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# Subsoil disturbance due to explosive ordnance site investigation

## Perturbations du sous-sol dues aux sondages de détection de munitions explosives

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**ABSTRACT:** In UneXploded Ordnance (UXO) suspected areas, where due to local conditions a direct nondestructive investigation is impossible, an UXO site investigation using boreholes has to be carried out. While the UXO investigation requires a very narrow borehole grid for reliable statements on the UXO content, the investigation means for the client – additional to time and costs – a disturbance of the subsoil and an increasing ground risk. Currently, there is no reliable quantitative information on the change in strength properties. However, this would be an important basis for earth statical analyses and therefore for the dimensioning of constructions. Hence, since 2013 the disturbance of the subsoil caused by UXO investigation is analyzed by the German Federal Waterways Engeneering and Research Institute in a R&D project. The evaluation of three field tests leads to the result, that the main influencing parameters on the change of soil strength are the subsoil type and the borehole distance, followed by the borehole filling, and the drilling method. Additionally, the evaluation shows, that the influencing factors act independent. For the evaluated soil types a "typical" UXO investigation results in an average softening up to 40% of the initial strength. Another field test, which is scheduled for May 2019, will lead to quantiative results for cohesive soil below GW-level.

**RÉSUMÉ:** Dans des zones où l'on suspecte la présence de munitions explosives et où, à cause des conditions locales, les méthodes d'enquête non destructives ne peuvent pas être appliquées immédiatement, il faut procéder à des forages. Pour obtenir des résultats fiables, les enquêtes de munitions explosives requièrent une grille de trous de forage la plus étroite possible. Cependant, cette exigence implique non seulement des délais et des coûts supplémentaires pour le maître d'ouvrage, mais également une perturbation du sous-sol et un risque plus élevé lié au sous-sol. À ce jour, il n'existe pas de données sures concernant le niveau de modification des caractéristiques de la solidité du sous-sol résultant des forages visant à sonder les munitions explosives. De telles données constitueraient en effet une base importante pour les mesures statiques du sol et donc pour le dimensionnement d'éléments d'ouvrages. C'est pourquoi la perturbation du sous-sol résultant des sondages de munitions explosives est étudiée depuis 2013 dans le cadre d'un projet R&D par l'Institut Fédéral Allemand d'Études et de Recherches des Voies Navigables. Les analyses de trois essais sur le terrain réalisés jusqu'à présent ont montré que les facteurs les plus déterminants sur les modifications de la solidité sont : le type de sous-sol et la distance entre les trous de forage, le remplissage des trous de forage et, enfin, la méthode de forage. L'interprétation montre, de plus, que les différents facteurs déterminants sont interdépendants. Pour les types de sol étudiés jusqu'à présent un sondage « typique » de munitions explosives provoque un ameublissement du sol allant jusqu'à 40 % de la solidité d'origine. Un autre essai sur le terrain, prévu pour mai 2019, permettra d'obtenir des résultats quantitatifs pour des sols cohésifs pâteux à mous.

**Keywords:** UXO investigation; soil disturbance; strength change factor

*Figure 1. Construction area after an UXO site investigation (Port of Hamburg)*

# 1 BACKGROUND

All over the world UneXploded Ordnance (UXO) from wars or military training grounds lies undiscovered in the subsoil. In preparation for a construction project the ordnance-freedom in the construction area has to be guaranteed. Although the magnetic and electromagnetic tests themselves are nondestructively, they often require boreholes in which the measuring probe is used. While the ordnance investigation requires a very narrow borehole grid for reliable statements on the UXO content, the investigation means for the client – additional to time and costs – a disturbance of the subsoil and an increasing ground risk.

Currently, there is no reliable quantitative information on the change in strength properties. However, this would be an important basis for earth statical analyses and therefore for the dimensioning of constructions. Since 2013 the disturbance of the subsoil caused by UXO investigation is analysed by the German Federal Waterways Engeneering and Research Institute (Bundesanstalt für Wasserbau, BAW) in a R&D project.

# 2 BASICS

## 2.1 Responsibilities

In Germany, UXO disposal and deactivation is a task of general security. Therefore, the basic responsibility is up to the interior ministries of the federal states, respectively their explosive ordnance disposal (E.O.D.) teams. By evaluating historical data (e.g. old aereal photos) areas are judged to be UXO-suspected or -free.

