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Potential UXO seabed migration in the German Bight

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Severe storms marked by very high wave conditions occur several times per year in the German Bight (North Sea). In places and at certain times the wave-induced flows at the seabed are then powerful enough to significantly displace exposed, heavy UXO such as mines and bombs from the two world wars. To investigate we used kinematic modelling of the objects supported by good-resolution wave and current data. We tested the results against actual observations. Return times on likely object migration are the output. The result provides a more precise and quantitative understanding of UXO object behaviour under the severe storm conditions of the Bight. Subsea infrastructure projects in the region need no longer assume that movements occur everywhere, but have tools to determine where and when different objects in the spectrum of UXO have the potential to migrate and repopulate the operating areas.

UXO | UXO migration | storm events | seabed | return time
UXO | UXO Migration | Sturmereignisse | Meeresboden | Rückkehrzeit

In der Deutschen Bucht (Nordsee) treten mehrmals im Jahr schwere Stürme auf, die durch sehr hohe Wellenbedingungen gekennzeichnet sind. Stellenweise und zu bestimmten Zeiten sind die welleninduzierten Strömungen am Meeresboden dann stark genug, um exponierte, schwere UXO wie Minen und Bomben aus den beiden Weltkriegen deutlich zu verdrängen. Zur Untersuchung verwendeten wir eine kinematische Modellierung der Objekte, unterstützt durch gut aufgelöste Wellen- und Strömungsdaten. Wir testeten die Ergebnisse mit realen Beobachtungen. Das Ergebnis sind die Rückkehrzeiten bei wahrscheinlicher Objektmigration. Das Ergebnis liefert ein präziseres und quantitatives Verständnis des Verhaltens der UXO-Objekte unter den schweren Sturmbedingungen der Bucht. Unter-Wasser-Infrastrukturprojekte in der Region müssen nicht mehr davon ausgehen, dass Bewegungen überall stattfinden, sondern können bestimmen, wo und wann verschiedene UXO-Objekte das Potenzial haben, zu wandern.

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Introduction

The presence of unexploded underwater munitions from the world wars is a problem for engineering projects in the north European region. Telecommunication, gas and electricity cable installations, wind-energy and petroleum platforms, bridge constructions and trawl-fishing ventures share the problem. For fixed-location projects geophysical surveys locate the most problematic objects close-in to the installations and a clearance can be carried out. But then there are lingering worries that objects outside the narrow survey corridor might migrate back in during strong weather events under severe wave/current conditions.

Some research in Germany has already taken place to address the concerns for offshore projects over potential UXO movement. It has involved advanced modelling of thresholds of movement for different types of UXO, flume tank testing of migration physics under flows (Menzel et al. 2018), and analysis of object responses under changing sea-state conditions (Jenkins 2018). Here we report on work that advances from the earlier studies, especially with real observational validation of the results.

It is a long time since the original munitions were laid out, and now many are degraded by corrosion, or deeply buried in sediments. The issue of UXO migration therefore applies to a small cohort of the original large population – those which remain at the seabed sediment surface or unbury, either naturally during storms, or by human disturbance.

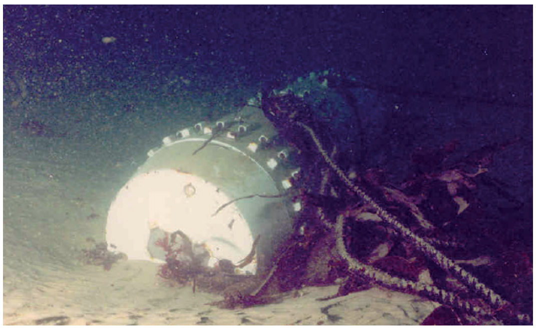

Photo courtesy of: US Naval Postgraduate School, Monterey Bay, USA, and WTD 71, Germany

Fig. 1: An instrumented heavy BRM (Burial Registration Mine) module, a surrogate for some types of UXO, resting on the seafloor during a calm period. Note the scour pit

