PROJECT NO. 516290

SCOUT

SUSTAINABLE CONSTRUCTION OF UNDERGROUND TRANSPORT INFRASTRUCTURES

Specific Targeted Research or Innovation Project
Priority SUSTDEV-2002-3.2.2.2.6
DESIGN AND MANUFACTURE OF NEW CONSTRUCTION CONCEPTS

Publishable Final Activity Report

Date of preparation: 31/01/2007

Start date of project: 1 January 2005 Duration: 36 months

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Project Coordinator Organisation Name: SOLETANCHE BACHY

Revision: Version 0.5, March 31st; 2008
Ref SB SB.DTTAP-NOT-8.112

Publishable Final Activity Report

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1 Project execution

1.1 Summary description of project objectives

The development of the Trans-European Transport Network (TEN-T) requires the construction of many new railways or highways or waterborne connections. Underground transport infrastructures are in many cases the best option in urban centres to avoid congestion at the surface and noise impact, and in many projects the only possible option to build inter-modal connections such as links between underground stations and airports, parking lots, pedestrian access, etc.

The cut-and-cover construction method is a cost-effective alternative to tunnels, and the best option when the tunnel is relatively shallow (max depth <20m) and surface is free from buildings – a roadway for example. This method has been used since the beginning of history of subways, (Figure 1) with the following phasing of works :

1. cutting a trench from the surface,
2. building the subway tunnel in the trench,
3. backfilling the soil above the tunnel structure.

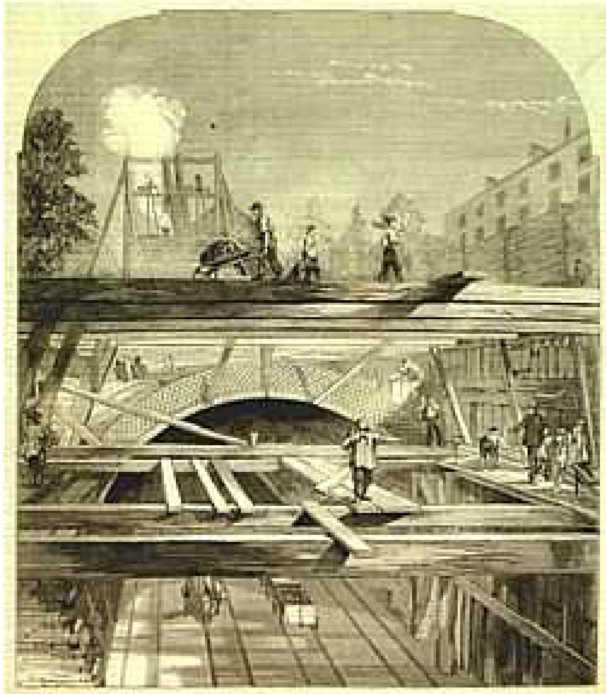

Figure 1 Construction of London subway in open cuts in the 19th century.

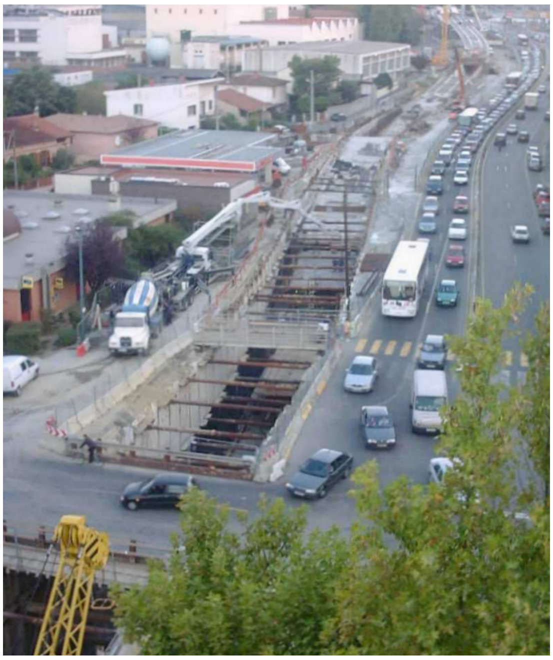

Figure 2 Construction of Toulouse Line A by cut-and-cover , 2001

The diaphragm walls technique was introduced in the 1960's. It consists into building a deep underground wall made with reinforced concrete, installed from the surface prior to any excavation. Main application is to shield deep excavations under the water table in urban sites. Applied to cut and cover method, it offers many advantages: size of the trench is minimum, diaphragm wall can be part of the final structure. But the main advantage is still to be extremely safe and to minimise soil movements on adjacent structures. On top of this, it is very industrial and economical, which justifies its broad use and a number of references in cut and cover projects (see Figure 2).

