Introduction

Prior to building activities, the subsoil that some structure is going to be built on or in, may have to be scanned for risks that are related to the building activity itself, or for possible consequences after the building process is finished. Hazards due to UXOs (UneXploded Ordnances, also known as ERW, Explosive Remnants of War) that are present in the subsoil, is one of them. In Western Europe, many World War II UXOs, ranging from small ammunition to large aeroplane bombs, are still present in the subsoil. The risks are especially there at depths where the soil has not been touched or moved since the end of WW II and where new building activities will take place for the first time. This includes new lateral positions and new depth positions. Think of a houses building project, where piles have to be dug to many meters depth on a site that was previously used for crops growing with sub meter digging activity.

World War II UXO detection

World War II UXOs are still abundantly present in the subsoil in Western Europe, both onshore and offshore. Tens or hundreds of thousands of aeroplane bombs and millions of smaller munition items (estimates vary greatly due to many unknown factors) are still present in the North Sea floor that may cause a threat during the building of wind farms and oil and gas recovery installations, cabling installation and sand extraction projects.

It is estimated that of all dropped bombs on land, 10% did not explode, due to malfunctioning igniters. This is especially the case in soft soils such as wet peat and clay soils near the coast in low lying river delta's such as in the western part of the Netherlands. About 2000-2500 munition items are cleared per year by the Dutch explosives disposal unit (EOD, 2017). Most of these items on land cause no danger if left untouched, although for items in the sea, it is unclear whether corrosion in salt water will cause release of poisonous contents of the bombs. However, onshore and offshore, during digging and piling activities, during building of houses or bridge foundations, these items may be hit and detonate.

To prevent this, prior to building projects, UXO search and removal projects are carried out. These projects include four phases:

- A historical desk study: During the war, bombing and fighting activities have been documented. Aerial photographs are available of pre and post bombing situations. This information is available in national and local community archives. The information is systematically processed and leads to conclusions on whether a particular site is suspected to contain buried UXOs, the type of UXO (small calibre ammunition, grenades, bombs), an accurate contour of the actual part of the site that is considered suspicious and a demarcation in depth. The depth delineation is done using models that compute the maximum intrusion of a bomb based on bomber flying altitude and velocity, bomb aerodynamic properties and soil layered mechanical resistance. The latter is an estimate based on current cone penetration tests (CPTs) and historical information about subsidence and water level changes. Finally, the depth demarcation is dependent on previous post war soil additions and removals at the site location.
- Geophysical study: If the historical desk study states that (a part of) the site soil is suspected to contain UXOs, then geophysical research is carried out. The type of geophysical technique(s) that is used depends on the type of UXOs that are sought, the depth demarcation, the size of the area and the presence of possible disturbing objects nearby, such as sheet piles and (electric current carrying) railway overhead lines. Measurements are carried out from the surface such as illustrated in Figure 1, from boreholes or by CPT or from a vessel or a towed fish behind a vessel. The result of the geophysical survey is a target list.
- Constructing a dig list: The target list is filtered to form a dig list in order to minimize the costs of digging so called false targets, debris, that arose in the target list. Targets may be removed from the dig list when they are classified as other known objects in the soil. Spending relatively much time on dig list reduction is economical in view of the costs of target removal.

Figure 1 *A field specialist carrying out target detection measurements in the field. For efficiency, eight probes are operated simultaneously, towed by an all-terrain vehicle. The frame carrying the probes is separated from the vehicle by a long non-magnetic aluminium rod, so as to minimize the magnetic disturbance of the vehicle.*

- UXO removal: Digging is carried out for every item on the dig list. It is done in an iterative sequence of measurement and digging. In the target is a UXO, it is secured temporarily and transported later on. For large objects at large depth, and high ground water table, it is necessary to set a building pit in place. An UXO detection certified diver will characterise the object and, if applicable, the type of UXO and ignition, see Figure 2. For aeroplane bombs, a removal plan is set up. Detonation of the bomb is often done at another site because the original location may not be suited because of nearby infrastructure or unsuitable soil with low soil wave attenuation or ground water impenetrable layers that may not be cut through.