To start construction activities the German developer is legally obligated to provide an UXO-freedom confirmation. To get this, suspected areas require an UXO site investigation, which is planned on the basis of federal-state-specific regulations (BMI, BMVg 2018; annexe A-1.3) and carried out by the responsible E.O.D.-team or by a specialized private company.

For construction activities in other countries the UXO is mostly a question of general safety at work. Often neither the extent of UXO investigation nor the way of execution is regulated.

## 2.2 *UXO site investigation*

In those UXO-suspected areas, where local conditions don't allow a nondestructive investigation, an UXO site investigation using boreholes has to be projected on the basis of the different federal-state-specific regulations (with different requirements).

In addition to the drilling method, the distance and the depth of the boreholes has to be determined.

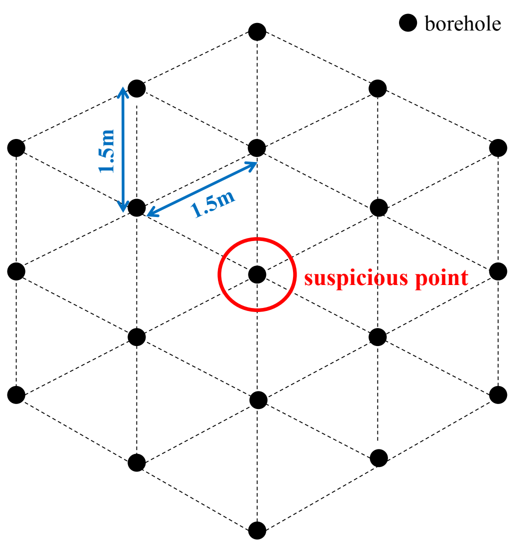


*Figure 2. Example of borehole arrangement around a suspicious point*

### 2.2.1 *Distance of boreholes*

Following the different regulations, the boreholes usually have to be located in the three corners of a triangle (s. Figures 1 and 2). Generally, the side length of the triangles depends on the task of the construction project (exploration of a planar, linear or punctual element). Typical side lengths are between 0.5m and 3.0m. A suspicious point (e.g. from an aereal photo evaluation) may lead – depending on the valid regulation – to an UXO site investigation of 19 boreholes (Figure 2).

### 2.2.2 *Investigation depth*

The required investigation depth usually depends on the subsoil: under the after-war anthropogenic filling and soft sediments, the different regulations demand e.g. in the northern part of Germany mostly an exploration depth of about 1m or 2m into the sandy subsoil.

## 2.3 *Influencing factors*

According to theoretical considerations, the following parameters are expected to be the geotechnically most relevant influencing factors on the soils strength change:

- subsoil type (cohesive / non-cohesive, initial strength, groundwater)
- drilling method
- borehole distance
- borehole filling
- drilling depth

In addition, the following factors may also influence the change in soil strength:

- drilling diameter, drilling bit, operating pressure, drilling speed, drill pipe rack
- load of the drilling equipment, distance of the equipment to the borehole, tracted vehicle or vehicle on pneumatic tyres, axial spacing
- qualification of the drill operator
- …

# 3 METHODOLOGY

## 3.1 Literature research

At first the ordnance regulations of the German federal states were surveyed with regard to geotechnically relevant specifications.

As a result of the literature research no scientific publications on the R&D subject could be found.

## 3.2 Questionnaire survey

Not all the federal states issue regulations, and in consultation with the public E.O.D.-teams or with private specialist companies also variant site investigation procedures are permitted.

Therefore, in 2014 questionnaires were sent to E.O.D.-teams, specialist companies, and landowners to find out, how UXO site investigations are mostly executed in practice. The result was - beside other aspects - that

- hollow drill and flight augers are the most common drilling methods.
- The drilling triangle grid mostly has a side-length of 1.5m.
- The most common drilling depth is approx. 6m bgl.
- Boreholes usally remain unfilled or are filled with drill cuttings.

## 3.3 Field tests

### 3.3.1 Standard field test

The influence of an UXO site investigation is studied on the basis of field tests for different types of subsoil, which are presented in Table 1.