Main objective of the SCOUT project is to develop a new concept for sustainable construction of "cut-and-cover" tunnels that optimises the safety and life-cycle cost of the construction and eliminates or drastically reduces most nuisances to urban environment classically associated to construction projects: noise, dust, and large size of construction equipment causing long traffic disruption at the surface. The project uses a holistic approach characterised by three main axis of complementary innovations: design, construction equipment and materials. More precisely , main targets of the project are the following :

- Implementation of the Observational Method for a full control of construction and delays,
- Optimisation of the design leading to important savings in materials,
- A radically new construction concept of equipment, with a modular architecture to be used in a large variety of soil profiles and of tunnel configurations in urban context,
- Development and testing of new applications of composite materials to optimise the efficiency of the structure,
- Leading the way towards the recycling of excavated materials.

1.2 Contractors involved

	SOLETANCHE BACHY FRANCE (FR)
	IBDIM (PL)
	ARUP (GB)
	SANDVIK (SE)
	ECCON (AT)
	ZIPACON (RO)
	AITEMIN (ES)
	RIGA TECHNICAL UNIVERSITY (LV)
	ARMINES (FR)

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The Consortium is led by Soletanche Bachy (France). It includes 9 partners from 8 European countries (France, Poland, UK, Sweden, Austria, Romania, Spain, Latvia). It is industrially-driven, includes 2 SMEs and 3 Large Industrials – each being international leader in their own field of activity - , 3 Research Organisations and 1 University.

Organisation Name	Type	Country	Organisation's activity
Soletanche Bachy	IND	F	Contractor specialised in geotechnique
IBDiM	RES	PL	Road/ Railway research
ARUP	IND	GB	Construction Engineer
SANDVIK	IND	SE	Drilling equipment manufacturer
ECCON	SME	AT	Engineering
ZIPACON	SME	RO	Mechanical Construction
AITEMIN	RES	ES	Research on construction and mining
Riga Technical University	HES	LV	Education and Research
ARMINES	RES	F	Research on construction and mining

1.3 Work performed and end results

1.3.1 Observational Method

1.3.1.1 Project objectives

Soil heterogeneity and running ground water are in “cut-and-cover” tunnels, like in every geotechnical construction project, a permanent source of hazard, which creates a constant need to check the design parameters and to remain ready to adjust to changing conditions.

The Observational Method is a recent concept of project management that starts with a Risk Assessment Design and organises a continuous feed-back between observation of real soil conditions and critical review of design assumptions: main achievement of the method is to minimise project costs while maintaining high safety standard at all times. This method of design forms part of the design approaches recommended by EUROCODE 7 for geotechnical construction project, but it is not widely implemented.

One of the primary objectives of the SCOUT project was to develop the tools which are necessary for a systematic deployment of the Observational Method (OM) on cut-and-cover tunnels under the framework of Eurocode (EC7 for geotechnical design). The design approach using the OM has been chosen because it offers the following benefits:

- To minimise construction risks by systematic application of carefully planned construction control and
- To provide a sustainable design by design optimisation and savings in construction cost and programme.

1.3.1.2 Contractors involved

Research was lead by ARUP, contributing to most of the work, with participation of IBDiM and Soletanche Bachy.

1.3.1.3 Work performed

The design based on the OM approach is not new. Its application could be found in documents dated back to the 1940s. It was not until 1969 when Peck presented his Rankine lecture that the OM in the current form which encompasses an integrated process of design, monitoring and design modification was initiated. CIRIA 185 is the latest of a series of publications specifically targeting the application of OM in geotechnical engineering. Despite the differences in the treatment of the design and controlling process during construction in these publications, the fundamental of OM approach is to reap any potential benefits obtainable from the most likely behaviour of the structure found in an environment with many uncertainties.

