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Reducing Risk on Unexploded Ordnance by Vibrations in the Rotterdam Subsoil

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Abstract. During World War II the city of Rotterdam endured hundreds of air raids. Expectations are that a few dozens of UXOs are still to be found in the Rotterdam soil. UXOs can still go off to this day due to vibrations caused by construction activities. The vibration impact on the environment around the activities can be accurately predicted. The specific limit for vibrations near the detonator, or for the subsidence of the subsoil, can be set so no increased risk of detonation arises. The municipality of Rotterdam has gained much relevant experience with field measurements and tests in the past few years in order to determine the structure of the soil specific limit as well as the prediction model.

Keywords. risk management; unexploded ordnance, world war two, dynamics, exploratory soil investigation, modelling

1. Introduction

During World War II the city of Rotterdam endured hundreds of air raids. Apart from the German bombardment of 14 May 1940 the largest part of the bombings was performed by the British while the city was in German hands.

From reports of eye witnesses and from footage, which was primarily taken by the British during the dropping of the bombs from airplanes, a historical assumption is that about 10-15% of the bombs did not go off after the impact but this cannot be verified to this day. Some of the unexploded ordnance (UXO) is known to have been cleared away during or directly after the war. Later more so-called UXOs were cleared during construction activities. Expectations are that a few dozens of UXOs are still to be found in the Rotterdam soil.

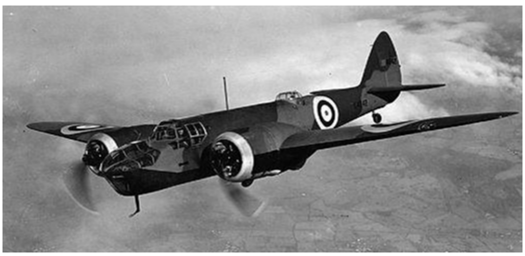

Figure 1. A Bristol Blenheim bomber of No. 53 Squadron. (Source: www.wikipedia.com)

2. Risk of Detonation

2.1. Existing Risk

UXOs can still go off to this day. Construction activities which cause vibrations, like driving foundation piles into the ground and applying sheetpiles by means of vibration, are a risk. Over the years certain types of detonator have become unstable and as a consequence very sensitive to vibrations and reorientation with possible unintentional detonation as a result. Other types of detonator have become more stable over the years and are not expected to detonated anymore.

The main reason reorientation of an UXO occurs is because of the subsidence of the subsoil by means of settlement or increasing density of the intermediate sand layers in the subsoil by activities causing vibration. Too large a vibration load may immediately activate the detonator and by effect the UXO. The main cause for an UXO to detonate is direct contact.

2.2. Reducing Risk

By means of performing a (historical) preliminary investigation the suspected area, type of explosive and type of detonator can be retrieved. Set against project specific construction activities a risk profile can be made and the necessity to do exploratory soil investigation in order to find UXOs can be determined. This kind of investigation is costly and interferes with the lead time of the project, both unwanted aspects. Especially when one is confronted with it unexpectedly.

In high risk areas, in which one or more UXOs are expected to be present, exploratory soil investigation is being carried out by means of probing with magnetocone e.g.: Figure 2. Deflections in the magnetic field, caused by ferrous containing elements, are being observed in the depth. When a deflection is detected the subsoil around the steel object is being mapped more accurately and with more resolution. Advanced 3D software is able to map and plot the ferrous containing element. Munition experts will then be able to determine if the element is indeed an UXO or just another random steel element left behind in the past by man. It should be noted that this is very subjective and therefore much non-explosives are unearthed, a false positive.

Figure 2. A probing crane with magnetocone instrumentation (Source: van den Herik, Sliedrecht)

When an UXO is located in the subsoil, it can be determined what kind of explosive it is based on a desk study on historical data. Then the UXO can be approached, defused and safely removed.

The Municipality of Rotterdam has the obligation to keep the costs for this investigation as low as possible by reducing the risk area and with that the area to be investigated, without compromising the safety of the construction workers and the existing infrastructure.

It is common to investigate the project location and approximately 50 meters around the project area. In order to justify a smaller area more information is needed about the type of activity and influence on the surrounding area. Also, the maximum depth location is of interest because the research area is three-dimensional. Saving in depth is just as a saving on the amount of probing and a saving on lead time and costs.