The evidence for migration

There is little doubt that heavy objects, including UXO, can move around on the seafloor during extreme weather events in some submerged locations. For instance, the SERDP program of the U.S. has released much data showing explicitly that small UXO do migrate under waves and currents in sandy environments (Traykowski 2015). Those data include scanning sonar imagery, monitorings of tagged objects, and repeat multibeam imagery. Other programs in Belgium, France and the U.S. demonstrate with on-board accelerometers that heavy cylinders (500 kg mass, imitating naval ground mines; Fig. 1) shift under strong enough wave conditions (Papili et al. 2014; Guyonic et al. 2007; Bower et al. 2007). While most small movements seem to be related to settlement of the objects into the sediments, there are larger motions, rarer, which are wholesale relocations of the objects. They are documented from fractions of metres over minutes to many metres in the space of weeks.

There is also strong evidence from oil-gas pipelines (data in Tian et al. 2015; and nearshore German North Sea in Bruschi et al. 2014), artificial reef materials (Turpin and Bortone 2002), and coastal boulder deposits (e.g., Cox et al. 2018) supporting the fact of wave/current induced movement of heavy objects at the seafloor, but chiefly in inshore depth-zones.

Severe weather events

Do the necessary conditions for strong movement occur in the German Bight? Certainly, there is a history of very severe storms exceeding wind speeds of 120 km/hr (base of hurricane category), at a frequency of several per year. One dramatic, publicised event in the science realm was storm »Britta« (Pleskachevsky et al. 2012) during which a set of high (>18 m) and long (25 s period, 400 m wavelength) waves caused breakage of equipment high on the FINO1 platform. In the Bight most waves longer than 8 s period are classified as ›shallow‹ or ›intermediate‹ – with strong bottom interaction over most of the basin.

To assess UXO migration potential of the Bight in more detail, West-European Shelf Wavewatch III modelled data are used (source: Copernicus – marine.copernicus.eu). This is a well-validated data product (Tolman et al. 2002) which is widely used for research and engineering purposes. It allows wave climate to be resolved geographically and temporally at 8 km and 1 hour resolution. Waves of >5 m height and >8 s period, representing developed storm conditions, are reported through a subset of data – for 20 months' duration through 2017 to 2018 (Fig. 2). The wave heights and periods lessen to the coasts as wave energy is attenuated by bottom friction, especially at longer wave periods. The surface-wave statistics are converted to near-seabed velocity amplitudes (U_{WS}) and Shields Parameter values (θ), amongst other parameters. The basis at this stage is Airy theory. The necessary substrate grainsize and stiffness information is obtained from the db-SEABED system (Jenkins 2017), augmented with data from the Bundesamt für Seeschifffahrt und Hydrographie (BSH).