By comparing the soil strengths after and before a simulated UXO site investigation (Figure 3), the influence of the main relevant factors on the strength change – described by the dimensionless “strength change factor” (SCF) – is studied. The interpretation of the SCF is shown in Table 2.

*Table 1. Subsoil types*

| Soil | Initial strength | Groundwater |
|---|---|---|
| cohesive or organic | very soft - soft | above GW-level |
| | | below GW-level |
| | soft - firm | above GW-level |
| | | below GW-level |
| non-cohesive | very loose – medium dense | above GW-level |
| | | below GW-level |
| | mendium dense – very dense | above GW-level |
| | | below GW-level |

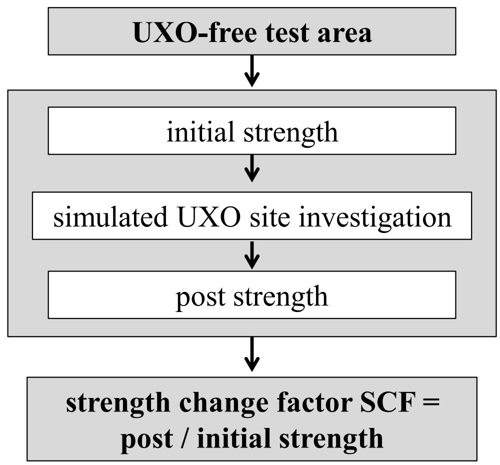


*Figure 3. Philosophy of the field tests*

*Table 2. Interpretation of the strength change factor SCF*

| SCF | Interpretation |
|---|---|
| 0 to 0.5 | intense softening |
| > 0.5 to 0.9 | slight softening |
| > 0.9 to 1.1 | no relevant strength change |
| > 1.1 to 1.5 | slight hardening |
| > 1.5 | intense hardening |

Appropriate probing procedures may be cone penetration tests (CPT), which offer the cone resistance $q_c$ as a measure for the soils strength, and dynamic probing heavy (DPH) or light (DPL), which indicate the strength in the form of $N_{10}$-values (= blows per 10cm penetration). Only within one field test the same probing method should be used to determine the SCF.

The influence of a "typical" UXO site investigation (s. Chapter 3.2) is examined as well as less common methods, which may disturb the soil more or less intensely, to determine the range of strength changes. The following parameters are the fixed factors in all the field tests:

- drilling method:
  - hollow drill and flight auger
  - dry core drilling
  - hydraulic circulation drilling, (not in the first field test)
- borehole distance: 0.5m / 1.5m / 3m
- borehole filling:
  - drill cuttings
  - bentonit-cement-suspension ("Dämmer Typ 2")
- drilling depth: 6m, probing depth: 7m (first field test: 3m / 3-4m)

For each subsoil type the in-situ strength before and after a simulated UXO site investigation is determined in a test field group consisting of five fields. Each single test field represents a special combination of drilling method and borehole filling (s. Table 3) and consists of five initial probings, 13 boreholes and 13 post probings. Figure 4 shows the structure of a test field.

*Table 3. Test field types*

| test field type | drilling method | borehole filling |
|---|---|---|
| A | dry core | drill cutting |
| B | dry core | bentonit-cement-suspension |
| C | auger | drill cutting |
| D | auger | bentonit-cement-suspension |
| E | hydraulic circulation drilling | drill cutting |

At first, the five initial probings (blue in Figure 4) on the outer lines of the test field are carried out, followed by 13 "ordnance" drillings (red) which form the corners of triangles with side length of 0.5m, 1.5m, and 3m. At last, the post probings (green) were performed in the triangle centers. In addition, further post probings are carried out uprigth to the 1.5m grid to allow a more accurate examination of the influence radius of the UXO site investigation. The post probings are the actual measuring points.

Between 2013 und 2016, three field tests were carried out. An additional field test is scheduled for May 2019. The characteristics of all tests are presented in Table 4.

