Statistical basis for assessing the risk of unexploded bombs during site investigations and foundation piling

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Summary

The threat of buried unexploded bombs (UXB) to land developments in some areas of the UK has been well publicised. A formalised statistical approach to assessing this risk for land owners, developers or consultants is, however, lacking. This note introduces a statistically rigorous method for quantifying these risks so that the potential impact of a few boreholes on a site or a dense grid of clustered piles can be accurately quantified.

Stages in UXB risk management

Large areas of Europe were bombed heavily during the Second World War, and those bombs which failed to explode still pose a danger to construction work in these areas. When it comes to assisting professionals in assessing the degree of construction risk associated with such sites however, there is still neither regulation, guidance, nor industry consensus on good practice in this regard. The authors recommend the following steps for dealing with the threat of UXB:

1. Determine the overall risk of UXB existing in an area by downloading public domain regional risk maps [1]
2. If a risk is indicated, conduct or commission a desktop study of available site-specific evidence including records of known enemy air-raids, the MOD's official register of abandoned UXB, contemporary aerial photographs, the presence of strategic targets such as munitions facilities and firing ranges, to name but a few.
3. If the potential for UXB is highlighted by the desk study, then the risk of **detonating** any UXB should be formally assessed. This involves a review of development plans including site investigation methods (eg boreholes, CPT's), foundation designs (eg raft or piled), records of post-war land use, composition of made ground, and near-surface geology. To date sites have been qualitatively ranked as low, medium or high risk in terms of the likelihood of detonating UXB. The qualitative and often subjective nature of this ranking process has been brought into question and is the focus of this note.
4. If a significant threat exists then the process moves towards appropriate risk **mitigation**. A new CIRIA steering group has recently been set up to standardise UXB risk mitigation methodologies.

Assessment of sampling theory applied to UXB

Published techniques to compute the probability of detonating at least one of several potentially buried UXB have been investigated. The discussion of sampling theory presented in 'Sampling strategies for contaminated land' [CLR4] relies heavily on a single reference in this area, 'Statistical basis for sampling contaminated land' [Ferguson 1992].

There are no (published) analytical expressions to compute the probability of detecting a hot-spot, nor for the number of samples required to achieve 95% detection probability. Rather, the figures and mathematical expressions presented are the result of curve fitting to numerical simulation results. The Elipgrid software [3] for example, deals only with single hot-spots.

These results are of limited relevance to the application of understanding the risk of UXB, as the desired result is to not disturb the hot-spots rather than to detect them with a 95% probability. Furthermore, they are unable to deal with multiple elliptical hot-spots, nor are they suitable for multiple hot-spots with a non-herringbone sampling pattern.

The problem is complicated by the fact that a UXB detonation can be initiated without a direct strike by impacting the surrounding ground with significant shock forces as caused by piling and drilling, as in Figure 1. The authors are not aware of any published literature that refers to a 'zone of influence' surrounding a hot-spot.

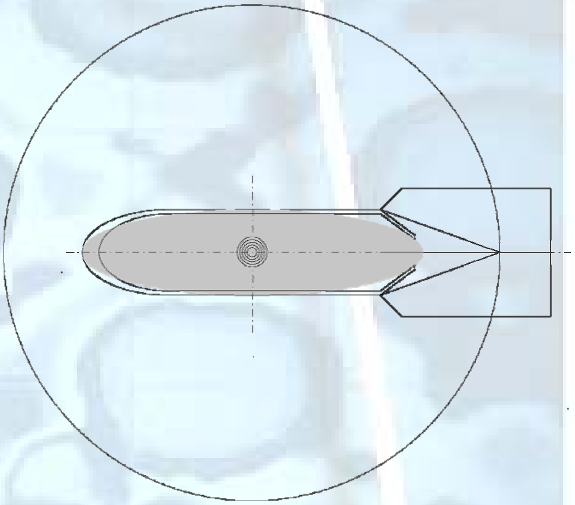

Figure 1 Illustration of bomb shape, ellipsoidal model and circular zone of influence centred at the fuze

A more robust solution is thus required to be capable of dealing with the following issues:

- Multiple hot-spots (user-defined number of UXB derived from desk study)
- Target of user-defined shape and size

- Random and regular sample locations
- Grouped (clustered) samples on a regular grid
- Zone of variable influence around a UXB (up to 2m) where sampling risks detonating it
- Computing the probability of detonating a UXB with a given grid spacing
- Computing the grid spacing (and number of samples) required to achieve a given probability of detonation or detection

Zetica's approach (UXB Probability Calculator 'UXB-PC') computes the probability of detecting multiple ellipsoidal UXB by means of either random (boreholes or CPT for SI) or regular grid (pile layout) sampling. In the case of uniform simple random sampling, the probability of striking at least one of multiple UXB can be computed both analytically in closed form using probability theory, as well as numerically using Monte Carlo simulation, and results are almost identical.