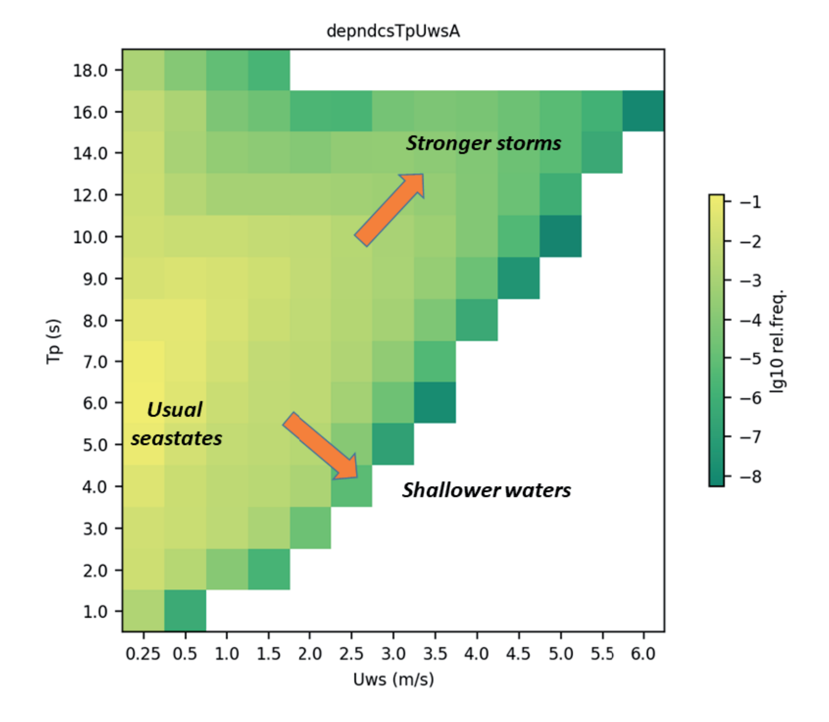

Fig. 2: The total population of wave-induced bottom-velocity amplitudes (U_{WS}) and periods (T_P) in the German North Sea, based on 20 months of Wavewatch III data. The population is over all spatial pixels * time slices. Yellow areas are ›usual‹ conditions and the arrows show important trends in the data. Note the prevalence of events with storm severity, approximately U_{WS} > 2.5 m/s

Also for the project, calibrated model data on the currents of the sector are obtained from the BSH. The current data covers months to years in duration from 2006 (including »Britta«) and 2017. They represent most of the flow phenomena: wind-driven geostrophic flows, tidal flows, longshore drift, storm surge effects. The data are spatial and temporal – at 7 km and 0.25 hour resolution.

In this part of the North Sea near-bottom and on the scales of the UXO, effects from wave-induced ›oscillating‹ flows dominate over effects from the ›steady‹ wind-driven and tidal flows. Tidal flows may be strong at the surface in some channels (up to 2 m/s), but they decrease strongly towards the near-bottom in a thick log-layer. Geostrophic current velocities may attain velocities of 1 m/s, but fade to ~0.2 m within 0.1 to 0.3 mab (metres above bottom). Such near-bottom speeds are insufficient to mobilise the heavy UXO which are of concern here. The wave boundary layer on the other hand is very thin, and substantial velocities – up to 5 m/s or more – appear to operate to within 0.01 to 0.02 mab, so they are the primary forcings

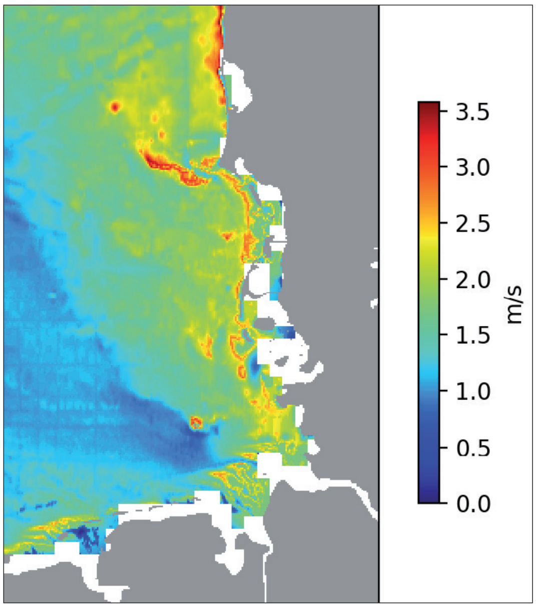

Fig. 3: Near-bottom wave-induced flow velocity amplitudes (m/s) during a severe event in 2018, calculated from Wavewatch III data. The high values (red) tend to coincide with shallow-water areas. (Blank areas are not covered by the wave statistics.) During the event sea-surface significant wave heights (H_S) attained 6 to 9 m over much of the area

to consider for UXO migration. Fig. 3 shows the geographic distribution of the maximum near-bottom wave-induced flow speeds during one severe storm event.

Understanding the scalings of the various flows in their bottom boundary layers is most important for assessing UXO migration potential. Furthermore, it is the peak conditions of the flows which are most important for dislodging and moving the objects. The maximum amplitude of the wave-driven bottom oscillations is the germane statistic, not the ›representative‹ RMS of velocities.

