions were conducted with French Navy vessels on March 10 and March 11, using a “DUBM-41” Side Scan Sonar and a “DUBM-21E” Hull Mounted Sonar, respectively, “Fig. 2 and 3”. These sonar images again show the variability of the sea floor where the mines and equipment were laid out. The coarse sand area covered with ripples and the flat bed with finer sand are visible. Ripple wavelength is estimated to be about 1 m by comparing the length of the ripples with the length of the shadow of the BRM observed on sonar images. Comparison of the Reson sonar pictures taken at the beginning of the experiment and the sonar pictures taken on March 10 shows that the ripples appear to have moved between January 29 and March 10. On January 29, the BRM was 3 - 4 meters outside the ripple area whereas it lies at the edge of the ripple field on the images in “Fig. 2 and 3”. Tripods, Manta and Rockan mines are also seen in these images. The Rockan mine is inside the ripple field whereas the Manta mine is on the flat fine sand area.

The sonar operation on March 11 was performed as a “Mine Hunting Operation” with the use of two sonars, one for detection and the second for classification.

This mine hunting operation was thus conducted in order to correlate detection and classification performances with the degree of mine burial. During the mine hunting operation performed on March 11, the BRM was both detected and classified successfully as a cylindrical mine resting on the sea floor and the exact size of the object was found. The mine was not in fact buried that day, as discussed in Section III.C. The Manta mine was more than half buried and located at the centre of a large basin. It was detected but not classified. The mine's position inside the crater did not permit observation of a shadow. Neither detection nor classification of the flush-buried Rockan mine was possible that day.

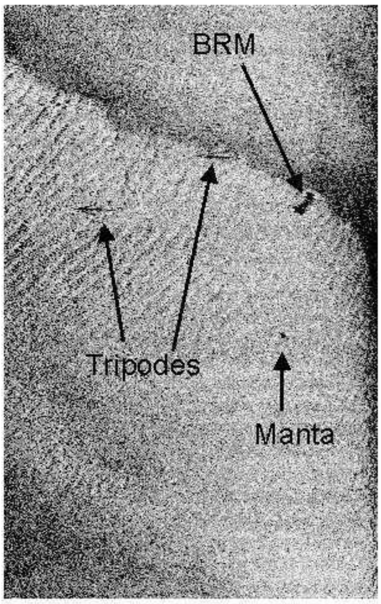


Fig. 2:Sonar image from the DUBM-41B (10 March 2004).

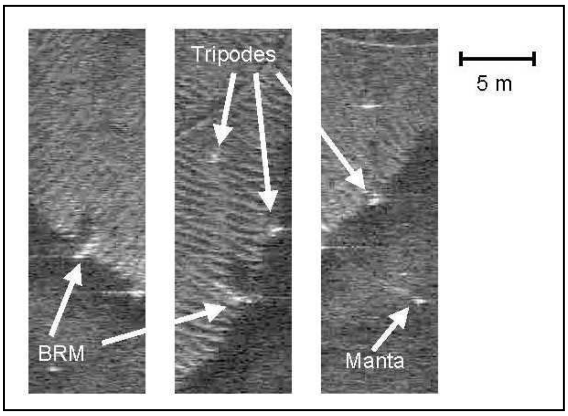


Fig.3 : Pictures from Classificator screen of the DUBM-21E (11 March 2004).

