Geoelectrical Imaging for Site Investigation for Urban Underground Infrastructure

2012-09-03

A. Purpose and aims

The TRUST project brings together scientists from the Swedish Universities of the Built Environment (SBU, i.e. Chalmers University of Technology, Royal Institute of Technology, Luleå University of Technology and Lund University Faculty of Engineering), Uppsala University (UU), the Geological Survey of Sweden (SGU) and a number of private companies with the aim to improve tools for planning, design and construction of underground facilities. The structure of the TRUST project is outlined in figure 1.

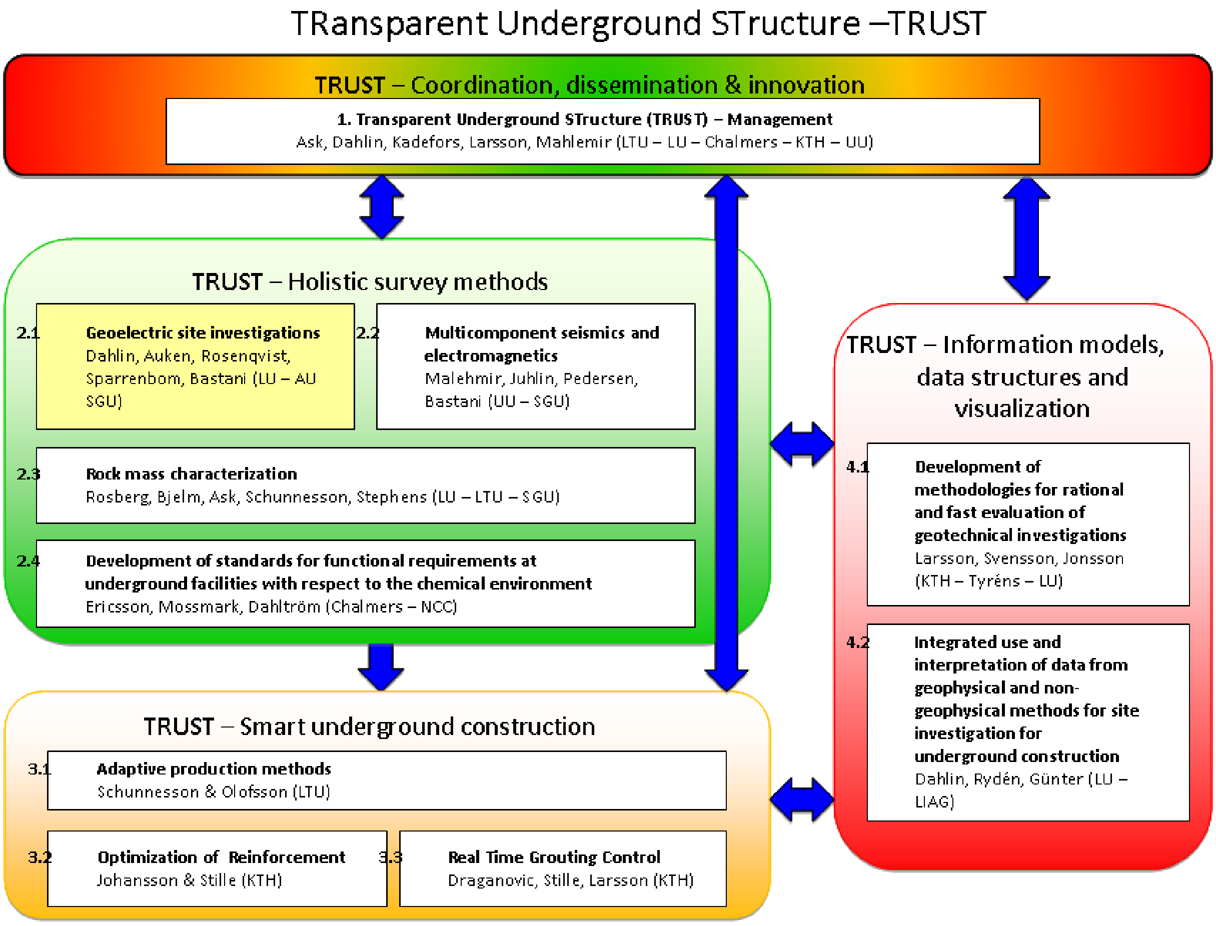

Figure 1 Outline of the TRUST project with this sub-project highlighted with yellow.