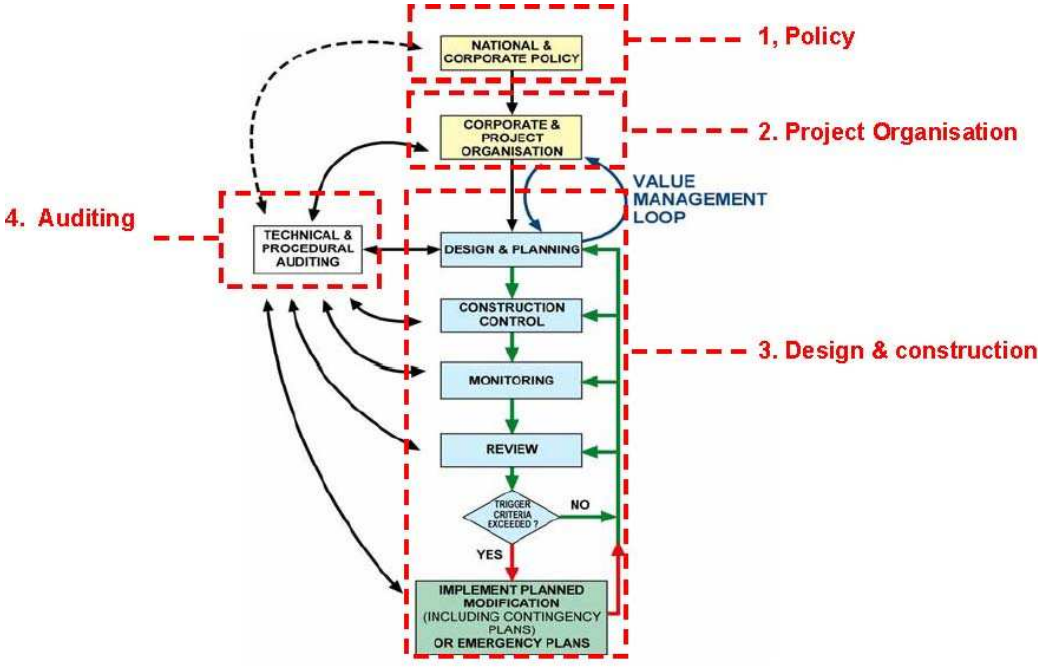

Figure 3 Four main ingredients of the Observational Method (*source : CIRIA-185)*

The main sources of reference documents used to produce this work are:

- The Observational Method in ground engineering – principles and applications. Report 185, CIRIA, London, 1999
- Eurocode 7 (EN 1997-1:2004) "Geotechnical design - Part 1: General rules"
- The Observational Method in Geotechnics, GeoTechnet Workpackage WP3, 2005

There are four main ingredients of the OM approach (Figure 3) namely:

1. national and corporate policies governing design codes
2. corporate and project organisation
3. management structure and process during design and construction stage
4. auditing

First stage of the research was to collect from the partners case histories of cut and cover tunnels for Soil Types 1 (Clay) and 2 (Sand) with adequate documentation on soil characteristics, soil movements correlated to excavation phases, etc. Attempts were also made to find and collect published examples (English, German, Polish) of cut-and-cover tunnels and other projects. However, measurements of wall performance and construction details have been found only for a limited number of projects, all of them involving excavations in Soil Type 1, i.e. stiff clay.

Figure 4 Observational Method was used for this deepest single prop excavation in London *(photo courtesy of Sir Robert McAlpine)*

Further steps of the research involved the following main aspects :

- The definition of a method to determine the “most probable” and “characteristic” sets of soil parameters for use in the OM;
- A critical review of widely-used linear elastic-plastic models and parameters;
- A back-analysis of case histories with the appropriate design tool to validate model parameters.

These allowed the use of a new framework for Observational Method fitting within EC7 requirements.

1.3.1.4 End results

Summary Major achievement of the SCOUT project :

A recommendation report has been drawn by ARUP with input from IBDiM, SOLBAC, for the implementation of the Observational Method on cut-and-cover projects. This public report is Deliverable 21 of the project, available on the project website, http://www.soletanche-bachy.com/scout.

This result is in line with project objective to prepare the way to a widespread use of the Observational Method in cut-and-cover projects.

1.3.2 Design Optimisation

1.3.2.1 Project objectives

All components of the cut and cover structure are closely interconnected, so that its optimisation must consider the phasing of construction works (drilling, material placement, reinforcement placement, concrete hardening, and service), the interaction between geotechnical design and structural design, and must satisfy multiple target criteria such as durability, strength, concrete rheological characteristics, strength, and costs. More practically, objective of the project was to explore new approach of the design to enable substantial savings in materials consumption.

1.3.2.2 Contractors involved

Research was led by ARUP, with support of IBDiM, RTU and SOLBAC

1.3.2.3 Work performed

Research on the development of fibre reinforced concrete revealed more difficult and time consuming than anticipated at the beginning of the project. Therefore, potential savings from this technology could not be integrated in this research on design optimisation.

The following aspects of design were considered:

- the analytical model;
- existing crack width requirements, especially in respect to their influence on cost, water ingress and the corrosion of both bar and steel fibre reinforcement;
- the benefits and disadvantages of including non-metallic fibres, water-stops, crack inducers and drains;
- bending moment continuity between walls and slabs;
- provision of haunches to aid arch action in slabs;
- beneficial effects of axial load in the slabs;
- horizontal bending moment continuity.

Precast reinforced concrete, reinforced concrete with conventional steel bars/steel sections and fibre reinforced concrete were also considered. Both single skin and double skin walls were considered in the studies. Consideration was also given to the different loading conditions for double skin wall, during construction and in the long term.