C *Analysis of superficial sediments*

Sediment core samples were taken by divers on several occasions during the experiment, four times at Rascas and five times at Bertheaume. The sediment distributions were determined as averaged values over each core (the length of the sediment cores varied between 10 cm and 27 cm). Because spatial heterogeneity was visually observed, core samples were taken at two different locations at Bertheaume, one close to the BRM and the other close to the Manta mine. The first observation is that the mud content is very low. The sediment is mainly sand at the two sites, with a significant quantity of shell debris at Rascas. Another feature of the core samples observed at the two sites during the experiment was their variability. The sediment surface layer was regularly washed away at Rascas. The change in sediment grain size distribution at Bertheaume over the duration of the experiment is displayed in “Fig. 4”. The sea bed near the BRM consisted of fine sand at the beginning and at the end of the experiment, but this sand layer was covered in the meantime with coarser sand. Average values are given in “Fig. 4”, but the vertical structure of some cores reveals that the coarse sand was covering the fine sand. Changes in the sediment size over a depth of 20 cm were observed. This is a clear indication that the mine burial observed between the beginning of the experiment and February 18 is caused partly by the transport of coarser sediment into the vicinity of the mine where sediment was deposited. This is quantified by the core analysis and is also accounted for by the sonar images. The mega-ripples move over coarse sand in response to hydrodynamic forcing.

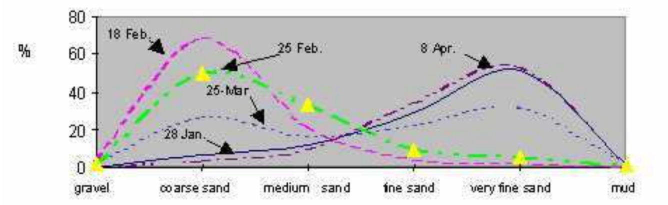


Fig.4: Change in sediment grain size distribution at Bertheaume (near the BRM).(Gravel: d > 2mm ; Coarse: d = [0.5 - 2] mm ; Medium: d = [0.25 – 0.5] mm ; Fine: d = [0.125 – 0.25] mm ; Very Fine: d = [0.05 – 0.125] mm : Mud: d = [5 – 50] µm).

III. OBSERVATION OF MINE BURIAL

A. *Mine burial measurement procedure*

Mine burial was monitored using Burial Recording Mines (BRM) deployed at the two sites for the period of the experiment. BRM were developed by the German Forschunganstalt der Bundeswehr für Wasserschall und Geophysik (FWG) and were operated by FWG during trials.

BRM's are equipped with three rings of 24 light bridges equally spaced around the mine at 15° intervals. The light bridges (light emitters and receivers) are in small housings welded onto the mine casing. At pre-set intervals (15 minutes for our experiments) light is emitted for a short period. Any bridges in which the receiver detects no light is interpreted as a buried sensor and a "1" is recorded. If light is detected by the receiver a "0" is recorded. Analysis of the sequence of 24 numbers "0" or "1" recorded at a specific time for all sensors determines which of the light bridges are buried. The BRM's are also equipped with motion sensors that yield the pitch and roll angles of the mine. The three rings are denoted "RB", "RM" and "RF". The soil levels h_1 and h_2 are measured by the three sensor rings on both sides.

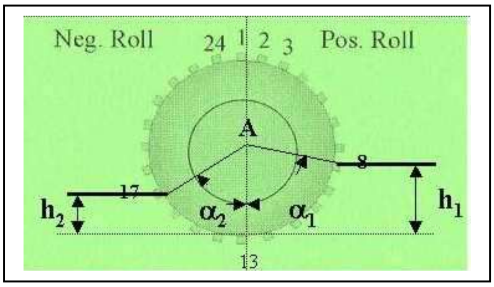


Fig.5 Cross section of BRM

Determining the soil levels h_1 and h_2 allows any asymmetry in the process of burial to be detected. The dimensionless burial measured by each of the three rings of sensors is given by

$$\frac{h_m}{D} = 0.5 - 0.5\cos(\frac{\alpha_1 + \alpha_2}{2}) = 0.5 - 0.5\cos(\frac{\pi N}{24}) \quad .(1)$$

The angle $\alpha_1+\alpha_2$ is determined from the number N of buried bridges.