The purpose of this sub-project in TRUST is to develop and adapt the resistivity-induced polarisation (DCIP) imaging method for use in infrastructural developments in urban environments. Through this a methodology for a more far-reaching site investigation is developed. The methodology will save energy, time, resources and emissions by reducing the risk of unforeseen ground conditions. The subsequent geotechnical and environmental investigation can be focused on verification of the interpretation of the results from the geophysical investigation concerning geological and geotechnical properties of the soil, hidden constructions and distribution of contaminations in soil and groundwater.

The increased amount of information obtained in the investigation decreases the uncertainties and risks in the subsequent process of planning, construction and operation of underground infrastructures. A greater knowledge of the site conditions will lead to better planning for the construction project and to a reduction of waste and a decreased need for virgin resources in process. The proposed methodology optimises the use of resources in consecutive studies and thus contributes to cost- and resource effective planning and implementation.

The aims of the project are summarized in the following points:

- **Adaption of DCIP imaging.** Development and adaptation of DCIP imaging for use in urban environments; adaptation of data acquisition strategies and methodology and data processing.
- **Prototype instruments.** Developing prototype DCIP equipment for time and cost efficient acquisition of data for description of the subsurface in three dimensions (3D).
- **3D inversion of DCIP.** Development of algorithms for 3D inversion of DCIP data. The software will build on the novel algorithms for 1D and 2D inversion by Fiandaca et al (2012).
- **Engineering and environmental properties.** Investigation of possible correlations between geophysical and engineering/environmental key parameters, e.g. soil conditions, tectonic structures, waste as well as water and contaminant occurrence and transport.
- **Integration in TRUST.** Integration of all the TRUST sub-projects, for building up a holistic survey method, together with model and data visualisation for a smart underground construction. .
- **Dissemination.** Dissemination of the results to authorities, industry and academy.

B. Background

Problem Description

Unforeseen ground conditions is a risk factor often leading to delays and significant additional costs in connection with underground infrastructure construction work. There are two main geological hazards that are important to identify, manage, or possibly avoid, for safe and efficient underground construction. The first is unstable rock and the second is large inflow of groundwater. Groundwater inflow is a problem that exists in most underground projects. In order to handle these risks first-rate knowledge of structural data, bedrock and soil geology, geotechnical conditions, joints, fault zones, as well as nearby underground facilities, ground- and surface water is needed. Furthermore, damage on buildings and infrastructure may occur due to subsidence or change in natural geo-chemical conditions.

Infrastructure projects are closely linked to various environmental requirements, which in turn may be related to the sub-surface. Incomplete investigations lead to a negative impact on human health and the environment (HHE) whereas carefully designed and relevant site investigation aiming at reducing risk of both HHE and technical problems is crucial for underground infrastructure projects.

Another problem is waste deposits and industrial areas. On these sites the market value of real estates often increase as cities expand leading to an interest in development. These old and often abandoned areas (former chemical industry, gasworks, impregnation plants, chemical cleaning, etc.) are often associated with highly contaminated soil and soil water. One of the main problems at these sites is to identify and map the source of contamination. In many cases the area has been used with different activities over a prolonged period of time and therefore there is often a need to identify and map a number of sources of contamination.

Waste deposits were in former days often placed outside the cities without any measures for environmental protection during landfilling of waste. When the waste deposits were closed they were often left without environmental protection such as an inadequate soil cover. Construction on top of or below landfills is however associated with severe geo-technical and geo-environmental risks, such as subsidence and spreading of waterborne contaminants and gases. Moreover, documentation of the geometrical extent and composition of the waste is generally poor or non-existent.

Since old landfills are highly heterogeneous, some of the waste fractions can be hazardous to HHE, whereas others are harmless. Consequently, there is a need to distinguish between waste fractions in order to separate hazardous fractions needing treatment and the harmless fractions that can be reused at site or elsewhere. This is sometimes called landfill mining.