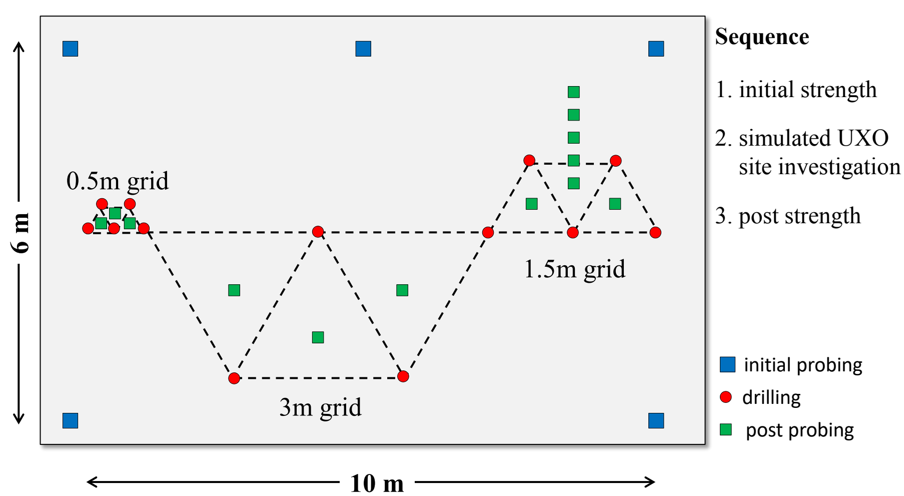


*Figure 4. Test field*

*Table 4. Performed and projected field tests*

| field test | subsoil | drilling / probing depth [m] | test field types |
|---|---|---|---|
| 2013 | very loose to medium dense sand above GW-level | 3 / 3 - 4 | A - D |
| 2015 | mainly medium dense to dense sand above and below GW-level; partly soft to firm till below GW-level | 6 / 7 | A - E |
| 2016 | mainly soft to firm till and glacial clay and silt, partly loose to dense sand above GW-level | 6 / 7 | A - E |
| *2019* | *very soft to soft clay mainly below GW-level* | *6 / 7* | *A - E* |

### *3.3.2 Special field tests*

Other issues of interest in the context of an UXO site investigation will also be examined in 2019, both for cohesive and non-cohesive soils:

- The influence of other common borehole fillings on the soil strength change will be investigated as well as of unfilled boreholes.
- Over a longer period (presumably a maximum of 100 days), it will be checked whether unfilled boring and probing holes close automatically.

## *3.4 Numerics*

Subsequent to the field tests, a numerical modeling of the soils strength change is planned for 2020. Sensitivity studies will be carried out filling the gaps in the field test matrix.

# 4 EVALUATION AND FIRST RESULTS

At first an evalution – including numerous classificating tests (e.g. grain size distribution, plasticity) – was carried out for each field test.

Since the in-situ (initial) strengths has a natural range of variation, the initial strength for every single post probing was determined for different depths by an isoline map, calculated from the average strength data of the pre probings in the specified depth (s. Figure 5).

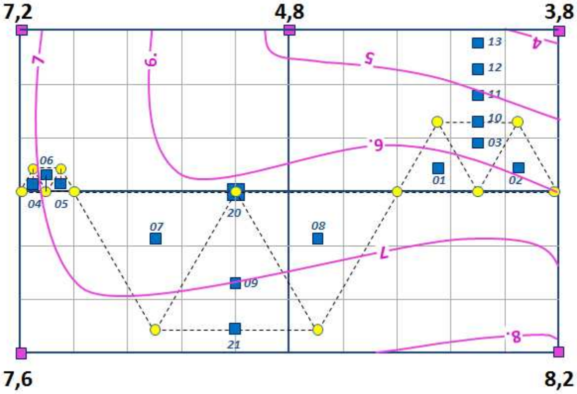


*Figure 5. Isoline map of initial strength (example: DPL-blows/10cm, field test 2013, field C, sand, depth range 0.6m to 1.0m)*