Return times on the strong near-bottom flows

Exceedance counts were calculated per geographic pixel for a set of thresholds of the wave-induced bottom-flow speeds per class of wave period (e.g., >4.0 m/s speeds at 6.0 to 7.0 s periods). Also, for the steady currents similar velocity exceedance counts were tallied. The counts were converted to exceedance return times relative to the data set durations and observation intervals. Return times are an inverse of frequencies. At extremes, one data record exceeding a threshold makes a rare event with a long return time equal to the data set duration, while if the entire data set is over a threshold the return time equates to the observation interval.

UXO kinematics

How should the physics of object mobility be joined with this oceanographic data? First the object mobility physics is analysed by flow speed and period using a set of simulations. The results per class of velocity and period are compiled into a matrix paralleling that of Fig. 2. Using joint probability the probabilities on the flows are joined with the results of the simulations, to yield joint probabilities of significant movements, i.e., migration.

Simulation is the chosen method because existing parametric models (see Rennie et al. 2017) are valid only for small velocities (approximately <1 m/s), and/or for steady flows. They do not apply to the severe events necessary to move heavy UXO. But also, many ignore the possibilities of objects being ›hidden‹ from flows in scour pits or buried by mobilising sediments. Furthermore, they generally assume an undeformable bottom whereas the UXO of the German Bight are mostly on a soft, mobile sandy substrate.

With proper software coding, simulations can meet the project requirements. The Morison equations provide per-cycle analyses of the in-line motions under the currents and waves. The methods are not as sophisticated as the Navier-Stokes or Lattice-Boltzman styles of computational fluid dynamics, but are scalable with the problem of determining UXO migration potential reasonably accurately over millions of geographic pixels across the area through time periods of decades.

The Morison equations operate in a phase-explicit manner. Active fluid drag, lift and the impulse ›added mass‹ and Froude-Krylov forces are balanced against object inertia, bed frictions (sliding and rolling) and gradients up out of a scour pit. By time-integration the accelerations are converted to velocities and then to displacements – if any occur. The simulations monitor the stages of motion: no motion, rocking through small angles, shifting position slightly, and breaking out (which is deemed as moving the object >1 diameters or leaving the scour pit). Even a small displacement per wave cycle can readily add over time – in one or several storms – to constitute a migration, especially when it is considered that one hour holds 360 10-s cycles. For projects using a narrow survey corridor in some UXO-prone area, even 10 to 20 m of object migration could require a new UXO survey for safety of operations or insurance reasons.

At present the simulation only applies to objects which are not appreciably buried in sediment, that is, are free to move. Directionality and actual paths of migration were not a concern, only whether an object can physically be moved in successive wave cycles – for instance during a storm. And how much movement is possible per wave cycle? Fig. 4 shows some details of the simulation outputs, notably the integrated accelerations, velocities and displacements (red) and their contributing components.