Underground construction commonly affects groundwater levels, which can change the geochemical conditions in the groundwater as well as activate contaminant transport. Changes in groundwater characteristics (e.g., groundwater level) may for example cause changes in redox conditions and lead to unpredictable mobilization of hazardous chemicals. Furthermore, changes in groundwater conditions may enhance gas production from organic waste leading to an increased risk for explosion, fire and health problems. There is thus a need to develop methods for mapping and characterising groundwater conditions prior to underground construction at landfills and contaminated sites.

Geophysics and DCIP in Site Investigation for Urban Underground Infrastructure

Mapping environmental risks and/or impact with geophysical methods, five main properties need to be identified for a successful understanding of the sub-surface. These are:

- **Constructions at site**. Waste deposits and industrial sites contain various sub-surface constructions. These constructions need to be identified and mapped.
- **Geological information.** Type of soil, degree of sorting, layer thickness and lateral extent, depth to rock, type of rock, structure, joints, faults and variation in properties.
- **Hydrogeological information**. Groundwater level, aquifer extent and type, and aquifer boundaries, hydraulic gradients, flow direction
- **Geo-chemical information**. Redox conditions, pH, salinity, groundwater temperature, dissolved oxygen, TDS, turbidity, concentration of pollutants, etc.
- **Other information**. Water content in unsaturated zone, soil temperature, pore pressure, etc

On the contrary, preliminary site investigation for underground construction is often exclusively based on drilling. Drilling provide highly detailed information in discrete points, but no information between boreholes. It is impossible to build reliable 3D models of the underground space based on drilling alone as illustrated by the example in Figure 2. Modern geophysical imaging techniques on the other hand can map the variation in characteristics of the subsurface space in 3D in a time-and cost-effective way.

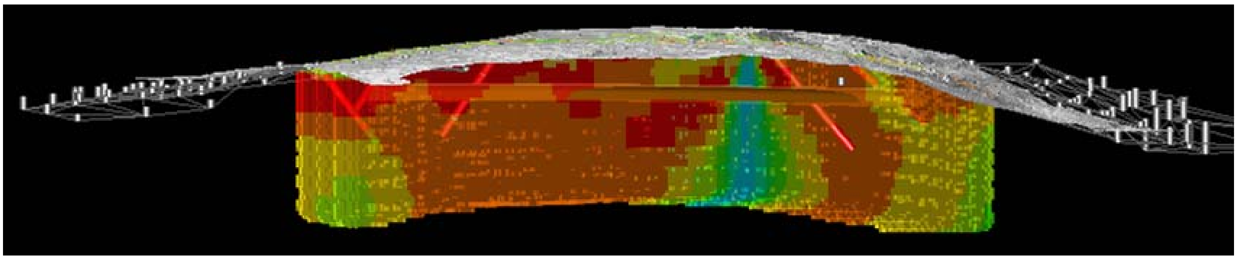

Figure 2. 3D model of the rock resistivity along a road tunnel, with tunnel and borehole positions shown. The low resistive zone probably means fractured and weathered or water bearing rock. Since the drilling was done before the geophysics the zone was missed.

Combined mapping of DCIP together with a few carefully placed boreholes has shown great applicability for the investigation of soil and rock in infrastructure applications (e.g. Danielsen and Dahlin 2009). In fact, it has been demonstrated that DCIP is a powerful tool for lithotype characterization and for delineating the extent of buried waste (e.g. Dahlin et al. 2010; e.g. Rosqvist et al 2011; Dahlin et al 2012; Gazoty et al. 2012). Furthermore, DCIP has also shown potential in characterising waste in terms of type of material and in tracing migration of fluids, contaminants and gas in the ground. Figure 3 shows the results of from the Filborna landfill in Helsingborg. Soil cover conditions, groundwater level and geological properties are clearly visible in the section.