B. *Observations of mine burial in a current-dominated environment*

Almost no mine burial was observed at Rascas, where the flow is produced mainly by tidal motions. Wind waves generated in the bay are not long and high enough to create significant velocities at the site. The dimensionless mine burial h_m / D was measured by the BRM at less than 7% over the one and half months of the experiment. These very limited changes were confirmed by photographs and divers' observations. No burial was visible. These experimental data are still useful for a model sensitivity analysis. Possible mine burial prediction by models has be considered in our study, starting from the field conditions achieved at Rascas during the experiment. The mean water depth was 35 m. The tidal amplitude was 6.5 m for spring tide conditions (with a maximum velocity at the bottom of 0.45 m/s measured at 1 m above the bed) and 2 m for neap tide conditions (maximum velocity at the bottom of 0.1 m/s). Wave properties were not measured at Rascas and are expected to be insignificant.

C. *Observations of mine burial in a wave-dominated environment*

The change in H_s at Bertheaume is shown in “Fig. 6”, revealing several wave events that occurred during the experiment. Storm conditions with a wave height continuously above 2 m and reaching 3.8 m existed from January 31 to February 6. Long waves generated by distant storms arrived as swells with several events for which H_s peaked between 1.5 and 2.5 m (February 13 and 16, March 4, 12 and 22, April 4).

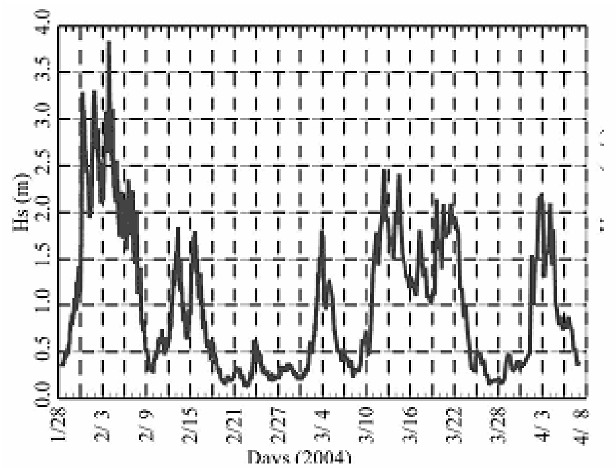
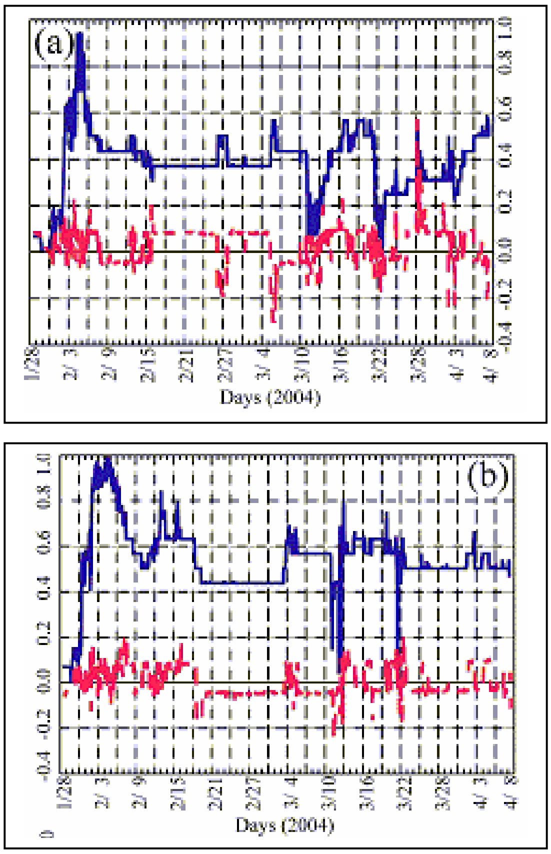


Fig.6: Reconstructed wave height time series (H_s)

The peak wave periods generally varied between 10 to 14 s, reaching 22 s on one occasion on 22 February. The bottom r.m.s. velocity variations produced by waves (i.e. excluding the 15 to 30 minutes average current) has been calculated and appeared closely correlated because of the moderate water depth and fairly constant peak period.