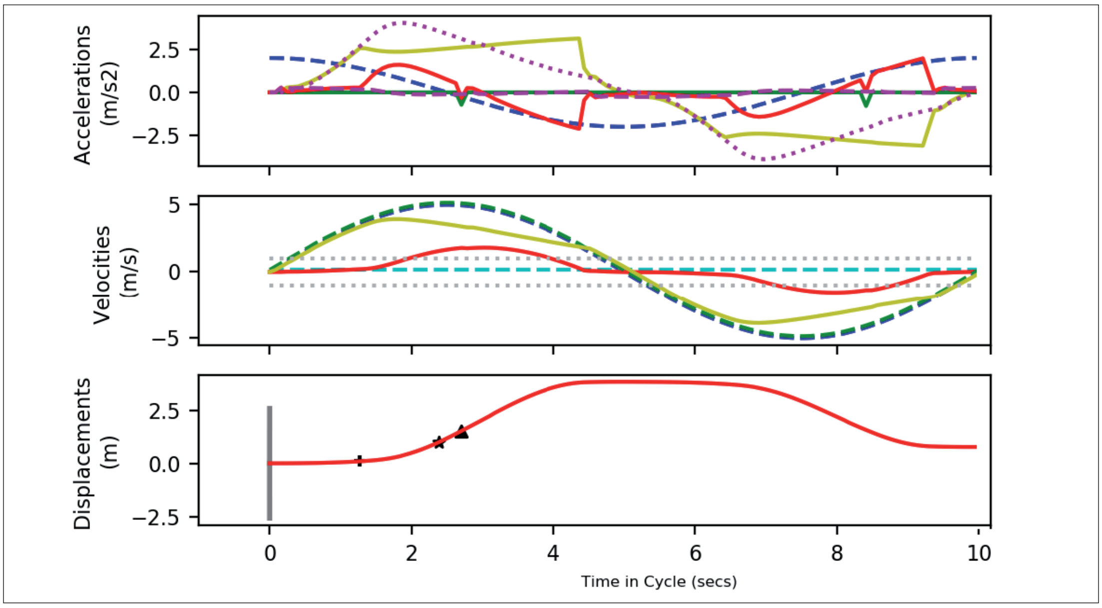

Fig. 4: Results of a kinematic simulation for a BRM object under wave-induced near-bottom flows of 5 m/s speed amplitude and 10 s period. Only a small amount of research has extended into the field of such high flows for seabed environments, but simulations can be applied. The red lines mark the integrated object accelerations, velocities and displacements through one wave cycle. Other-patterned lines represent phase-varying components of the fluid and object accelerations and velocities. The +, ★, ▲ symbols indicate the predicted first rocking, shifting and break-out

The simulations also allow for changes to the dimensions of the scour pits themselves. They are linked to values such as the non-dimensional Shields Parameter, at: <0.05, 0.05 to 2.0, >2.0 respectively for bed-load, suspended-load and shear-flow of the surface sediments. In the third class – necessary to move heavy objects – scour pits shallow considerably (e.g., Voropaev et al. 2003) which itself enhances the potential for migration. Object buoyancy in seawater and the sediments affects the degree of burial, especially with jostling by the wave-induced motions.

The final joint probability oceanographic/physics data product yields quantitative values on how often defined objects can be expected to move in different areas of the German Bight. Depending on previous finds in a project area (e.g., OSPAR 2018) simulations should be run for a spectrum of historical objects: general purpose bombs, moored mines, ground mines, large bombs, naval artillery shells and torpedoes. These have varying shapes, dimensions and buoyancies in water and sediment.

Validation testing

As might be imagined, validation data for conditions at the seabed during severe storms affecting heavy UXO objects is extremely difficult to come by. But in recent decades NATO entities have deployed instrumented cylindrical modules on the seabed where they have been subjected to storm conditions. They include the BRM (Burial Registration Mines) of the WTD-71 (Papili et al. 2014) deployed in Germany, France, the United States and Belgium. But also in hurricane-prone waters of the U.S. some observations of object displacements are available. The collated data for these and similar objects (points, Fig. 5) suggests that near-bottom flow amplitudes of 4 m/s at periods of 6 s are required for appreciable movement. Most records are from shallow waters (<20 m in water depth). The simulation results are broadly compatible with