Critical Issues for the DCIP Method

Ambiguities are inherent in the interpretation of geophysical data. By carrying out geophysical measurements in an early stage of a project and basing the drilling and sampling programme on the results, a more comprehensive picture of the underground volume can be achieved and the risk of missing important information can be minimised. This way is by far a more cost-efficient way to achieve comprehensive cover of a volume than the use of drilling alone. By using the results from follow-up investigation to constrain the inversion and interpretation the inherent ambiguities in the geophysical models are greatly reduced.

But four critical issues of the DCIP method should be addressed to completely explore its capability in urban environment for underground infrastructures:

- **Specificity of the urban environment.** The urban environment is intrinsically three dimensional and presents logistic limitations that often prevent regular geometries of the electrode spreads. Furthermore, several sources of noise are present. These specificities require adapted electrode configurations and advanced signal processing schemes.
- **Low suitability of commercial acquisition systems.** The need of using 3D models in turn demands much greater amounts of data. More scalable and faster acquisition systems are required for a cost effective applicability of DCIP.
- **Oversimplified inversion schemes for 3D DCIP.** Commercial 3D algorithms for DCIP inversion completely disregard the spectral content contained in the IP decays. This implies a significant loss of information in the inversion process. More sophisticated inversion approaches are needed (e.g. Hönig, and Tezkan 2007; Fiandaca et al. 2012).
- **No clear link between IP and engineering/environmental properties.** A lack of understanding exists in the correlations between IP and the engineering/environmental parameters, especially about the IP spectral characteristics.

The project aims at answering all these issues, as explained in details in the next sections.