“Fig.7” shows the change in the dimensionless mine burial h_m/D measured during the experiment at Bertheaume by the three rings of the BRM respectively. Data are plotted every hour, with each data point being the average value of the 5 records in a one-hour window centered on the averaging time. Rapid mine burial occurred during the initial storm (January 31 to February 6). The mine was almost completely buried on February 5 when wave activity was maximum. The degree of burial then decreased when wave activity became weaker. For most of the experiment, the degree of burial measured around the three rings is about half the mine diameter. The degree of burial measured by the middle ring was often greater than the burial around the rings located near the mine ends. This is shown by “Fig.7” and confirmed by the statistical estimates. Changes in the position of the BRM were observed only during the early days of the experiment (January 28 to February 2) and suddenly for two events (March 12 and March 21) discussed later. For most of the experiment the mine's position was stabilized by the sand surrounding and covering it and the burial was increased by sediment transport and accumulation around the mine.



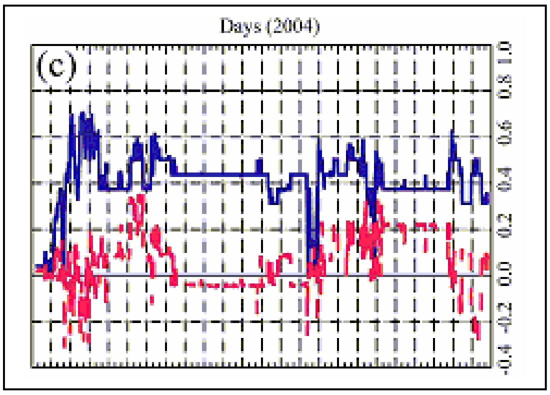


Fig.7: Mine burial measured at Bertheaume by the 3 BRM sensors rings. (a). RB ring**,** (b). Ring RM**,** (c). RF ring -blue line, h_m/D; red line, $(h_1-h_2)/D$.

Variations in the quantity $(h_1-h_2)/D$ are also plotted in “Fig. 7”. The quantity $(h_1-h_2)/D$ is usually much smaller than h_m/D, indicating that no significant asymmetry in bed level was measured between one side of the mine and the other The mean values and rms variances of $(h_1-h_2)/D$ are less than 6% and 12%, respectively. There is no clear indication that mine burial occurred as a result of sand wave migration. Nor do the bed level changes occur at delayed intervals at different positions around the mine. Although the ripple field contributes to sediment transport in the area, as suggested by the sonar images the sediment transport and deposition causing mine burial occur at a scale greater than the ripple wavelength.

Several important events of different types can be identified in “Fig. 7”. The first one is the very rapid burial of the BRM observed during the storm at the beginning of the experiment (January 31 to February 6). It can also be seen in the burial record that the BRM became almost completely uncovered during two short periods observed on March 12 and on March 21. The dimensionless sediment levels h_1/D and h_2/D measured by the three sensor rings on the right and left sides of the BRM during the initial storm highlight the fact that the sediment deposits vary in the same manner and at the same time on both sides of the BRM. It is also clearly observed that burial at the middle of the BRM is more rapid and significant than it is at both ends of the mine. The variations are about the same and they occur simultaneously at both ends. This may be due to the horseshoe-shaped vortices attached at both ends of the mine, as described after in relation to the model of Voropayev *et al.* (2003), [5]. A careful analysis of the burial records shows that the RB and RF rings were sometimes totally uncovered for about 1 hour during these periods. This presumably coincided with the occurrence of a scour pit and the sudden change in pitch angle may indicate that the mine was falling into it. However, although the phenomenon was clearly observed, its few occurrences show that it can only explain a limited amount of the mine burial.