3. Depth Delineation

A limitation in the depth is of great importance to the survey area to be kept as optimal as possible. At this time the maximum depth location of an UXO adopted the geotechnical principle that an UXO remains on a sand layer larger than 0.5 meters with a minimal cone resistance of 10 MPa. With a maximum of 10 to 12 meters below the old surface level, based on experiences from the EODD (the Dutch Explosives detection service of the Defense department).

At the time, there were developments to propose models that were able to calculate the energy upon impact on the surface level based on available historical data, such as release velocity, angle of release and weight of the UXO. Directly after the impact a decrease of energy due to the friction between the exterior of the UXO and the surrounding subsoil was developed as a function of the depth. There where the energy has been reduced this fully relates to the maximum depth level.

4. Influence on Surroundings

4.1. Effects of Construction Activities

The Municipality of Rotterdam has gained much relevant experience with field measurements and tests in the past few years in order to determine the structure of the soil specific limit as well as assumptions about implementation of certain construction activities.

Rotterdam has therefore developed a prediction model that accurately estimates the acceleration at project specific parameters as the type of inserted elements, used pile driving and vibration hammers, soil constitution and depth aspects.

The prediction analyses can be made with three different reliability indexes. Resulting from the prediction analyses is an optimized area of investigation, which lead to less magnetocone probing and therefore less costs and stagnation in the lead time.

In addition, there where postwar buildings were realized close to the project location, the influence of the vibrations at the time can be prognosticated based on archive research or additional calculations. This vibrations load functions as 'proven strength' and can be deducted from the area to be investigated. With the exception of the locations of the new (sheet)pile. Direct contact should always be avoided.

4.2. Limit States

The prediction results are compared across known limits for acceleration where the different kinds of detonator remain inactive. This aspect will be further investigated in 2015-2016 in cooperation with TNO (a highly regarded Dutch research facility) and the VEO (Association of Explosives Detection).

Another limit state is the maximum allowed acceleration where no subsidence of the subsoil or increasing density of the intermediate sand layers occurs. The findings of Hergarde and van Tol (2001) show the relationship between the increase in relative density, derived from Cone Penetration Tests (CPT), and the required acceleration to achieve this. Depending on the initial relative density at the site, a location-specific maximum allowable acceleration can be determined. In general, 1.0 m/s^2 is used but it can be optimized if sufficient CPTs are available.

5. Prediction Model

In order to determine the distance where the acceleration remains below the limit state for subsidence, a prediction should be made. To make a valid prognosis two important aspects need to be defined: an indication of the source intensity and an indication of decrease in acceleration over distance.

5.1. Prediction Model

Making a prediction for vibrations is a complex issue. For years man has tried to obviate this in simple empirical models.

A development in the last few years is to refine the prediction method with computer programs or define it in Finite Element Methods. Although results are promising, this procedure remains intensive, expensive and requires a high level of knowledge of dynamics.

Application of the empirical model, based on an unstratified soil structure, elastic, isotropic half space is still widely used. This is very appropriate for the UXO issue, since the UXOs are particularly found in the Rotterdam subsoil on homogeneous sandlayers in the Holocene starta.

5.2. Source Intensity

There are many parameters that affect the source intensity. The energy input and operating frequency level of the impact hammer or the vibratory hammer are the most important.

To a vibratory hammer the weight of the dynamic assembly of the vibrating block and the inserted element are equally as important, for it determines whether the dynamic assembly is expected to operate in harmony.

If so, the dynamic assembly operates as effectively as possible with as less side effects as possible, such as different and / or varying frequencies and vibration levels excluded. Only with these principles a well-matched prediction succeeds.

CUR166 (1997) defines a good starting point as a rule of thumb for this mass - frequency analysis. For impact hammers the actual applied energy and efficiency of impact hammers are decisive. These are by a higher degree of adjustability in practice, often different than the maximum values of the pile driver. An additional advantage is that the simulation of point loads is easier.

CUR166 (1997) & CUR166 (2012), as well as some calculation programs also provide good starting points to determine the initial source level of a vibrator. Recently published articles make it possible to carry out additional analyses to lower reliability and corrected parameters for vibration strength.

