Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds)

Circular economy and reuse of excavated materials from TBM excavations

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ABSTRACT: The management of excavated materials is one of the major issues for tunnelling projects from environmental, logistical, administrative and economical point of views. Despite the extreme importance of the topic and the huge volumes of materials produced in the context of major works, the excavated materials are too often considered as a waste and therefore their reuse is not a widely established practice. Webuild and GEEG have launched a research activity aimed at developing an integrated management system for excavated soils that involved numerous real tunnelling projects in Italy and abroad and a relevant number of different reuse modality, from the most common, as the morphological re-profiling, up to innovative uses with high added value. This paper, after a general introduction to the topic, intends to provide an overall description of the WE CYCLE Project and an update of the experimental evidences collected on the applicability of several methods of reuse of different soil typologies.

1 GENERAL INTRODUCTION

1.1 *The sustainable development goals and underground excavation*

The United Nations Sustainable Development Goals (SDGs) directly and indirectly involve the underground space and the land and soil management and it is widely recognized that several SDGs cannot be achieved without achieving healthy soils, sustainable land use and soil re-use, as described in Figure 1. Tunnelling and underground works generates high volume of soil and rocks often of good mechanical properties which should be managed to contribute to the SDGs, enhancing the territory, favoring ecosystem remediation and improvement, promoting circular economy solution.

For Webuild Sustainability is not only related to the project under construction but also to the way to plan in the future since the preliminary design phase the material balance (quantity and quality of excavated material and its re-use on or off site) allows to identify the best scenario maximizing the possible soil reuse on- and off-site considering the ecosystem environmental characteristics, timing, logistics and the stakeholder expectations.

GEEG, as a Research body, has as its mission the support of Engineering Companies and Contractors in the development of innovative and sustainable processes through the development of experimental activities.

Thus, the WE CYCLE project represents the desire to share the specific strengths of the two entities to promote innovative solutions in one of the key areas for sustainability and circularity of processes in tunnel excavation.

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1.2 *The management of soils and rocks from TBM excavation*

In the last few decades the underground world has seen an increasing use of mechanized excavation modes thanks to the development of increasingly versatile and high-performance TBMs.

This has enabled the development of bolder and more complex projects (Pirone et al., 2018) and, in general, an increase in the use of underground space for infrastructure use. Not only more cubic meters of excavation to be managed on site but also more rocks and soils with different geomechanical characteristics to be relocated off-site (Miliziano et al., 2016; Haas et al. 2020 and 2021).

Figure 1. Sustainable development goals (SDGs) for 2030 (www.eea.europa.eu).

The situation gets more complicated when using EPB TBMs – the most popular since its range of application has increased significantly with the development of new technologies and methods/products of conditioning – because of the need to use conditioning agents mixed to the excavated material and its environmental implications (Pirone et al., 2018).

Therefore, a virtuous process of reusing soils and rocks from excavation possesses a number of elements briefly described in the table below:

In extreme summary though there is an increasing desire and need to reuse soils and rocks from excavation (Magnusson et al., 2015), this desire often runs up against a number of complexities and constraints of various kinds that greatly limit actual reuse (Simion et al., 2013). In order to overcome these limitations and unlock the real potential for reuse of these natural resources, Webuild and GEEG developed the We Cycle project.

Table 1. Different elements of innovation of reusing soils and rocks.