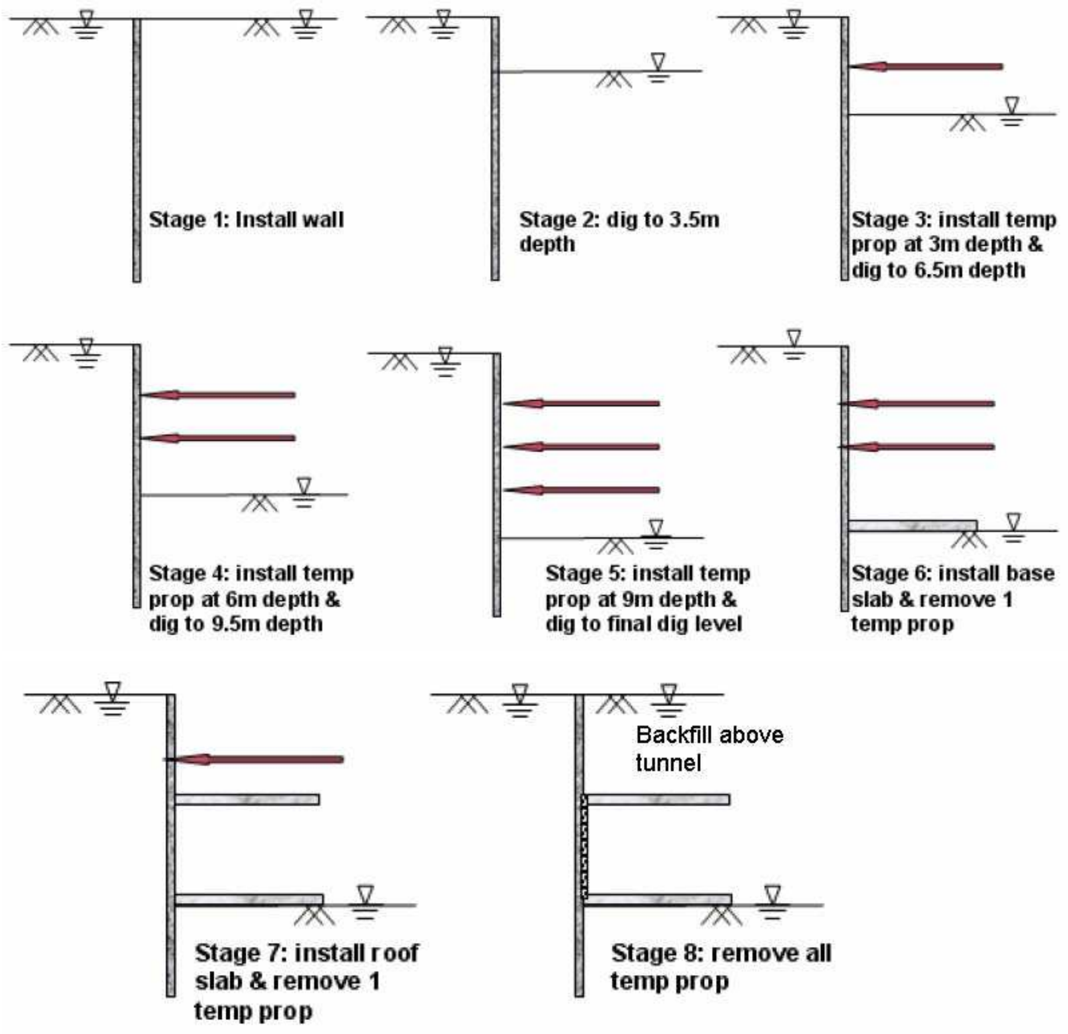

Figure 5 Typical construction sequence of the cut-and-cover structure

1.3.2.4 End results

The design optimisation assessments undertaken in the analysis of the cut-and-cover retaining structure have shown that substantial savings can be obtained when one or a combination of the following design approach is adopted:

- The use of more complex finite element design approach;
- Use a variable bending stiffness approach instead of constant stiffness approach in the design of the retaining wall;
- Allow less stringent or even no crack width consideration and properly advise the owner /client of the watertightness and aesthetic issues;
- Use more efficient structural form to encourage arching to reduce the amount of reinforcement.

The optimisation assessments show that a saving of material cost of more than 15% could be achieved based on comparison using conventional reinforced concrete, since fibre reinforced concrete has not yet been sufficiently developed.

Summary Major achievement of the SCOUT project :

Research by ARUP with input from IBDiM, SOLBAC and RTU was mainly focussing on the issues of - crack width considerations and their influence on the design;
- composite action of the double-skin design;
- using structure elements with variable bending stiffness.

Combinations of these issues are leading to savings in construction materials costs higher than 15% with conventional reinforced concrete, and in line with project objectives. These concepts have been applied already for a major construction project in UK worth £ 1,6 bn.

