Industrial experience feedback of a geostatistical estimation of contaminated soil volumes

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Context

- Former TOTAL oil deposit in France
- High hydrocarbon grades in the lower part of a backfill layer

Detailed risk evaluation in 2002:
- Remediation threshold for THC: 2500 ppm
- Suspected contaminated surface: 7,775 m² (in yellow)
- Corresponding contaminated volume: 11,650 to 15,550 m³ (1.5 to 2 m depth)

- Part of demonstration studies carried out for GeoSiPol and with the financial contribution of Ademe.

Objectives:
- Quantify and locate the contaminated volumes
- Estimate the volumes to be excavated

Key points:
- Consideration of all available data
- Iterative geostatistical approach & sampling recommendation
- Quantification of the uncertainty
- Consideration of remediation constraints
Available data: two campaigns

- **December 2005:**
  - Systematic sampling of potentially contaminated areas with a 15 m mesh
  - 82 boreholes: 2 samples taken between 0 and 1 m and 1 and 2 m, depending on organoleptic observations
  → First geostatistical study in 2006

- **June 2006:**
  - 17 complementary boreholes, in uncertain areas
  → Update of the geostatistical study

+ 82 initial boreholes
* 17 complementary boreholes
Available data

- Examples of boreholes

<table>
<thead>
<tr>
<th></th>
<th>H_A (m)</th>
<th>THC_A (mg/kg)</th>
<th>H_B (m)</th>
<th>THC_B (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.6</td>
<td>160</td>
<td>1.7</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.8</td>
<td>190</td>
<td>0.7</td>
<td>3200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>1100</td>
<td>0.3</td>
<td>4200</td>
</tr>
</tbody>
</table>

Thickness of the potentially contaminated layer (threshold = 1000 ppm):

- Thickness: 0 m
- Thickness: 0.7 m
- Thickness: 0.9 m
  \[ \text{THC}_{\text{mean}} = 2133 \, \text{mg/kg} \]

- Two steps procedure given the conditions of investigation:
  - Geometric estimation of the potentially contaminated layer
  - Estimation of the grades inside this layer (2D)
Modeling the geometry of the target layer

- Geometry of the potentially contaminated layer
  - Modeling of the top, the thickness and the bottom of the layer
  - Geostatistical simulations, quantification of the uncertainty (mesh: 1 m)

- 50% quantiles for:
Modeling of the THC grades

- First geostatistical study using the 82 initial boreholes:
  - Simulation mesh: 1x1m
  - 3 target areas
  - 2D Map of the probability to exceed the 2500 ppm threshold

![Variogram of THC grades](image1)
![Histogram of THC grades](image2)

![2D Map of the probability to exceed the 2500 ppm threshold](image3)
Contaminated soil volumes

- Computation of the total contaminated volume over the three target areas using:
  - Simulations of the contaminated layer thickness
  - Simulations of the grades inside the layer

Most probable volume: 9 217 m³
CI$_{90\%}$ = [7 874 ; 11 265]
Volume to be excavated

- How much should we excavate to remove all the contamination?
  
  Because of:
  - Uncertainty about depth and thickness of the contaminated layer
  - Spatial variability of the grades inside this layer

→ Volume to be excavated > Contaminated volume

- Several scenarios:

<table>
<thead>
<tr>
<th>$Z_{\text{min}}$ Quantile (Top)</th>
<th>$Z_{\text{max}}$ Quantile (Bottom)</th>
<th>THC Quantile</th>
<th>Volume to be excavated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q50 (probable)</td>
<td>Q50 (probable)</td>
<td>Q50 (probable)</td>
<td>8 674 m$^3$</td>
</tr>
<tr>
<td>Q50 (probable)</td>
<td>Q50 (probable)</td>
<td>Q10 (safe)</td>
<td>18 108 m$^3$</td>
</tr>
<tr>
<td>Q25 (safe)</td>
<td>Q75 (safe)</td>
<td>Q10 (safe)</td>
<td>33 755 m$^3$</td>
</tr>
</tbody>
</table>
Excavation

- Main steps of the site remediation

  June 2006: 17 complementary boreholes (recommendations after the first geostatistical study)

  Evaluation of the contaminated volume based on the analytical results (without geostatistics): 8,300 m³

  Summer 2006: Excavation and sorting of 22,347 m³ of soil, of which 13,171 m³ are contaminated

  ➔ Contaminated volumes roughly computed from analytical results clearly underestimate the amount of pollution
Comparison with geostatistical prediction

Remediation: \(13\ 171\ \text{m}^3\) of contaminated soils...