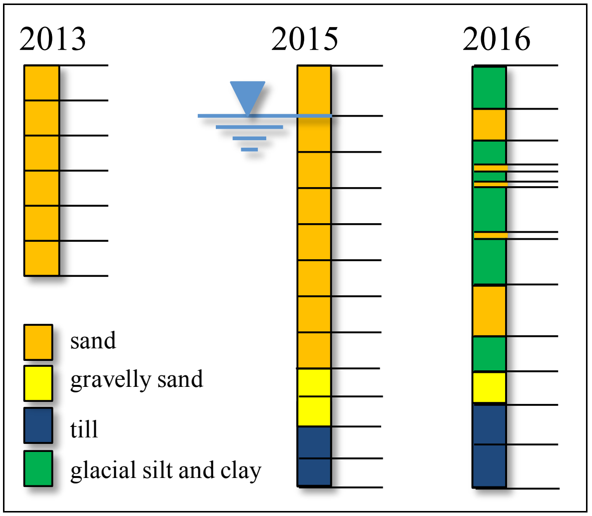


*Figure 6. Soil elements of the field tests 2013 - 2016*

Thus from each single post probing a sequence of mostly 0.5m to 1.0m thick soil elements is defined (Figure 6), each element not only with a known initial and post strength (i.e. the SCF), but also with a lot of corresponding informations like e.g. distance to the boreholes, soil characteristics, groundwater influence, drilling method, borehole filling, …

From the SCF, a depth profile of the average hardening or softening can be created for each grid of each test field. Figure 7 shows e.g. a depth profile of a very loose to medium dense sand above GW-level: In the upper 1.5m a slight to intense hardening of the subsoil due to surface activities (e.g. movement of the drilling equipment) can be seen. In initially harder soils the thickness of this compacted zone is mostly only about 1m. The distinct near-surface hardening in the 1.5m-grid in Figure 7 is the result of technical problems which lead to an intense movement of the heavy drill equipment at the surface of the grid area and therefore to a stronger compaction.

At approx. 1.5m bgl a slight to intense softening of the soil due to the UXO site investigation occures in the 0.5m- and 1.5m-grid, whereas the 3.0m-grid shows nearly no influence.

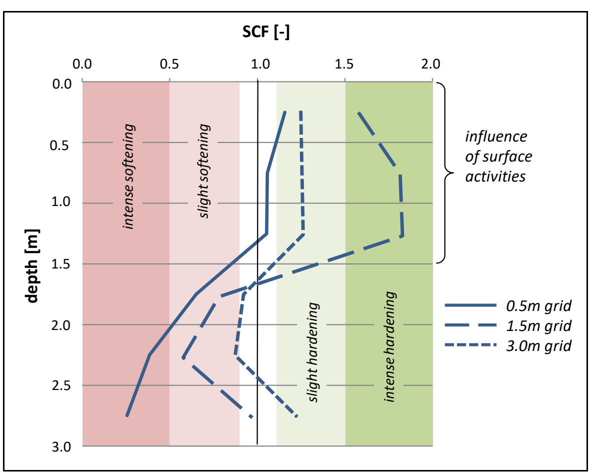


*Figure 7. SCF profile (here: very loose to medium dense sand above GW-level, auger drilling, borehole filled with drill cuttings)*

*Table 5. Average SCF depending on subsoil type, drilling method, borehole filling, and borehole grid (bold: results for a "typical" UXO site investigation)*