They are reported in Deliverable 20, a public recommendations report available on the project website, http://www.soletanche-bachy.com/scout.

1.3.3 NEW CONSTRUCTION METHOD

1.3.3.1 Project objectives

Main objective of the SCOUT project is to introduce and validate a radically new construction concept of tunnel walls where the drilling process is continuous and horizontal, in order to minimise environmental impact and optimise the safety of the construction process.

This is a breakthrough concept compared to existing techniques for the construction of the so-called 'diaphragm walls', with two major drawbacks:

- It is based on a complex sequence of primary and secondary wall panels, source of many logistic problems : multiple movements of heavy equipment on the working platform;
- The drilling process needs a bentonite mud, that pollutes excavated soil and turns it into a waste, becoming always more difficult to treat and dispose of.

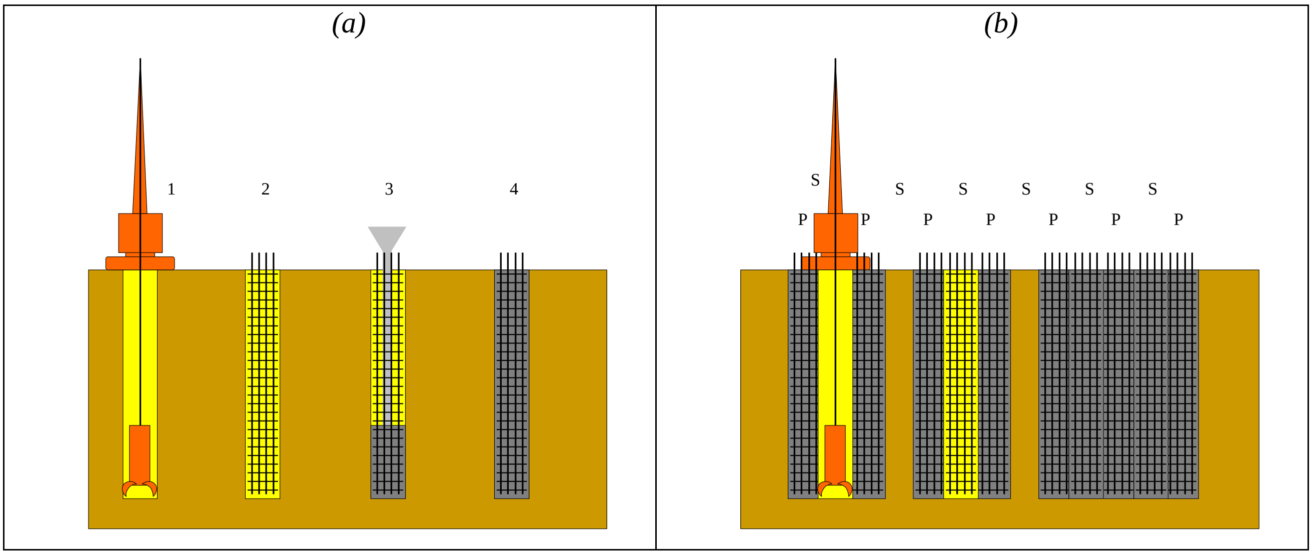

Figure 6 Classical construction sequence of tunnel walls : (a) (1) excavating the trench under drilling mud, (2) installation of the steel reinforcement, (3) concreting under the mud by means of a tremie pipe , (4) finished wall segment ; (b) construction of a continuous wall by an alternate sequence of primary panels (P) and secondary panels (S) interlocking between the primaries.

1.3.3.2 Contractors involved

Involved contractors were SOLBAC, ECCON, ZIPACON, SANDVIK, ARMINES, AITEMIN.

1.3.3.3 Work performed

1.3.3.3.1 Development of the new construction concept

The new construction concept was developed around a modular architecture, in two parts :

- first part of the machine was designed and built by SOLBAC;
- second part of the machine was designed by ECCON and built by ZIPACON.

ARMINES provided a very important support by developing numerical models and executing lab tests supporting the design of the new equipment. Main fields of investigation have been the efficiency of soil cutting tools, the capacity of the machine to evacuate soil cuttings to the surface, the capacity of the machine to build curved walls, etc.

SANDVIK provided advice on the choice of the cutting tools, and made new development :

- design of a new cutting tool, the 'reversible' pick, that can be used on a cutting drum rotating in two opposite directions;
- SANDVIK's current lines of products are optimised to cut through hard rock whereas geotechnical construction uses cutting tools to cut through various types of soils (in presence of groundwater, alternating soft soils with boulders, etc). A specific study was led to optimise the choice of materials to this specific case of geotechnical works.