Geophysical methods

The toolbox of geophysical methods contains many items, spanning characteristics such as:
- Material properties: electrical permittivity (tendency of a molecule to stretch and rotate in place due to an external electric field), electrical conductivity (tendency of a molecule to translate), magnetic permeability (tendency of a molecule to align to an external magnetic field), mass density and pressure.
- Source: active/controlled source versus passive/external uncontrolled source.
- Time variation: static, diffusive and wave propagation methods.

Making use of the above properties, the following techniques are used in UXO detection on land:
- Magnetometer: Many UXOs have a metal shell, containing a large amount of highly magnetic permeable iron. Therefore, most UXOs locally perturb the, at site scale uniform, magnetic field of the earth and this local variation in magnetic field is measured by magnetometers or gradiometers. Magnetometer research is often carried out directly from the surface, but more and more geophysical research in general including inspection and monitoring, dike inspection, archaeology and UXO detection is carried out using drones.
- Electromagnetic induction: Next to the magnetic properties, the conductive properties of the metal (not limited to iron now) shell is exploited. Both the 90 degrees phase change with respect to the primary inductive field and the time delay (frequency dependence) due to the diffusion of the current in the objects metal, indicate the presence of a metal object in the soil. The spectrum of the received signal may theoretically indicate extra characteristics such as metal type and shape of the object, although in practice such deductions seem difficult to reliably realize.

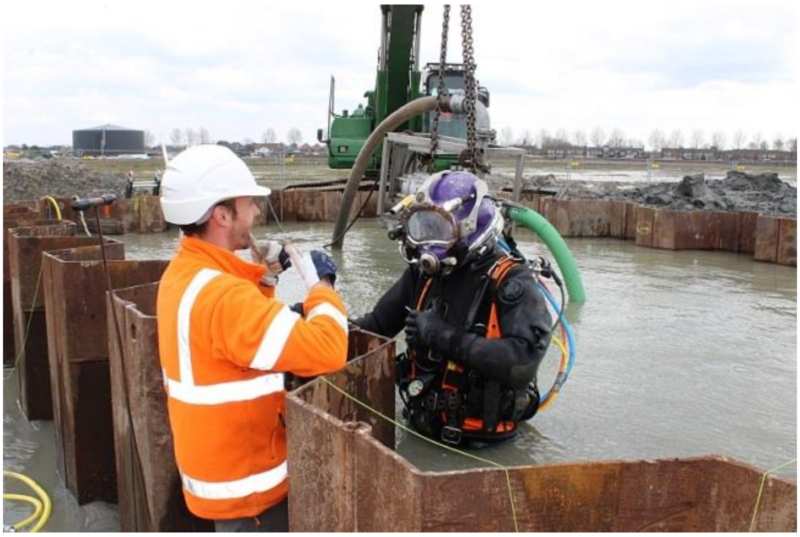

Figure 2 *A diver doing classification of a detected target at large depth. A building pit is set in place by inserting sheet piles and excavating the soil. The pit is fully filled due to ground water that is present almost up to the surface at this location.*

- GPR: GPR is applied both from the surface in single and multiple source/receiver setups and from boreholes. From boreholes, three methods can be applied. 1. In transillumination, the source and receiver are in separate boreholes, potential objects in between disturb the signal travelling from one to the other and this is registered. 2. In 2D reflection mode, the source and receiver are in the same borehole. Target depth and radial distance from the borehole can be detected. Azimuthal information is acquired by combining results of measurements taken from several boreholes. 3. 3D reflection mode is like 2D reflection mode, with the additional property that the measurement system radiates in a preferential direction. By rotating the system, azimuthal information can be acquired from a single borehole.