“Fig. 7” shows a dramatic sequence that occurred during the days around March 12, 2004. The significant wave height reached about 2m “Fig.6” and, within a period of 3 days shown, sediment was washed away three times. The observation cannot be attributed to measurement errors, as sudden changes in the pitch or roll angles occurred simultaneously. A significant amount of sediment was again deposited around the BRM between these three events. In the middle of the mine, the sediment deposit reached a depth of about half a mine diameter during the interval between the first and second event, and about 75% of the mine diameter during that between the second and third events. The period between the first and second events was one day, but only half a day between the second and third events. These data indicate that the phenomena observed are very rapid and extreme events. It is also striking to see that sand erosion or deposition occur simultaneously all around the mine. Sediment bottom changes occur at a scale that is larger than the size of the mine. As observed previously, the depth of sediment deposits is greater in the middle of the mine than at the ends.

Photographs were taken by divers on five occasions during the experiment. The first pictures were taken on January 28, when the mines were installed at the site and the last ones were taken, when they were recovered. Some photographs are shown hereafter. Each of the pictures gives only limited insight into the phenomena described above, because the photographs could only be taken when the sea was quiet.

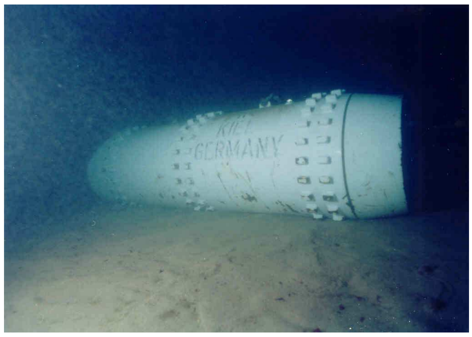


Fig.8: BRM – January 28

The extreme phenomena discussed above cannot be checked visually in the pictures. The photographs, however, confirm that significant burial occurred at Bertheaume, at least up to 50% of the BRM diameter “Fig. 9”.

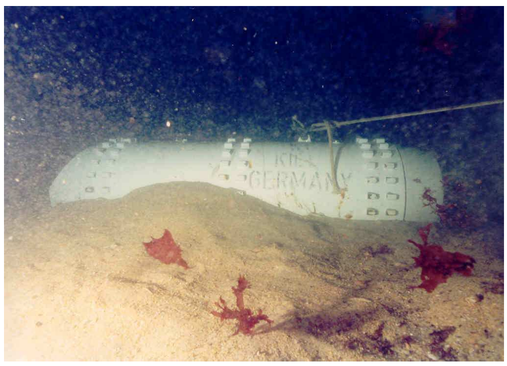


Fig.9 : BRM status on February 18

Although the bottom is covered with ripples, they do not appear to be the morphodynamic feature of the sediment that determines the degree of mine burial.

Similar burial of the Rockan and Manta mines are also observed (Figs.10 and 11).

Fig.10: Rockan mine status on February 18

In particular, larger scale morphodynamic bottom changes are noticed around the Manta mine “Fig. 11”. This was located on February 18 inside a large basin which was not observed before.

Fig.11: Manta mine - February 18

The mines were initially located on a flat bottom “Fig. 8”.

IV. COMPARISON OF MINE BURIAL WITH MODELS

A. *Mine burial models*

Observations and measurements of mine burial in the field were compared with predictions by especially two models:

- ✓ A model of the momentary liquefaction of a sandy bed under the action of waves, which was developed by GESMA (Groupe d'Etudes Sous Marines de l'Atlantique).
- ✓ A new scour model recently proposed by Voropayev et al. (2003), [5] that predicts the scour produced by waves around a cylinder of finite length.

The GESMA momentary liquefaction model is based on the equations published by Sakaï, see reference [2]. The degree of burial of mine-like objects of different shapes is determined from the static equilibrium of the object in the liquefied layer. The reader is referred to Gratiot and Mory [2] for a detailed description of the model and a sensitivity analysis of the momentary liquefaction model with regard to its parameters. The main result is that momentary liquefaction is usually triggered by the gas contained inside the soil, for representative sediment and hydrodynamic conditions.