A prototype of the new equipment was built, with the capacity to build walls to depth 8 m. A validation site was organised in SOLBAC's yard, demonstrating the interest of the concept and providing evidence of its capacity to reach the production objectives assigned at the beginning of the project.

Development of this new construction concept is now continuing, which explains why details of the research remain confidential. SOLBAC, is currently developing the concept to make it industrial and compatible with deep foundations projects (objective : 20 m deep walls).

1.3.3.3.2 Control of concrete placing

Accurate control of concrete placing is a requirement in the new equipment. Research by AITEMIN was devoted on this aspect of the construction process. It involved the following main aspects :

- Assessment of the feasibility of fiber concrete pumping
- Development and validation of an automated system to be installed on commercial concrete pumps, with the capacity to accurately control the volume and flowrate of concrete.

This control unit was targeting the new equipment developed in the SCOUT project, but it can be used for many other types of construction processes using concrete pumps.

1.3.3.4 End results

Main objectives of the project have been reached:

- Development and validation of a breakthrough concept for the construction of underground walls. Impact of this development is very important, but will be effective when it has reached industrial stage of exploitation; it will impact the way underground infrastructure can be integrated into a crowded urban context. It must be noted here that, like construction products, most construction processes have a very long life span: 50-100 years and more

being a normal range. For example, the diaphragm walls system – targeted by the SCOUT project – traces its origin in the 1960's. This explains why development cycles are so long, but also bring prolonged benefit to the industry;
- Development of a new cutting tool and improvement of existing cutting tools for the excavation of soils;
- Development and validation of a new control system to control the volume of concrete. This new development is readily available for exploitation.

Summary Major achievement of the SCOUT project :

A breakthrough concept for the construction of tunnel walls was developed with the objective of building at least 20 m deep walls. A first prototype 8m deep was designed, built and validated on a trial site in SOLBAC's yard, in Montereau (France).

The trial site validated the concept of the new construction equipment. Research is continuing after this project to further industrialise the concept, with the objective of a pre-industrial 20m deep prototype.

Summary Major achievement of the SCOUT project :

A new electronic control system was developed by AITEMIN with the objective to provide a precise real-time control of concrete volume and flow rate on concrete pumps.
This system was validated and is now available for commercial use, either as a complete unit or as a kit.

1.3.4 Composite concrete

1.3.4.1 Project objectives

There was so far little research done on the implementation of new composite materials (fibre concrete) for underground "cut-and-cover" construction. "Cut-and-cover" tunnels built under the proposed method offer several opportunities for using these materials, as they will mix temporary and permanent structures. Objective of the project was therefore to investigate in a systematic way how composite materials can be used in both temporary and permanent structure members, so as to establish the basis for optimisation of the whole structure.

1.3.4.2 Contractors involved

Research on fiber concrete development was led by RTU, with support by IBDiM, ARUP, SOLBAC. It was concluded by full scale tests performed by IBDiM in their Zmigrod test site.

1.3.4.3 Work performed

Research performed was to investigate the possibility to replace (wholly or partially) conventional concrete reinforced by steel bars, by fiber reinforced concrete (fiberconcrete), without or with additional reinforcement by metallic, non-metallic or mixed (metallic and non-metallic) components.

First step was a comprehensive investigation of the state of the art for concrete constructions with non-traditional reinforcement based on modern composite materials use. Then most activity was to obtain steel fibre reinforced concrete (SFRC) with enough tensile strength to make an attractive constructive material for the new construction process developed by SCOUT.

Main selection criteria for the material to be developed were:

- The capacity to carry very high applied external loads, as required by the cut-and-cover structure;
- A very high workability, necessary to cast the concrete in the deep walls;
- An affordable price.

Classical formulations of SFRC, using a concrete matrix with compressive strength 50-110MPa and ‘classical’ fibre amounts (60-120kg/m^3) were the starting point of investigation, but it became clear from the first steps that necessary amount of fibres would be much higher.

Comprehensive and detailed research was undertaken to investigate SFRCs with fibre amounts from 100kg/m^3 to 400kg/m^3:

- More than 80 mixes of SFRC were elaborated and tested with multiple combinations of concrete matrix, selections of fibres types and fibre cocktails ;
- Full scale concrete pumping tests were organized in Spain by AITEMIN and in Latvia by RTU;
- New testing equipment was elaborated for the determination on site of SFRC rheological parameters;
- Numerical models have been developed
  - o to simulate the flow of SFRC in the trench
  - o to simulate the fracture mechanism of SFRC and to better understand the interaction between fibres of various shapes and resistance with concrete matrix.

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Figure 7. Fiberconcrete pumping tests in Ribera de la Folgoso (with 120kg/m3 steel fibers).

Figure 8. Fiberconcrete pumping test in Riga (with 160kg/m3 steel fibers).