The Monte Carlo method encompasses any technique of statistical sampling employed to approximate solutions to quantitative real-life problems such as this. This numerical simulation is carried out with user-defined parameters (such as the expected number of UXB per hectare, the expected UXB dimensions and the sampling density and type), and the sampling experiment is repeated 100,000 times, presenting the mean of the probabilities computed. The results are stable to within +/- 1%.

Monte Carlo analysis is similarly carried out when the UXB fuzes are assumed to be surrounded by a spherical zone of influence, with the probability of detonation decreasing linearly from 100% at the edge of the bomb to 5% at the zone boundary. UXB-PC has been validated against published benchmarks in the field as discussed below. This work is presented as a contribution to objectively quantify the probability of detonating a buried UXB by regular or random sampling.

Validation

The methodology employed was validated by comparing results of two sampling scenarios with results from three sources generally accepted as industry standards [1, 2 and 3]. These scenarios present only single elliptical hot-spots with no zone of influence (as Elipgrid cannot handle multiple hot-spots), and the corresponding results are as follows:

Scenario 1:

Number of hot-spots	1
Fractional area of hot-spots	5%
Hot-spot aspect ratio	1

	CLR4/Ferguson [1, 2]	**Elipgrid-PC [3]**	**UXB-PC**
Number of regular grid samples to achieve 95% probability of hit	~23	23	25
Grid spacing to achieve 95% probability of hit	20.85m	21.086m	20.00
Probability of hitting hot-spot with 16 regular samples	~79%	80.1%	79.6%
Probability of hitting hot-spot with 23 random samples	~70%	n/a	69.23%

Scenario 2:

Number of hot-spots	5
Fractional area of a hot-spot	1%
Hot-spot aspect ratio	1

	CLR4/Ferguson [1, 2]	**Elipgrid-PC [3]**	**UXB-PC**
Number of regular grid samples to achieve 95% probability of hit	~45	n/a	49*
Grid spacing to achieve 95% probability of hit	14.91m	n/a	14.29*
Probability of hitting hot-spot with 23 random samples	n/a	n/a	69.24%

The results indicate that UXB-PC is an effective alternative for published procedures that rely on looking up values on a set of best-fit curves. It also successfully computes the probabilities of detection for a given number of samples, with single and multiple hot-spots of arbitrary aspect ratio.

Indicative results are presented in the following section for random sampling as assumed for site investigation boreholes and regular grids as assumed for piles.

Example 1 – Site investigation (random sampling)

- 18 site investigation boreholes planned for a 1ha site

The following assumptions were made:

- Random sample distribution
- No prior knowledge of location of any UXB
- UXB lie in any orientation in the horizontal plane
- UXB bomb size 2m x 1m (ellipse shape)
- UXB within penetration depth of boreholes
- Desk study indicates a possible 2 UXB/ha in the area

Results:

1. Fractional area covered by one UXB is 0.0157% (0.05% including 2m zone of influence)
2. Probability of detonating a UXB with 18 boreholes is <1.78% (with 2m zone of influence)
3. Probability of detonating a UXB with 18 boreholes is <0.56% (without 2m zone of influence)
4. Number of boreholes required for a 95% probability of detonating one UXB is 9,534 ignoring the zone of influence, and 3,000 if this zone is taken into consideration.