...to be compared to the \(9\ 217\ \text{m}^3\) obtained during 1\textsuperscript{st} geostatistical study – \(\text{CI}_{90\%}=[7\ 874; 11\ 265\ \text{m}^3]\)

→ Underestimation of 30%
→ True value not even comprised in the confidence interval

- Two main reasons:
  - Difference of support:
    o simulations (1x1 m mesh)
    o excavation (15x15 m mesh)
  - The 17 complementary boreholes of June 2006 (before excavation) are not yet integrated in the study
Taking the remediation support into account

- New maps and quantification of contaminated soils considering a 15x15 m mesh

Probability map to exceed the threshold of 2500 ppm

Most probable volume: 11 773 m³

CI₉₀% = [9 498 ; 14 726]

- Underestimation of 10.6%
- True value comprised in the CI₉₀%
Taking complementary boreholes into account

New boreholes, located in uncertain areas (following the 1st geostatistical study)

With complementary boreholes

New map of the probability to exceed 2500 ppm

→ Decrease of the uncertainty in the new sampled areas
Taking complementary boreholes into account

- Comparison of P[HCT>2500 ppm] maps before and after integration of the 17 new boreholes
Update of the contaminated volumes

- New quantification of contaminated volumes over the three target areas, taking into account:
  - The 15x15 m remediation mesh
  - The 17 complementary boreholes

Most probable volume: 12 059 m$^3$

→ Underestimation of 8.4%

CI$_{90\%}$ = [10 028 ; 15 421]

→ True value included

The true contaminated volume of 13 171 m$^3$ corresponds to the 25% quantile

Remarks:

→ Evaluation of the contaminated volume based on the analytical results (without geostatistics): 8 300 m$^3$

→ Excavation was carried out on a 15m basis but with some irregular blocks

→ estimation takes into account the exact thickness whereas excavation has probably been done with 0.5m benches and remains unknown
Update of the volumes to be excavated

- Using geostatistics: prediction of how much soil should have been excavated to remove all the contamination?

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<td>31 239 m$^3$</td>
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... to be compared to the real excavated volume of 22 348 m$^3$.

- These volumes can be reduced during the excavation as the sorting progresses and if visual/organoleptic observations of the areas to excavate are used.

- Such results are useful to optimize the planning of the excavation phase and to better assess its related costs.
Remediation in practice

- What has been done:
Remediation in practice: with geostatistics

- What could have been done:

  After choosing a scenario for both geometry and THC grades, for example Q25/Q75/Q25:
  
  - Horizontal extension is given by the 25% isoline (bold) of the probability map to exceed 2500 ppm
  
  - Inside those areas, depths to remediate are obtained thanks to:
    
    - $Q_{25\%}$ map for top of layer
    - $Q_{75\%}$ map for bottom of layer
Remediation in practice: comparison

- Superimposition of excavated soils and probability map:
  - Very good concordance
  - Boundaries of the excavated area close to the 50% probability isoline
  - Irregular limit: excavation is stopped when possible
  - Bituminous areas: different problematic, detailed excavation
Conclusion

- Geostatistics provide a relevant prediction of the contaminated volumes if remediation constraints are taken into account (15x15 m mesh)

- Advantages of the iterative approach:
  - Orientation for further investigations
  - Better final accuracy
  - Real integration of geostatistics in the remediation workflow

- Geostatistical approach outcomes:
  - Data quality control
  - Relevant estimates...
    ...coupled with uncertainty quantification,
    ...for both contaminated and excavated volumes.
  - Cost / benefit analysis e.g. relevance of collecting additional data versus starting remediation?
Acknowledgments

- ADEME for financial support
- TOTAL for the authorization to present the results
- Other GeoSiPol members for their valuable contribution

... And thank you for your attention!