This research provided considerable amount of know-how on SFRC with extreme content of fibres – up to 400kg/m^3- on the way to prepare it, on the performance of various fibre cocktails. Pumping tests in Latvia have shown the possibility to pump SFRC with fibre content up to 160 kg/m^3.

Research conducted by RTU was assessed by testing only small samples of materials. A second stage of the research was to verify the resistance of medium scale beams (dimensions 0,3 x 0,3 x 3,0 m) and large scale beams (dimensions 0,6 x 0,6 x 5,1 m). These tests have been performed by IBDiM. Two SFRC mixes have been tested, with fibre contents 200 kg/m^3 and 300 kg/m^3 respectively. These tests provided an assessment of the workability and real strength properties of high resistance SFRC.

1.3.4.4 End results

Research undertaken in this project brings a significant progress on SFRC from state of the art :

- Quantified influence of the various design parameters (resistance of concrete matrix, composition of fibre cocktail);
- On the preparation process of high resistance SFRC, on its pumpability;
- On the scaling factors that are required to extrapolate results of small scale tests in the lab to full-scale structure;
- Numerical models calibrated on lab tests and on full-scale tests.

However, the research has shown that high resistance requirements of the project are leading to extreme fibre content SFRC, and to non competitive costs. Therefore further research is needed to improve the tensile resistance and improve the economy of this material.

Summary Major achievement of the SCOUT project :

The very high resistance requirements of the project induced RTU to perform an investigation of behaviour of Steel Fiber Reinforced Concrete (SFRC) with extremely high concentrations of fibres (up to 400 kg/m^3), that was validated by full scale beams tested by IBDiM.
Major achievement of the project in this domain is a better understanding of SFRC at this high level of fibre content, supported by lab tests, numerical models, full scale tests.

1.3.5 Materials Recycling

1.3.5.1 Project objectives

The future European thematic strategy on the prevention and recycling of waste will oblige the construction industry to systematically consider waste recycling in the near future. Objective of the project was to address this future requirement and to consider recycling excavated soil as a construction material during the construction process.

1.3.5.2 Contractors involved

Involved contractors were AITEMIN, with support of RTU.

1.3.5.3 Work performed

Research started by a state of the art on materials recycling on tunnelling sites, which show many similarities with the cut-and-cover process.