When objects are laying on or in a water floor, electromagnetic waves attenuate quickly due to conductive minerals in the water and due to high dielectric losses for relatively high frequency systems. Next to magnetic methods, pressure wave systems are used instead in this case:

- Single or multi beam echo sounder: can be compared to air radar in a water medium, with the probe located at the vessel and the waves traveling downwards. Apart from the medium, the main difference is the presence of the water/soil reflector at nearly the same distance as the objects. The usability of the method increases as this always present reflector is more laterally constant. The objects are located at least partially above the water floor.
- Side scan sonar: By transmitting sound waves at a broad and oblique angle to the water surface, intensity differences and shadows, similar to light, can be registered that provide an easy and quick intuitive interpretation of the shape and irregularities of the sea floor and objects thereon. For accurate ranging, an echo sounder is required.
- Sub bottom profiler: the principle is essentially the same as for the echo sounder, however, the emphasis is on the sub seabed reflections instead of the bathymetry of the seabed itself.

Magnetometer is often the method of preference. Alternatives include e.g. radar in railway track bed surveys, because of the presence of the rails and overhead lines. Induction methods are used close to fences, sheet piles etc. Offshore, magnetometer is often combined with side scan sonar for interpretation assistance. Often, object detection is preceded by multi beam sounding and side scan sonar to check the water surface for obstacles that hamper data acquisition.

Data processing and interpretation

Raw magnetometer data are displayed as a colormap such as in Figure 3. First, potential objects are selected manually based on the colours. After a selection of targets has been made, the target properties

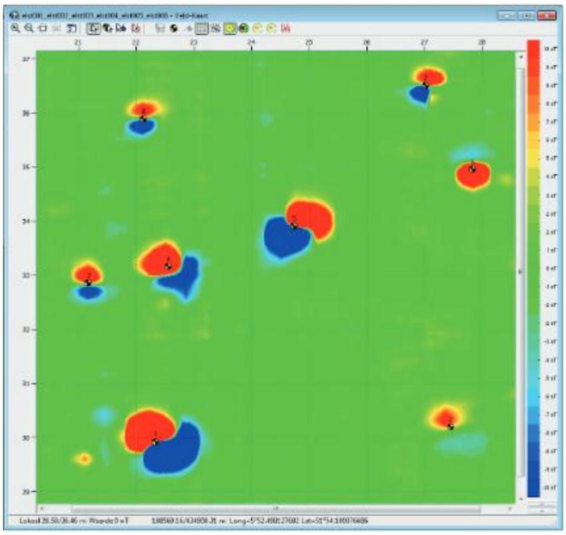

Figure 3 *Raw data of a land surface magnetometer survey. The colours represent the magnetic induction value in nanoTesla's. The intensity, footprint, relative size and orientation of the red and blue colours are indications for the size, depth and orientation of the object.*

magnetic moment, lateral position and depth are computed by inversion, in which targets are modelled as point objects. After all targets have been identified and their properties computed, they are converted to a target list or dig list for the client.

UXO detection in relation to geotechnics and infrastructure planning

Geotechnical CPTs provide a detailed description of soil mechanical parameters and their vertical stratifications. Tip resistance, friction ratio and pore pressure are interpreted in terms of soil type and lead to conclusions about the maximum depth that an unexploded aeroplane bomb may have penetrated the soil. The readings are recent and must be interpreted in view of possible changes in soil properties since WW II.

Of course, UXO detection can lead to delay in infrastructure planning. Delay factors include getting the necessary knowledge and advice, decision making time, etc. for the organisation itself, time for data acquisition and interpretation and for UXO removal. The amount of delay is dependent on the way UXO detection work can be integrated in the infrastructural work and the point in time when UXO detection is initiated. It good scenario's, extensive UXO detection will cause almost no delay.

UXO detection results are reported in maps indicating target locations and appendices listing the target properties and showing relevant photographs. For larger projects, detection results are reported in phases for parts of the total area, to enhance integration with the principals work.

Conclusions

UXO detection is often a necessary step prior to building activities in or on the subsurface. UXO detection can be done with many different geophysical techniques depending on suspected target properties, soil properties and potential external disturbances. Geotechnical measurements help UXO detection work by potentially reducing the detection volume. UXO detection is often perceived as an unwanted delay of the original project work. However, delay can be minimised by on time and careful planning.

References

EOD [2017] Overzicht Uitvoeringsopdrachten CONVENTIONEEL UO 201001153 (tot heden), (in Dutch), EOD, Soesterberg, The Netherlands.