Laboratory experiments on the scour produced by waves around a cylinder of finite length were recently reported by Voropayev et al. (2003). Five different scour regimes were identified, whose conditions of occurrence are defined in terms of the Keleugan-Carpenter number

$$KC = \frac{UT}{D} \qquad (2)$$

and the Shields number

$$Sh = \frac{\tau}{(\rho_s - \rho_w)gd} \qquad (3)$$

D is the cylinder diameter, T the wave period and U the amplitude of velocity motions at the bottom. τ is a characteristic skin friction acting on the sediment as a shear stress at the scale of the sand grains. Other parameters are the density of the sediment ρ_s and water ρ_w, the grain size d, and the acceleration of gravity g.

The five scour regimes are distinguished as follows:

- ✓ Regime with no scour (I): this is obtained when the Shields number is too low (*Sh<0.018*).
- ✓ Initial scour regime (II): local erosion holes are observed, in particular at the tips of the cylinder.
- ✓ Expanded scour regime (III): local scour holes are merged together at higher flow speeds.
- ✓ Periodic scour regime (IV): scour action is generated on both sides of the cylinder by a horse-shoe vortex attached at the two ends of the cylinder.
- ✓ Sheet-flow regime (V): this regime occurs for very high values of the Shields number. Non-uniformity of the sea bed is eliminated.

The conditions of occurrence of the five regimes were determined in terms of *KC* and *Sh* and the curves *KC(Sh)* separating the different regimes were interpolated.

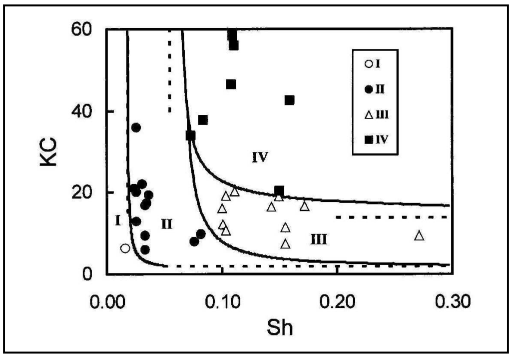


Fig.12: Figure from Voropayev *et al.* (2003), [5].

“Fig. 12” shows the conditions of the four regimes reproduced from [5]. The depth of scour was only determined for the initial scour regime (II). It was found to increase with time according to:

$$\frac{S(t)}{S^*} = 1 - \exp\left(-\frac{2\pi t}{3300.T}\right) \qquad (4)$$

The maximum scour depth S^* is :

$$\frac{S^*}{D} = 1.3\left[1 - e^{-0.06(KC-2)}\right]\left[1 - e^{-40(Sh-0.018)}\right] \qquad (5)$$

B. *Field experiment conditions*

Table 1 summarizes the conditions at Rascas and Bertheaume that were used for the computations. Two measured sediment conditions, one corresponding to fine sand and the other to coarse sand, were used for each site. Table 1 also includes the values of the porosity *n* and the permeability *k*, estimated using the Hamilton formula. The values of sediment density and water are ρ_s = *2650 g/l* and ρ_w = *1025 g/l*, respectively. The Shear modulus and the Poisson ratio of the solid soil skeleton were taken to be $G=10^8$ *Pa* and $\nu=0.49$.

No mine burial was observed at Rascas during the experiment. Computations also predicted no burial for the conditions of the field experiment. Two different wave conditions (storm and swell) were used to compute mine burial at Bertheaume as determined from observations. Wave height, period and bottom wave agitation velocity variations are given in Table 1

Table 1 Main characteristics observed at Bertheaume (resp. at Rascas)