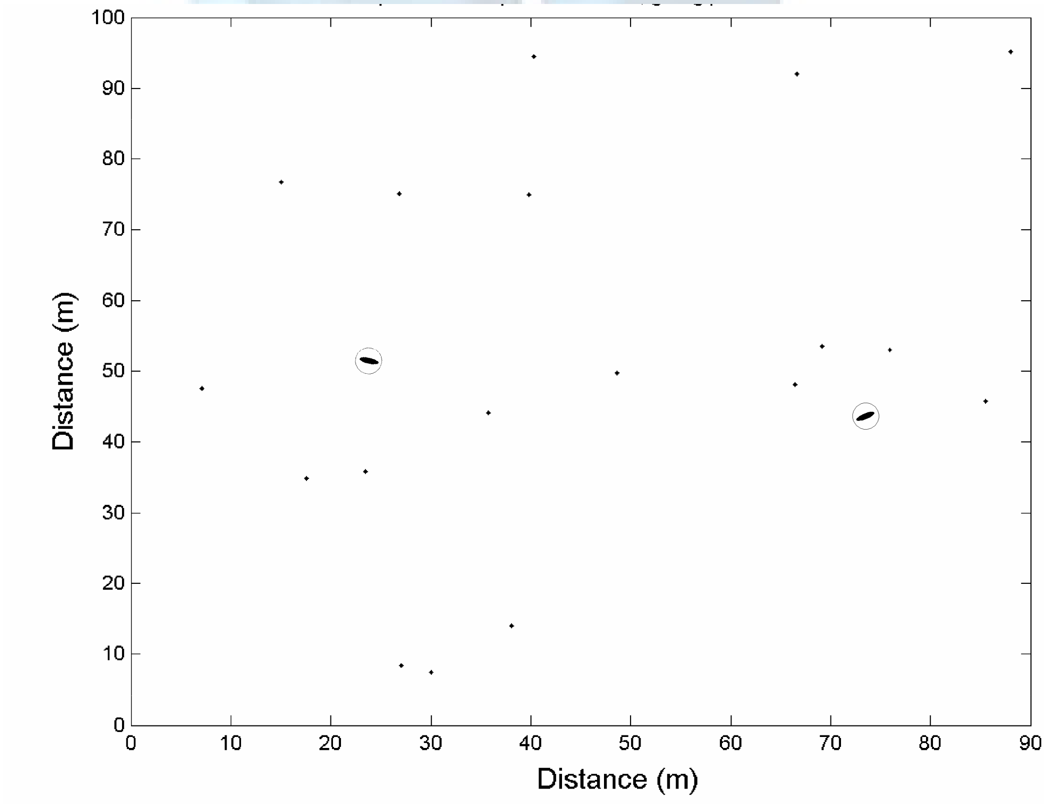

Figure 2 Distribution of 18 boreholes and 2 UXB on site (random)

Example 2 – Piling (regular grid)

- Regular grid at 8m pile group interval for a 1ha site (see Figure 3)
- 144 piles per ha - each group consists of **3 piles**
- **2m zone of influence** around each potential UXB

The following assumptions were made:

- No prior knowledge of location of any UXB
- 3m diameter for pile cluster in each group
- UXB lie in any orientation in the horizontal plane
- UXB bomb size 2m x 1m (ellipse shape)
- UXB within penetration depth of boreholes
- Desk study indicates possibility of 1 UXB/ha in the area

Results:

Probability of detonating a UXB with a 8m grid is <20.34%

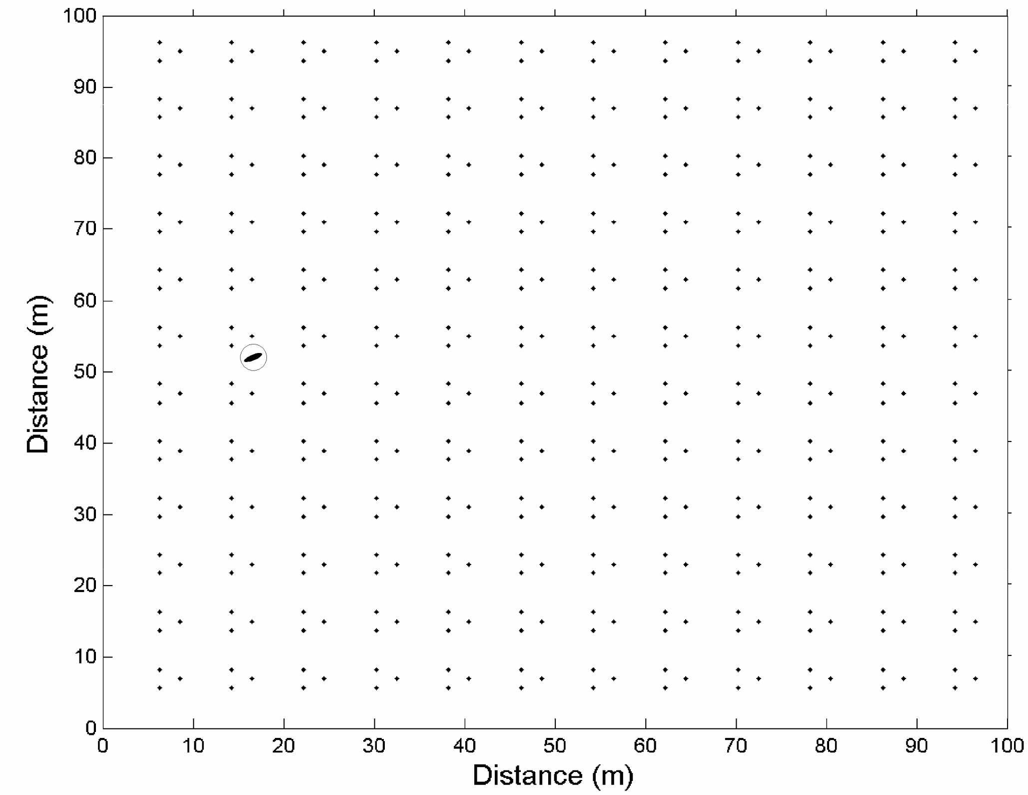

Figure 3 Layout of pile groups and randomly located UXB, showing 2m zone of influence covering 0.05% of site area