In addition, Rotterdam obtained a reasonable amount of measurements near installation works. With these the source intensity for a number of vibration and impact hammers is well mapped. It also includes the effect decreases of acceleration in the distance, as measured both at ground level and in the subsoil.

It would be perfect to have acceleration measurements during installation on the elements in order to be able to expand the empirical model for the vibration source. Although the municipality plans to carry out these measurements it now relies on a broadly based principle using a reference distance of 5.0 m. This is because stochastic waves require a certain distance to develop in speed, amplitude and frequency.

5.3. Damping over Distance

With the interaction of the dynamic assembly and the soil, propagation waves originated in various directions. In the vertical direction the Rayleigh waves occur, these waves contain the most energy. These vibrations are able to rearrange the sand grain structure the most (Wolf, 1985). The question remains at what distance this no longer occurs and if the considered depth is of influence.

Despite how well all the principles mentioned above are mapped, the soil properties are always the riskiest parameters in the model. Only defined by limited field measurements the material dampening factor (alpha) is a subjective parameter. A real relation between the soil and the alpha is yet to be made. The material dampening factor corrects the vibration energy per distance as it dissipates in the soil by the internal friction.

In addition to material dampening a decrease of the vibration intensity also occurs due to geometric attenuation based on circular spread. This is defined by the square root of the distance ratio in the model. As results later on show, this geometric attenuation is suspected to be frequency based as well. Much common with what is known from acoustics.

The CUR166 also specifies the attenuation model based on the half-space theory in which the attenuation over distance is defined (1).

$$A_r = A_0\sqrt{\frac{r_0}{r}}\exp\left[-\alpha(r-r_0)\right] \qquad (1)$$

<u>*Wherein:*</u>
r_0: is the reference distance from the source [m]
r: is the distance from the source [m]
A_0: is the vibration intensity at distance = r [mm/s]
A_r: is the vibration intensity at distance r [mm/s]
α: is the factor for material damping [-]

It should be noted that the model is based on a fully saturated or unsatured state, and is not an assembly such as, in practice, occurs near surface level.

5.4. Additional Damping Factor

The CUR166 provides for vibration hammers a dampening constant (α) of 0.00 to 0.02 in the Rotterdam subsoil and 0.03 for pile driving hammers.

Based on the database of the Municipality of Rotterdam with tests performed the damping constant for the Rotterdam subsoil can be refined.

At surface level it’s clearly visible that for the CUR166 model a difference in damping constant for the lower frequency range of 15.0 to 20.0 Hz and the higher frequency range (> 30 Hz) is present, e.g.: Figure 3 (each thin line is a separate measurement).

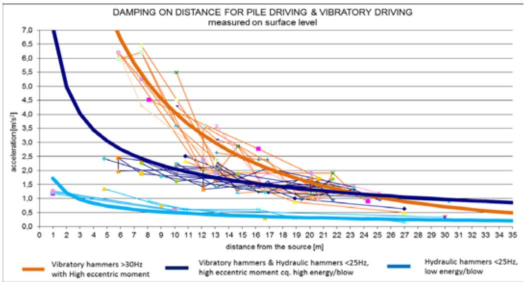

Figure 3. Damping on distance at surface level

The low-frequency part contains measurements on distance for (tube)pile driving with hydraulic hammers, vibratory hammers, diesel block hammers and low frequency vibrators (blue lines in Figure 3). Also distinction is made in energy of the vibration/hammer source in this low-frequency part. The higher frequency region almost exclusively contains (vibratory)hammers with high energy. Piling and vibratory hammers are taken together in this figure, as only the damping on distance is viewed here.

On the basis of a limited number of measurements in the Holocene, in the cohesive deeper layers of clay, just above the sand layer between which an UXO is supposed to be situated , a different dampening profile is visible, e.g.: Figure 4.

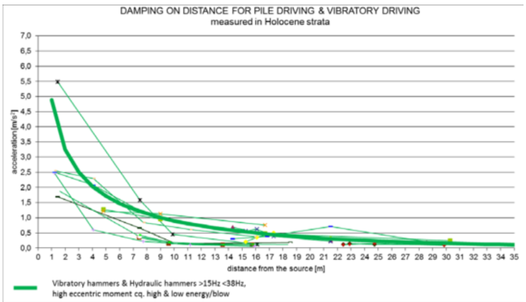

Figure 4. Damping on distance in Holocene

It's striking that the source vibrations are lower. This is partly due to the applied vibration and pile driving hammers, as well as to the dynamic assembly. Elements which are either too light or too heavy have a lower or higher level of vibration.