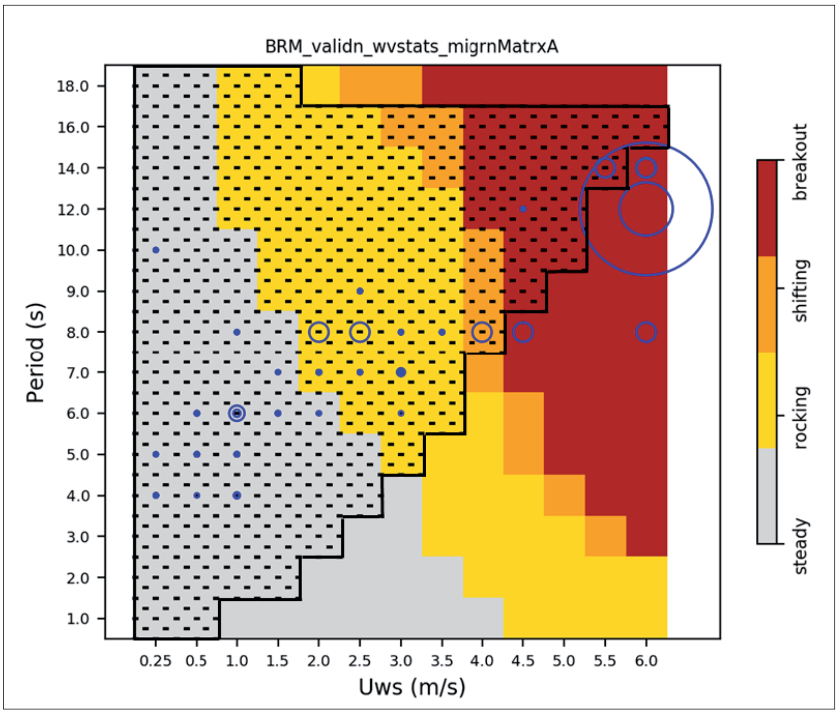

Fig. 5: (Colour grid) Matrix of simulation results by wave bottom orbital velocities and periods. It shows the largest motions possible for BRM objects under the varying conditions: larger object displacements from the yellow to red zones. (Stipple) Superimposed wave climate of the German Bight – same as Fig. 2. (Blue points) The validation data, with the symbol size representing actual displacements observed for BRMs and similar objects, in various worldwide studies

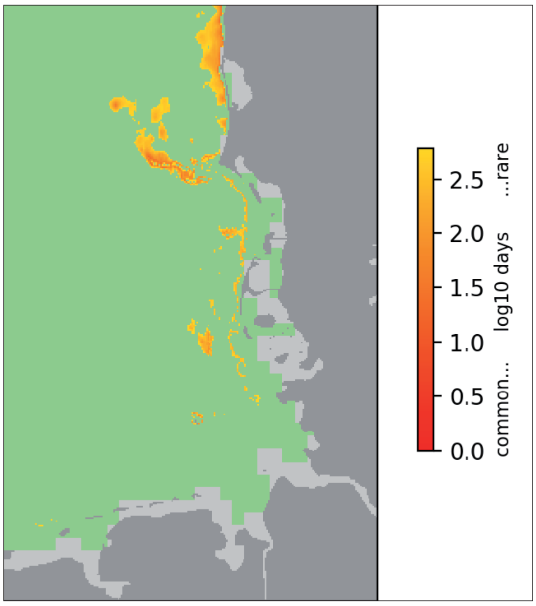

Fig. 6: Migration potential in terms of return times on significant movements for a BRM-type object, computed with 20 months of wave data. Movement is forecast in the orange areas for return times of months to years. (Pale green – no indications of movement. Grey marine areas – no wave data available)

the field data. Long trials of position-monitored objects at the seabed are needed – at locations based on the present results.

Implications

As a result of the study the migration potential of different types and conditions of UXO is better understood in quantitative terms. Previously the understanding was that UXO anywhere in the German Bight might migrate. This meant that expensive resurveys for UXO could be required for entire project areas. Now, narrow areas of concern can be defined precisely spatially (Fig. 6), for various types of UXO. It is also possible for migration risk to be monitored per severe weather event – even in near real-time.

In Fig. 6 is shown the pattern of areas (orange) where UXO migration of exposed objects like the BRM is physically possible at least each year, even monthly in some small areas.

Infrastructure development will certainly continue in the German North Sea. UXO will occasionally appear at the surface as it is disturbed by human activities or environmental changes (such as lower sediment supply from the land, ocean circulation changes). The good news from this project is that UXO migration appears to be highly limited to shallow inshore areas. And, once an episode of potential migration such as a storm is identified spatial patterns of risk can be analysed for that particular event to narrow or even delete the concerns for projects. In this way, the coupled oceanography–object kinematics model presented here provides a tool of use to industry and agencies. //

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