BERTHEAUME *(RASCAS)*		
	Sediment B1	**Sediment B2**
Grain size *d*	148 µm *(330)*	607 µm *(868)*
Porosity *n*	0.45 *(0.36)*	0.41 *(0.37)*
Permeability *k*	4.0 10^{-4} m/s *(7.5 10^{-4})*	44 10^{-4} m/s *(58 10^{-4})*
	Spring tide conditions	**Neap tide conditions**
Max. water depth	23 m *(38.5)*	20.5 m *(36)*
Min. water depth	17 m *(32)*	19.5 m *(34)*
Mean water depth	20 m *(35.25)*	20 m *(35)*
Max. bottom current	0.35 m/s *(0.45)*	0.05 m/s *(0.10)*
	Bottom wave agitation velocity	
Storm conditions	0.4 m/s - 0.7 m/s *(NO)*	
Swell conditions	0.3 m/s - 0.5 m/s *(NO)*	

C. *Mine burial predictions*

Computations of possible mine burial by liquefaction caused by waves were performed using the GESMA software. Considering the results of a former study by Gratiot and Mory [2], it was expected that liquefaction was unlikely to occur with the conditions of the field experiment. Gas content is the triggering parameter of liquefaction. Although the quantity was not measured, the expected values are less than 0.01% in the sandy beds at Rascas and Bertheaume, because the sea bed is neither in contact with the air, which happens in intertidal areas, nor is the decomposition of organic matter enough to create methane. No liquefaction was predicted by the GESMA model for the Rascas and Bertheaume site conditions when the gas content was 0.1% or less. Unrealistic wave height values are required to produce liquefaction. They confirm that momentary liquefaction cannot occur at Bertheaume and Rascas with the field conditions observed during the trial. The model does not take into account the possibility of cyclic liquefaction. This process of liquefaction can be observed in fine sediments like silt and is unlikely to occur in coarser sediment. Recent observations on a sandy beach did not show any cyclic increase in pressure inside the soil caused by waves and momentary liquefaction was observed [6]

The wave scour model of Voropayev [5] will now be considered. This is potentially much more relevant for the Bertheaume site, where observed mine burial is correlated with wave forcing. The Keleugan-Carpenter and Shields numbers (Eqs. 2-3) with the conditions observed at Bertheaume may be estimated from field data. The Keleugan-Carpenter number is determined using the measurements of $U_{b,r}$, and *D=0.47 m* for the mine diameter. The variation in wave period was determined from the peak frequency $f_p = 1/T$ in the wave spectra measured. f_p was found to vary little during the experiment ($0.07\ Hz < f_p < 0.1\ Hz$) and its value was not correlated to the magnitude of wave activity.

The variation in the Shields number during the experiment is shown in "Fig.13" for two typical grain sizes. Normalized Shields numbers $Sh_N=Sh/Sh_c$ are plotted using the critical Shields number Sh_c for two typical grain sizes, as estimated from [4]. The normalized Shields numbers are significantly larger than 1 during the storm and swell events, indicating that sediment transport should be significant. Ranges of variations of the Keleugan-Carpenter and Shields numbers has been estimated for the storm and swell conditions given in Table 1. The Shields number is found to be high with most conditions. Using the values of the *KC* and *Sh* numbers, the scour regime was determined for each condition from "Fig. 12", [1]. With coarse sand ($d=735\ \mu m$), all swell conditions correspond to the initial scour regime (II) whereas, with the storm conditions, this regime (II) is only found when the less active hydrodynamic conditions are considered. With the conditions of the initial scour regime (II), the maximum scour depth was determined from Eq. (11). No estimate of the maximum scour depth is given when the conditions correspond to the expanded scour regime (III) or the periodic scour regime (IV), as [5] did not provide any estimate for these regimes. This is the case in particular with fine sand ($d=174\ \mu m$). Fine sand conditions correspond to the expanded scour regime (III) or the periodic scour regime (IV).

Several conclusions emerge when comparing the predictions from the model of Voropayev *et al.* (2003) and field observations. The Voropayev *et al.* model [5] incompletely predicts mine burial by wave scour because scour depths are only predicted for the initial scour regime. However, the range of predicted scour depths in this regime is wide (21% to 67%). An accurate prediction of burial is not obtained, but the magnitude of predicted bed level displacements is in agreement with the observed mine burial, while the significant variation in predicted values with hydrodynamic parameters is also consistent with observations.