| subsoil | drilling method | borehole filling | test field type | grid [m] | SCF [-] |
|---|---|---|---|---|---|
| very loose to medium dense sand above GW-level (field test 2013) | dry core | drill cuttings | A | 0.5 | 0.8 |
| | | | | 1.5 | 0.4 |
| | | | | 3.0 | 1.2 |
| | | bentonit-cement-suspension | B | 0.5 | 1.1 |
| | | | | 1.5 | 1.0 |
| | | | | 3.0 | 2.0 |
| | auger | drill cuttings | C | 0.5 | 0.5 |
| | | | | 1.5 | **0,8** |
| | | | | 3.0 | 1.0 |
| | | bentonit-cement-suspension | D | 0.5 | 2.2 |
| | | | | 1.5 | 1.5 |
| | | | | 3.0 | 2.6 |
| mainly medium dense to dense sand above and below GW-level; partly soft to firm till below GW-level (field test 2015) | dry core | drill cuttings | A | 0.5 | 0.2 |
| | | | | 1.5 | 0.4 |
| | | | | 3.0 | 1.0 |
| | | bentonit-cement-suspension | B | 0.5 | 0.6 |
| | | | | 1.5 | 0.7 |
| | | | | 3.0 | 1.0 |
| | auger | drill cuttings | C | 0.5 | 0.1 |
| | | | | 1.5 | **0.4** |
| | | | | 3.0 | 0.9 |
| | | bentonit-cement-suspension | D | 0.5 | 0.2 |
| | | | | 1.5 | 0.5 |
| | | | | 3.0 | 0.9 |
| | hydraulic circulation | drill cuttings, water | E | 0.5 | 0.1 |
| | | | | 1.5 | 1.0 |
| | | | | 3.0 | 0.9 |
| mainly soft to firm till and glacial clay and silt; partly loose to dense sand above GW-level (field test 2016) | dry core | drill cuttings | A | 0.5 | 0.3 |
| | | | | 1.5 | 1.1 |
| | | | | 3.0 | 1.3 |
| | | bentonit-cement-suspension | B | 0.5 | 0.5 |
| | | | | 1.5 | 1.1 |
| | | | | 3.0 | 1.0 |
| | auger | drill cuttings | C | 0.5 | 0.2 |
| | | | | 1.5 | **0.9** |
| | | | | 3.0 | 0.9 |
| | | bentonit-cement-suspension | D | 0.5 | 0.8 |
| | | | | 1.5 | 1.2 |
| | | | | 3.0 | 1.0 |
| | hydraulic circulation | drill cuttings, water | E | 0.5 | 0.6 |
| | | | | 1.5 | 1.0 |
| | | | | 3.0 | 1.3 |

Table 5, in which only the data below the compacted zone are included, presents the average SCF's (interpretation and colours s. Table 2) for the borehole grids of the already executed field tests.

## 5 CONCLUSIONS

The results of the field test (Table 5) lead to the following conclusions:

- In loose non-cohesive soils above GW-level (field test 2013), the SCF is mainly effected by the borehole filling: drill cuttings result in a softening, bentonit-cement-suspension in a hardening or in unchanged strength properties. The intensity of this phenomenon depends on the distance to the borehole and on the drilling method (dry core drilling reduces the effect compared to the auger).
- In mainly dense non-cohesive soils (field test 2015), the UXO site investigation leads nearly always to a softening: more intensive when using the auger and filling the borehole with drill cuttings, less intensive in the case of dry core drilling and bentonit-cement-suspension. Hydraulic circulation drilling with a borehole filling of submerged drill cuttings leads to an intense softening, however only in a small distance to the borehole (0.5m-grid).
- In mainly cohesive soils above GW-level (field test 2016), only for the 0.5m-grid a softening occures, which is more intensive when the borehole is filled with drill cuttings than with bentonit-cement-suspension. The influence of the drilling method is insignificant.
- The UXO investigation leads to a surface-near zone of hardening. Depth and intensity of the zone depend on the subsoil type and on the kind and the handling of the drilling equipment.
- The bold marked numbers in Table 5 are the results of a "typical" UXO site investigation, i.e. auger drilling, borehole filled with drill cuttings, 1,5m-grid. Depending on the subsoil type a slight to intense softening occures: the post strength is in average between 40% and 90% of the initial strength.

In summary, the main influencing parameters on the change of soil strength are the subsoil type and the borehole distance, followed by the borehole filling, and the drilling method.

Additionally, it becomes apparent that the influencing factors act independent.

The disadvantage of this first assessment is the summarization of the data per test field. In reality, the soil characteristics (soil type, initial strength, groundwater …) vary also inside a single test field both in horizontal and especially in vertical direction (layering, GW-level). Hence, a more accurate quantitative analysis is only possible based on the single soil elements as shown in Figure 6 instead of an averaged SCF per test field. Only this data will allow the evalution of all combinations of influencing factors.

But to put this into practice, the last field test, which is scheduled for May 2019, is needed.

From the planned quantitative evaluation recommendations can be published, which will also take the aspects of time and costs into account, e.g. for the borehole filling depending on the soil characteristics.

Knowing the SCF, it will be also possible to estimate the soil strength after an UXO site investigation from probings, which were carried out before and thus enable a realistic design for constructions.

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