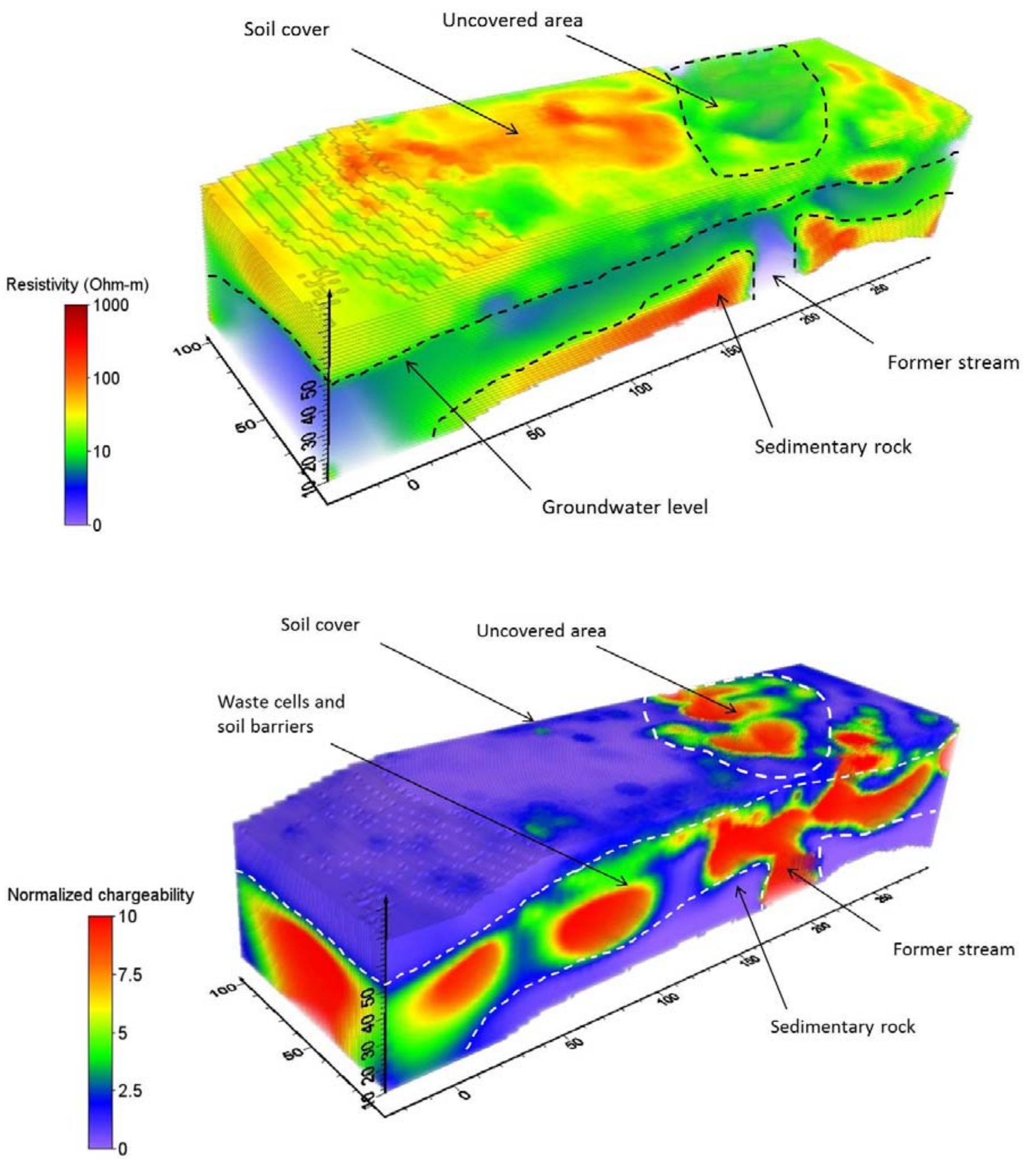

Figure 3. Example result from the MaLaGa-project - Large scale model based on resistivity and IP data from the Filborna landfill site, Helsingborg, Sweden.

Complementary Methods to DCIP.
Waste and derelict industrial areas often contain considerable amounts of metal that creates magnetic anomalies. Magnetic mapping provides information related to the metal content that is valuable when interpreting the DCIP data.

The resistivity of the ground can be measured with alternative techniques, where RMT (radio magnetotellurics) provides valuable information regarding the anisotropy. Anisotropy in the electrical properties can be an indication of anisotropy in the mechanical and hydraulic properties, which may be important for stability of rock and groundwater flow patterns.

Sub-project within TRUST will provide data from other geophysical methods at Förbifart Stockholm that will be valuable complementary information for interpreting the DCIP.results. This is not the case for the sites with environmental concerns, hence we include measurements with magnetic and RMT methods at those sites in this project.

C. Implementation

The work is naturally divided into five work packages (WP). The Work Package leaders are responsible for directing and coordinating the activities within each work package and to maintain smooth collaboration between all partners in their work package.

The field test activities will be coordinated with the activities of the other sub-projects within TRUST, and data from those be used as reference data for evaluation of the data generated. This includes not only geophysical but all types of relevant data such as for example drilling and sampling, laboratory analyses, chemical and tunnel documentation data. All data from this project will be entered into the database established by TRUST.

WP1: Geoelectrical Imaging Techniques in Urban Environments

Team leader: T Dahlin. Participants: PhD1, E Auken, G Fiandaca, J Moberg

WP1 comprises:

- Development of 3D data acquisition methodology and strategies. This includes different electrode arrays and combinations of electrode arrays in various urban environment scenarios, and also include surface electrode arrays, borehole arrays and combined surface and borehole arrays.
- Numerical modelling study to test and evaluate the developed 3D data acquisition methodology and strategies. A number of representative models will be tested by doing forward numerical modelling followed by inversion
- Design and manufacturing of prototype data acquisition equipment for 3D data acquisition.
- Adaptation of methods for visualisation of interpreted models in 2D and 3D.
- Signal analysis of full waveform recordings and application of different noise filtering approaches, with the aim to develop robust methods for extracting data from noisy environments.

WP2: 3D Inversion of DCIP Data

Team leader: E Auken. Participants: G Fiandaca, PhD1

WP2 has the following main categories:

- Development of a new 3D algorithm for DCIP. The new algorithm is based on the framework for 1D and 2D inversion codes developed at AU (Fiandaca et al., 2012). It will allow the reconstruction of the 3D distribution of resistivity and chargeability parameters, together with their complete uncertainty analysis, by inverting simultaneously the entire IP decays.
- Parallelisation of the code for fast computation on multi-cores machines.
- Robust computation of a reliable measure of the depth of investigation of the data (Christiansen and Auken, 2012).