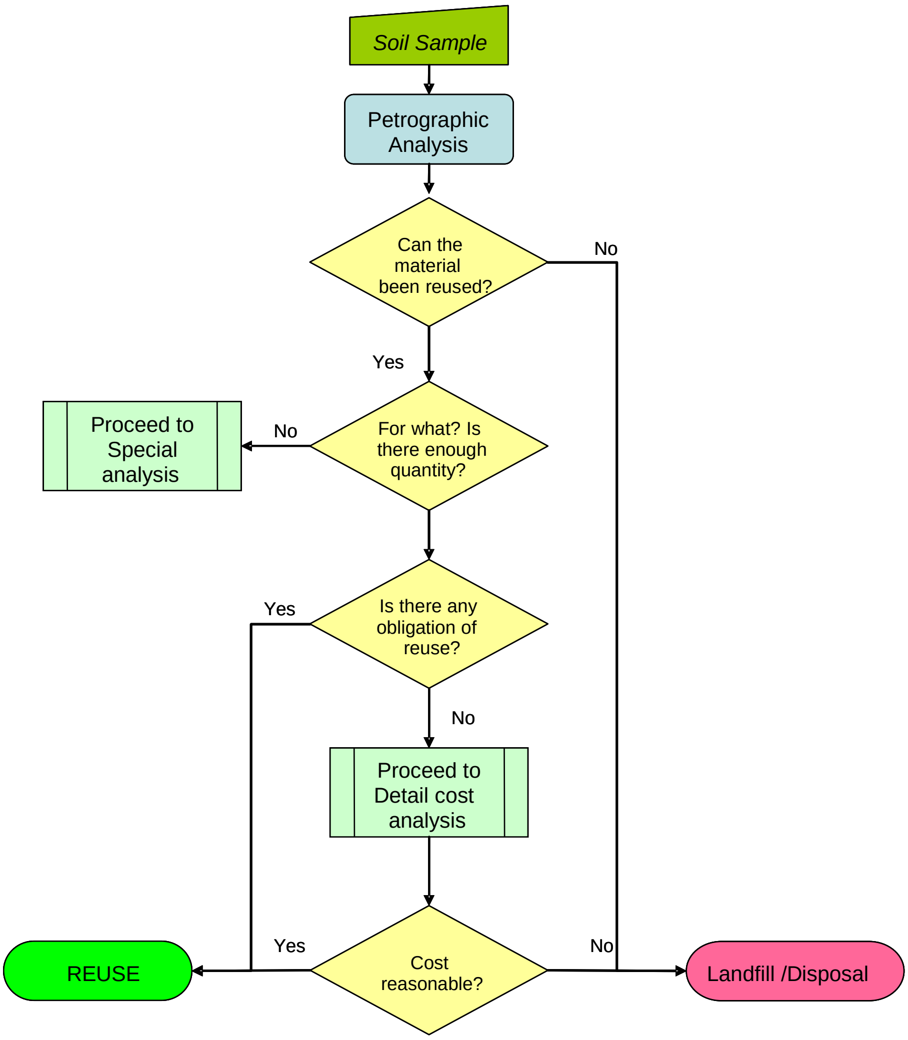

Figure 9 Soil recycling decision tree

It was found that, in most cases, the possible uses of excavated materials are somehow limited by the quality of the soils in which the SCOUT machine can operate. Currently, only hard rock excavation debris are reused as aggregates, and only when quality is excellent. Soils are usually disposed in dumping areas, and at most, used in embankments. Most of excavated volume must be anticipated of low-quality. Therefore, work was mostly focussing on reuse possibilities for "soil type" debris, using the following approach:

- Identifying the types of debris that may be generated, and identifying the possible use of each one;
- Identifying the tests needed for assessing the suitability of a given debris for each possible use;
- Identifying the processing plant needed in each case;
- Identifying other constraints affecting reuse possibilities;
- Giving guidelines for assigning a "cost" to the above factors;

This development led to production of guidelines for performing an assessment of reuse feasibility based on a systematic financial (cost/profit) approach.

Second step was to consider the multiple factors influencing the feasibility of recycling excavated materials : soil characteristics - standards and codes - local regulations - jobsite logistics (availability of space, of local aggregate plants, etc) – cost of plant equipment related to recycling process – potential presence of pollutants requiring specific treatment - etc.

The main conclusion extracted from the work carried out is that the possibilities of reuse depend on so many factors -both intrinsic and extrinsic- that no general statement can be made "a priori" on this issue. Therefore a specific analysis has to be made on a "case by case" or "job by job" basis.
Full details are presented in D16 and D22.

1.3.5.4 End results

Main conclusion from this work carried out is that the possibilities of reuse depend on so many factors -both intrinsic and extrinsic- that no general statement can be made "a priori"; a specific analysis has to be made on a "case by case" or "job by job" basis.
This result is on line with project expectations, that were mostly to prepare the way for a future reuse of excavated materials.

Summary Major achievement of the SCOUT project :
Investigations were carried by AITEMIN on the possible ways to recycle the excavated materials and led to a synthesis report, Deliverable 22 of the project, available on the project website, http://www.soletanche-bachy.com/scout.

1.4 Project logo

1.5 Reference to the project website.

URL of project web site is : http://www.soletanche-bachy.com/scout

2 Dissemination and use

Dissemination of project results has taken the following forms:

- Publication of project flyers;
- Publication of project reports, mostly via the project website;
- Publication of technical papers covering selected subjects to conferences and in specialised reviews.

The set of SCOUT Project flyers consist of five posters:

- Presentation of the whole project,
- Optimisation of Design,
- Observational Method
- Composite materials
- Materials recycling

The posters have been printed by IBDIM (1000 copies of each) and supplied to the partners in required number of copies. They have also been posted at the SCOUT Project website. The partners will use them accordingly to their needs.

IBDiM prepared also 3 SCOUT Project flyers in Polish for dissemination among Polish scientists and engineers.

The following project reports have been made public, through the project website (www.soletanche-bachy.com/scout) :

- (by ARUP) D20 Design guide to 'cut and cover' tunnels.
- (by ARUP) D21 Final guide on the Observational Method for Cut and Cover Tunnels
- (by AITEMIN) D22 Final Roadmap on Recycling Materials

The following publications have been published :

- 26/6/2006 EUROPEAN PARLIAMENT MAGAZINE – issue 277, 26 June 2006, (1 page)
- 7/2006 FP6 Surface Transport Research Synopses
- 21/11/2006 Poster at the 2nd Plenary Assembly of the European Construction Technology Platform
- 20/11/2007 Poster at the 3rd Plenary Assembly of the European Construction Technology Platform

Publications by RTU :

- Internal Thesis presentations, Riga Technical University

Publications by ARUP :

- D. Patel, D. Nicholson, N. Huybrechts, J. Maertens : The observational method in geotechnics., *XIV European Conf. on Soil Mechanics and Geotechnical Engineering, Madrid, 24 -27 September 2007*
- Hoe-Chian Yeow, Ian Feltham : Case histories back analyses for the application of the Observational Method under Eurocodes for the SCOUT project, *6th International Conf. on Case Histories in Geotechnical Engineering, Arlington, VA, August 11-16, 2008*