On the other hand, this is linked to the depth aspect. As the theory for wave speed prescribed in isotropic half-space that this is depth depending.

Based on the energy balance and the fact that the internal damping increases through higher effective grain tension, means that the developed initial vibration speed is lower as well.

5.5. Optimized Model Based on Measurements

Knowing where the shortcomings in the damping model are, the starting point for the municipality is to use the following adaptive damping factors for the CUR166 model in comparable locations in Rotterdam, specifically when UXOs are concerned:

- Surface level (sand layer) for frequency range > 20HZ → $\alpha = 0,05$
- Surface level (sand layer) for frequency range < 20HZ → $\alpha = 0,01$
- Deep cohesive soil layers (clay and peat layers) for frequency range < 40HZ → $\alpha = 0,06$

The damping factors are obtained by fitting the CUR166 model in to the measurements, the thick lines in Figure 3 and Figure 4.

6. Conclusions

6.1. Prediction Model

Based on measurement data, the damping factor appears to be frequency dependent. The initial (source) vibration seems to be depth dependent.

Due to insufficient measurement data in the intermediate sand layers, where the UXO is suspected to be, the principle at surface level is maintained here. Knowing that the ground pressure can affect the initial vibration level due to the influence on the damping material.

6.2. Effect of the Prediction Results on the Investigated Area for UXOs.

It is common to investigate the project location and approximately 50,0 meters around the project area. With the optimized model an impact distance for the specific type of activity can be made. The influence of the type of pile driving and vibratory hammer is highly dependent here. In many cases, the investigated area will be smaller than the generally adopted 50 meters, without compromising on safety. This means a saving in the number of probing and on lead time.

If, in the past, ground penetrating work has already been carried out in the suspicious region, this can be viewed as a decrease in the area to be investigated. These principles will be very important not to overstate the situation.

6.3. Limitations in the Model in Relation to the UXO-Issue

It is noted that as a function of the insertion of an element, the vibration development is depth dependent. P- and S-waves (spherical movement) do have effect on approaching the UXO in the suspected depth. Along with that the vibration propagation from bottom to top, in reality, is not equal to the horizontal propagation (isotropic model) because of secreting layers, these two aspects are excluded from this consideration. This is allowed because as a function of depth vibration prognosis on the CE suspected layer in the horizontal (R-waves) should be the greatest.

7. Recommendations

7.1. Decrease to Zero

For the consideration of the UXO issue, the measurements are carried out at a sufficient distance of approximately 30,0 m. It is recommended to measure at a greater distance as well for further development of the model. This allows for the asymptote to be forced more quickly to 0 in the model. It is expected that the decrease is going faster to 0 than calculated.

Plotting the results on a logarithmic scale can already serve as a basis for this. In theory, the zero point can then be better defined.

7.2. Deviating Soil Profile

Provided that a Rotterdam soil profile can also vary within the city limits, the local soil profile should always be considered. Possible deviations in the model based on this aspect can be found in the material damping.

7.3. Depth Vibration Sensor

Although there is reason to believe that the vibration development in depth is different, there is still too little data available specifically to adapt a model for making a prediction on the vibration level on the UXO suspected depth. Therefore measurements will still need to be carried out in depth. A special lost vibration cone is developed for this purpose in 2014 which is also expected to be deployed in the coming years. As well for UXO-issues as for other purposes.

7.4. Actual Depth Determination

The actual depth determination of an UXO can provide further optimization. Several munition experts have taken the lead in this. The Municipality of Rotterdam will validate these models by 2015.

7.5. Validation

The frequency-dependent damping will be validated by additional tests. For this an exitator (vibration generator) has been developed that can generate different speeds (0,0 mm/s – 25 mm/s) in different frequency ranges (8 HZ – 90 Hz). By placing the exitator on a sandy surface, a damping constant on distance in different frequency ranges can be determined. This will provide more insight into the findings based on the results presented above. A next step would be to conduct such a trial in the deeper cohesive layers.

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