- Development of a framework for using geological/geotechnical information from boreholes as a-priori information in to integrate it jointly in the inversion process. This is expected to greatly reduce the ambiguity of the geophysical data.

WP3: Field Data Acquisition

Team leader: H Rosqvist. Participants: G Fiandaca, PhD1, PhD2, C Sparrenbom, D Hagerberg, T , M Bastani

WP3 is the data collection part of the project where geoelectrical measurements will be carried out and ground truth will be collected as follows:

- DCIP field data acquisition at 3 sites common for TRUST. Reference data generated by other activities within TRUST will be available as reference data for those sites. Measurements with surface electrode arrays, borehole arrays and combined surface and borehole arrays will be included.
- Field data acquisition at a 3 selected sites with environmental concerns. Waste deposits will be selected in collaboration with waste and landfill management organisations, e.g. the landfill group at Swedish Waste Management (Avfall Sverige). For selection of relevant industrial sites the Swedish Geotechnical Institute (SGI), Naturvårdsverket (SNV) and the municipalities will be important collaborators.
- Data acquisition with additional geophysical methods such as magnetics and RMT.
- Drilling and installation of piezometers. Measurement and sampling of geological, chemical and hydrological parameters such as, water content, groundwater level, soil temperature, type of material/waste.
- Geo-chemical characterisation of soil and groundwater chemistry including laboratory analyses of oil, PAH, and 10 metals in soil and plus chlorinated solvents in water.

WP4: Applicability and Interpretation of Geophysical Results in Relation to Engineering and Environmental Properties

Team leader: C Sparrenbom. Participants: PhD2, D Hagerberg, T Dahlin, H Rosqvist, M Bastani, S Johansson

WP4 will deal with analysing the results from WP3 and to make a joint interpretation of the multiple measurements performed in WP3. WP4 has the following main categories

- Spectral IP inversion of the DCIP data.
- Joint interpretation of DCIP, RMT and magnetic data. Joint inversion of DC and RMT data using software described by Bastani et al (2012).
- Visualisation of survey results including uncertainty estimates.
- Analysis together with all relevant reference data (geological, mechanical, chemical, etc) using multivariate statistics and cluster analysis for calibration of the geophysical signatures vs. engineering and environmental properties. Joint analysis with data from the complementary methods.

WP5: Coordination and Dissemination

Team leader:T Dahlin. Participants: all

The coordination of the project is detailed in the Project Plan, in terms of management structure and scheduled verifications.

The coordination of the project for a successful implementation requires a strategy for handling failure risks. The major risk elements in the project implementation lies 1) in the challenges related to the development of the 3D DCIP inversion algorithm, that may be delayed due to unexpected programming challenges or challenges related to the actual scientific issues addressed, and 2) risks of instrument developments being delayed.

Internally in the project a community of professional program developers at AU can assist across WP2 to tackle various problems encountered. This, together with the expertise of the AU group in 1D and 2D DCIP inversion codes, minimises programming related risks. The risks relating to the instrument developments are anticipated to be minor. If the developments are delayed the overall progress of the project will not be significantly affected as data acquisition can be carried out using less advanced approaches.

Dissemination is a key point that will determine the success of the project. A Reference Group will be established in the project structure with the aim of strengthening the diffusion of project results to the user community and to facilitate feed back to the project from end users. The project will arrange seminar/workshop for the Reference Group and also produce electronic newsletters.

D. Equipment

A prototype system adapted for time and cost efficient DCIP data acquisition in 3D with sufficient resolution and quality will be developed. It will consist of multichannel receiver(s), transmitter, relay multiplexers, electrode cables, electrodes and various connectors. The different parts will be combined in a way that is to be determined in WP1. It will be based on the components of the Terrameter LS that are reconfigured and partly re-designed, which will make the development relatively fast and reasonable in cost. In the early parts of the project it will be necessary to use existing equipment solutions with tailor made configurations.

A powerful server computer will be purchased for 3D modelling and interpretation of data

Equipment for groundwater sampling and monitoring will need to be purchased to make it possible to acquire needed reference data.

E. Project plan

Time schedule

An outline and time schedule of the project activities are shown in the diagram in Figure 4. The diagram shows the various tasks for each of the work packages.