Example 3 – Piling (regular grid)

- Regular grid at 8m pile group interval for a 1ha site
- 144 pile groups per ha - each group consists of **3 piles**
- **0m zone of influence** around each potential UXB

The following assumptions were made:

- No prior knowledge of location of any UXB
- 3m diameter for pile cluster in each group
- UXB lie in any orientation in the horizontal plane
- UXB bomb size 2m x 1m (ellipse shape)
- UXB within penetration depth of boreholes
- Desk study indicates possibility of 1 UXB/ha in the area

Results:

Probability of detonating a UXB with a 8m grid is <6.6%. Note the reduced risk caused by ignoring the zone of influence.

Conclusions

Existing techniques for assessing the risk of disturbing contaminated land are incapable of dealing with scenarios involving UXB buried at a development site. Introduced here is UXB-PC, a quantitative technique for objectively calculating the probability of detonating UXB during intrusive works. Input parameters are the number and dimensions of possible UXB as supported by documentary evidence and details of the intrusive method to be used, i.e. randomly located individual boreholes / CPT's or a regular grid of piles. Figure 4 shows a monogram of grid spacing for intrusive works versus probability of detonation for a 1ha site expected to contain 1 UXB with fractional area of 0.016%, both with and without the 2m zone of influence. The additional risk posed by the zone of influence can be significant.

The method provides a quantitative and validated measure of the risk of striking a UXB which can be combined with other land development and construction risks.

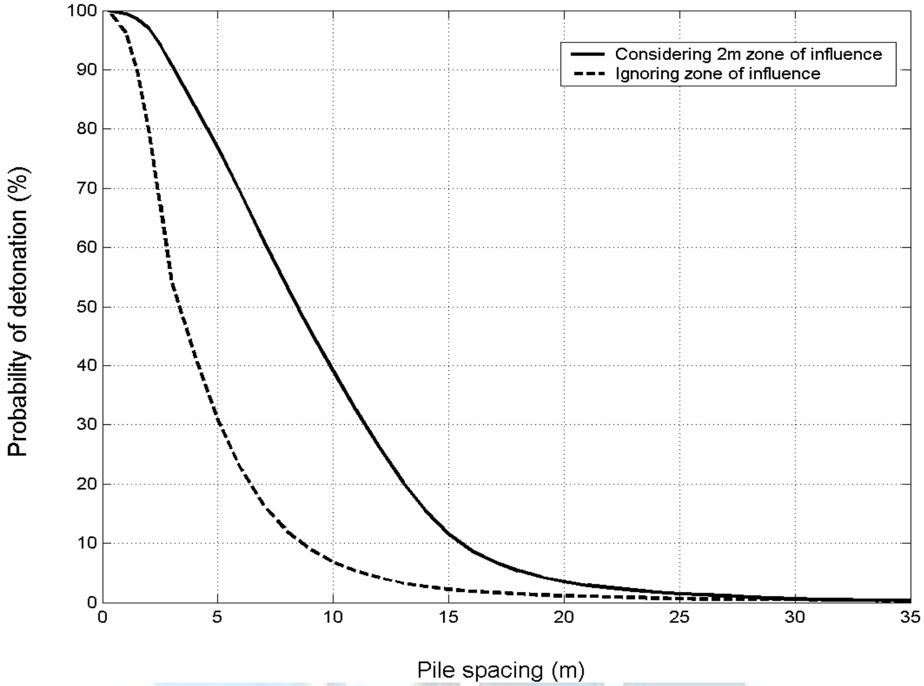

Figure 4 Probability of detonation for regular grid of different spacings and 1UXB/ha, with and without the 2m zone of influence

References

[1] UXB Risk Maps, Zetica website, http://www.zetica.com/uxb_downloads.htm

[2] Department of the Environment, Sampling Strategies for Contaminated Land, Department of the Environment: Contaminated Land Research Report, CLR Report No. 4, 1994.

[3] Ferguson, C. C., The statistical basis for spatial sampling of contaminated land, Ground Engineering, Vol 25, No 5, June 1992, pp. 34-38.

[4] Elipgrid-PC software, Oak Ridge National Laboratory, U.S. Department of Energy.