Comparing field observations of mine burial with predictions of scour depth should also be handled with care because scour depth and burial depth are not identical. Finally, it is worthwhile considering the time scale of scour pit formation as determined from Eq. (4). In the case of a wave period *T=10s*, the time scale $T^* = 3300.T / 2\pi$ for generating a scour hole is about 1.5 hours. This time scale is in qualitative agreement with the observations at Bertheaume.

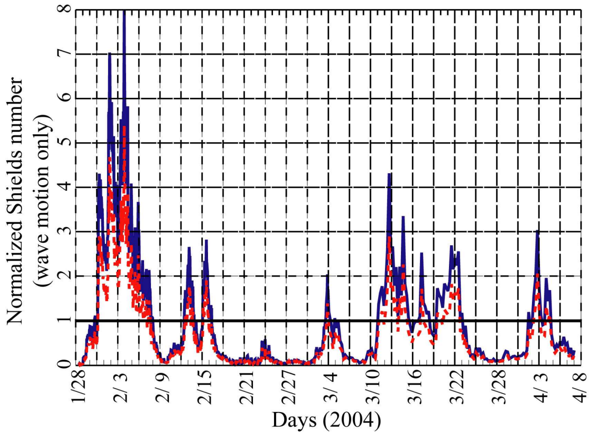


Fig.13 Shields Number time series at Bertheaume (normalized with the critical Sh number for the diameter considered) – Blue line d= 174µm - Sh_c=0.07 – Red line d= 735µm - Sh_c=0.03

V. CONCLUSIONS

This paper reports field experiments on mine burial conducted between January and April 2004 inside the Bay of Brest at two sites with sandy bottoms. The goal was to measure flow and burial simultaneously in order to analyse the dependence of mine burial on flow and sediment properties. Manta and Rockan mine-like targets were laid out at the two sites in addition to cylindrical BRM, allowing mine burial to be quantified with a time step of 15 minutes. The first site (Rascas) was located in an area sheltered from waves. The mine environment was only submitted to current flow. Almost no mine burial was measured during the experiment. Active burial was observed at the second site (Bertheaume), where wave activity was present. Strong wave forcing occurred during a storm (with wave heights up to 3.5 m above the mine) lasting for one week at the beginning of the experiment, and during several swell events with wave heights reaching 2 m. Significant mine burial was observed at this time. The average mine burial during the experiment ranged between 38% and 54% with almost complete burial achieved during the storm conditions. Burial was less at the ends than at the middle of the BRM and very limited variations in mine position were measured. Analysis of sediment cores show that the initial fine sediment was re-covered during the experiment by coarser sand. Sonar images confirm the variability of the bottom during the experiment. The mine burial observed appears to be the result of sediment transported into the area and deposited around the mine. Since deposition and erosion occurred evenly around the mine, the burial process cannot be attributed to sand ridge migration. The data also show that the formation of scour pits at the end of the cylindrical mine only occurred during a very short part of the experiment. This phenomenon is not responsible for most of the burial changes observed throughout the experiment. "Extreme events" were also observed, with burial occurring very rapidly (1.5 hours), or sediment being completely washed away from the mine within one hour, followed by re-burial. It was also observed that increasing wave activity tends to increase the average level of mine burial.

Mine burial observations were compared with the predictions of available models. Particular attention was paid to two mine burial models. The GESMA momentary liquefaction model predicted no mine burial for the conditions of the experiment. This was an expected result, considering the conclusions of previous studies. The main reason for not observing liquefaction is the absence of gas inside the soil.

This study highlights the need for mine burial models involving wave motion. The results were compared with Voropayev *et al.* [5]. Although it is not that obvious from the field results that burial was produced by wave scour rather than by the overall sediment transport in the area, the prediction of scour depth is, however, in general agreement with the sediment deposition depths measured in the field.

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