The project is scheduled to run from late 2012 to 2016. The post doc will in this case be available as soon as the proposal is approved, and development work in WP 1 and WP2 will start promptly. As experience has shown that recruiting PhD students takes time this will be started immediately in order to get good candidates on board a.s.a.p..

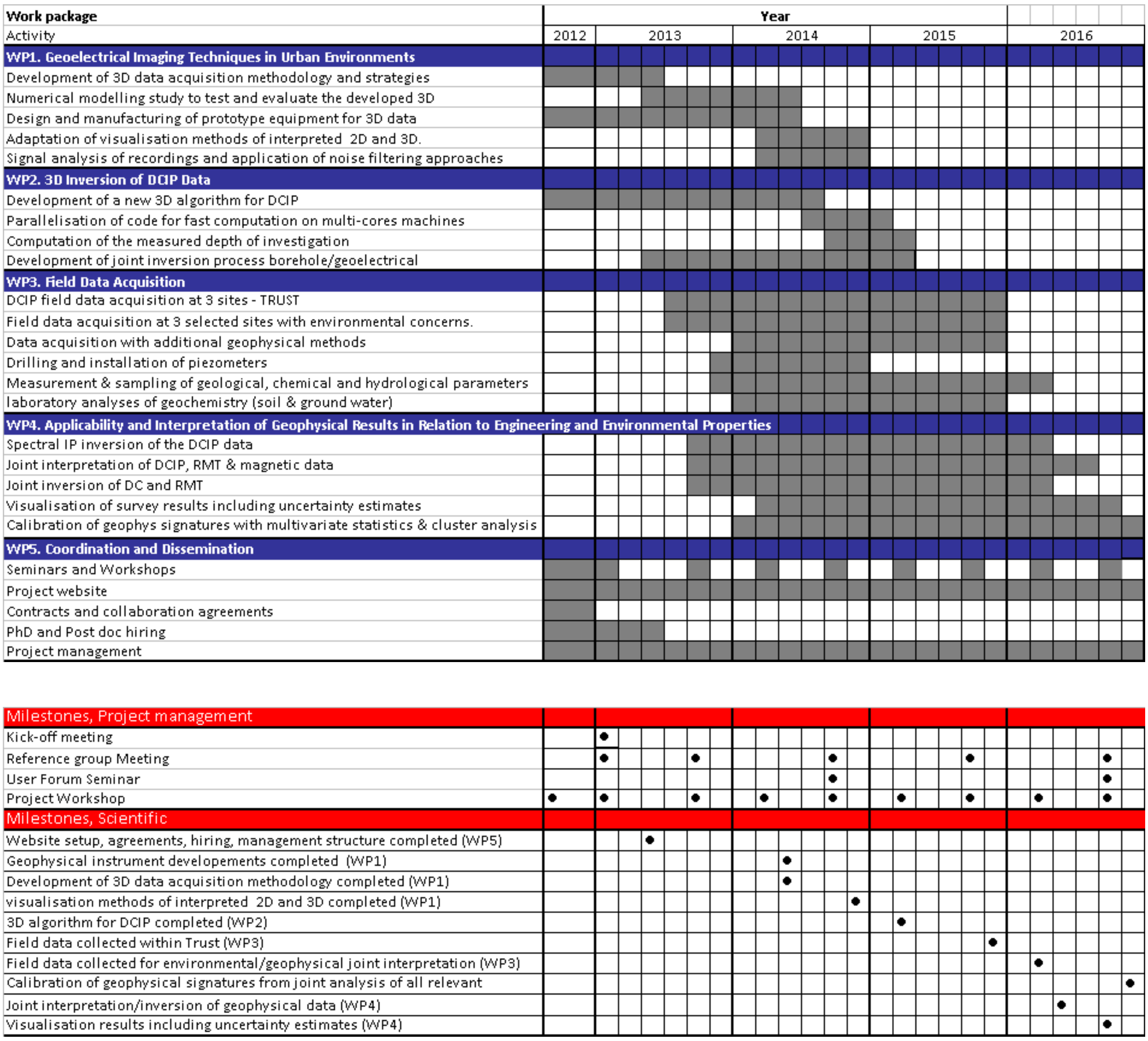

Figure 4. Time plan and

Organisation and Project Management

The Project Group consists of:

- Prof Torleif Dahlin, Lund Univ (LU)
- Dr Charlotte Sparrenbom, Lund Univ (LU)
- Ass Prof Esben Auken, Aarhus Univ (AU)
- Dr Gianluca Fiandaca, Aarhus Univ (AU)
- Dr Håkan Rosqvist, Rosqvist Resurs/LU
- Dr Mehrdad Bastani, SGU
- Dr David Hagerberg, Tyréns
- Dr Mats Svensson,Tyréns
- MSc Sara Johansson, Tyréns
- Jonas Moberg, ABEM Instrument
- PhD student 1, Lund Univ (LU)
- PhD student 2, Lund Univ (LU)

The Project Group will meet two times per year for a workshop to present and discuss the results produced within the project and to adjust research plans for the next year. Invitees will comprise all personnel and students working within the project. Ad hoc meetings will be arranged for sub-groups when needed and likewise the project can organise training courses at Ph.D. level in specific disciplines, e.g. statistics, inversion, etc.

A research project of this size, involving the participation of both research institutions and industry, requires a clearly defined management structure and a transparent decision making process to continue making and monitor the progress of the project. The Steering Group will have the responsibility for this. It consists of:

- Prof Torleif Dahlin, LU
- Dr Charlotte Sparrenbom, LU
- Ass Prof Esben Auken, AU
- Dr Håkan Rosqvist, RR /LU
- Dr Mats Svensson,Tyréns

Prof Torleif Dahlin is Project Leader with responsibility for:
1) the daily management in collaboration with the WP leaders,
2) the implementation of decisions made by the steering group, and
3) the dialogue with the funders.

A reference group will be appointed to provide a forum for a dialogue with authorities, industry, etc., preliminarily with representatives from the following organisations:

- BeFo
- NCC
- Skanska
- Trafikverket
- SGI
- NGI
- A consultant company (other than Tyréns)

An International Advisory Board containing three international experts who can be consulted at various stages of the project:

- Prof A. Binley, Lancaster Univ (geophysics and hydrogeology)
- Prof Lee Salter, Rutgers Univ (geophysics)
- Prof William Powrie, Univ of South Hampton(geotechnical eng./waste management)

Two Advisory Board meetings are planned. The first will take place at the kick-off workshop where the direction of the research can still be influenced. The second will be around a year from the end of the project to report and discuss preliminary results, which may influence the final analysis and presentation of results. One goal of the kick-off workshop is to facilitate strong collaboration between all partners right from the start. The kick-off workshop has been allocated specifically in the budget, and each foreign partner has been allocated funds for participating in the workshops.

Education

An important part is education and the project has 2 PhD students and 1 post-doc. These young and innovative people will be deeply integrated in the project from field work, instrument development, modelling, and dissemination of results. They will all be supervised and co-supervised by the supervisor group composed of the senior researchers. In addition to the WP activities the research students will participate in postgraduate courses. Undergraduate students will be involved in the project via MSc and BSc thesis projects.

Exchange visits between Lund and Aarhus universities are important. The research students and the post doc will spend longer periods (i.e. several weeks at a several instances) at the other university.

G. Deliverables, Reporting and Communication

Project deliverables include:

- Methodology for time and cost efficient 3D data acquisition in urban areas
- Methodology for data filtering and processing
- A prototype system optimised for 3D geoelectrical data acquisition
- 3D inversion software code for time-domain spectral IP data.
- Presentations at national and international scientific seminars, workshops and conferences
- Peer reviewed journal articles, conference proceedings, licentiate and doctorate theses.

Presentations targeting the industry will be done at national seminars and conferences, and an industry journal article. Regular reporting is handled within the project team and reference group at least 1 - 2 times / year. Progress and final reports to funders will be delivered according to stipulation.

A project web page will be set up with summary information about the project. The web page will be updated when new relevant information becomes available, for example publications and presentations.

H. References

The references can be found in the applicant’s publication lists.