Legislation	Legislation open to encouraging circular reuse of non-renewable natural materials and processes and timelines appropriate to the project development requirements
Client motivation	The topic of spoil management sometimes is underestimated, neglected and/or approached too late. Thus, a motivated Client to handle the issue of spoil management plant and elaboration of a spoil management concept in the very beginning phases of the project is fundamental.
Quantification & Qualification	A careful preliminary quantification (cubic meter) and qualification (geomechanical and chemical characteristics) of the material to be excavated is the basis for a good planning.
Good planning	In terms of space, time and procedures. To manage smoothly a huge volume of material the contractor has to: have foreesn and organized the necessary space on site to stockpile and biodegrade the material in a certain known time; studied the right cycle of trucks to take away the material from the primary storage area; have set a solid procedure for all tests and logistic matters.
Economy vs Ecology	All economical evaluations in the management of the spoil have to be made with respect of environment. Forms of motive power must be created, which are not damaging to health and which are of such a kind that we can deal with the relevant waste, recycle materials and compete by means of environmentally friendly and fuel-efficient cars. Transport, energy, CO2 production have to be evaluated to achieve the right balance between project's economy and environment's respect.
Innovative solution	Excavated material have often good chemical/physical/mechanical characteristics and thus they would be suitable for different use either on site that off-site. Nowadays, the management and the ways of re-use adopted are limited to application of low added value, example re-profiling or disused quarries. The investigation and use of cutting-edge technologies to reuse excavated materials and development of new eco-compatible products and processes is one of the future and key point for a successful management of the spoil in a circular economy approach.
Design of excavation methodologies, chemicals and materials to be used	The choice of excavation methodologies and, consequently, of treatments and the materials and chemicals to be used has a major effect in the possibility of reusing excavated material but also the administrative process required to approve it
Optimization of spoil	Optimization of the TBM excavation diameter to a minimum admissible by the project requirement allow to reduce the quantity of material to be managed. A proper design of the cutterhead and TBM allow to produce chips/materials of more suitable dimensions.
Logistical feasibility	The enormous volumes of soils and rocks require the utmost attention to logistical aspects that become crucial to avoid protracted delays or issues related to transportation or site area availability
Community and local government support	Reuse of soils and rocks often has logistical and practical impacts in local governments with respect to site location. The ability to consider circular economy processes, industry synergies, and collaborations between agencies and stakeholders is a crucial element in the success of a project

2 THE WE CYCLE PROJECT

2.1 *Aims and methodology*

The objectives of the We Cycle project can be synthesised as follows:

- setting up the study of conditioning and the geotechnical, logistical, environmental and economic implications in an innovative, systematic and integrated manner by means of a multidisciplinary and transversal approach to mechanised tunnel excavation projects;
- develop Research and Innovation activities in the exploration of new and more virtuous ways of reusing excavated soil and rocks in circular economy processes, in support of the territory or within existing production cycles;
- the identification and development of innovative control procedures and methods that, through rapid tests, process optimisation, organised and procedural changes, make it possible to reduce the time required for geotechnical and environmental investigations during the operational phases;
- objectively evaluate the pros and cons of each solution for the re-use of excavated earth and rocks from a technical, logistical, economic, administrative and environmental point of view in order to provide the most convenient and virtuous reuse methods for each project.

2.2 *Framework*

The activity was developed according to a series of phases described below.

An initial activity of analysis of the existing bibliography allowed the development of a continuously updated database of tunnel projects realised in Italy and abroad, containing:

- geological/geotechnical characterisation;
- design geometries and volumes of excavated soil and rock produced;
- technologies used for excavation;
- planned methods of use and verifications/controls performed;
- reference regulations.

This screening provided a broad and clear picture of the state of the art, which, combined with a study of potential alternatives for the reuse of excavated soil and rocks, led to the definition of 3 classes of reuse modes, that we will see in 3.1. The research activity involved a significant experimental activity for each reuse method considered on the basis of the actual need to acquire quantitative elements useful for evaluating technical and economic feasibility and compatibility with the current set of laws and regulations.

The project also included specific studies on the management of water on site and the management of treatment plants.

Finally, the project included an analysis of the sampling and analysis methods, both geotechnical and environmental (chemical and ecotoxicological), and the validation of a series of innovative methodologies capable of bringing significant advantages in terms of monitoring speed and accuracy.

3 DEVELOPMENT AND PRELIMINARY RESULTS

3.1 *The reuse modalities*

The bibliographic analysis carried out during the first phase of the Project made it possible to study in detail which reuse methods are widely considered and how often they are used.

The project analysed were 34 and have shown, as mentioned in the previous paragraphs, that the most frequently used reuse methods are those of Group 1, in detail 23 morphological reprofiling and 5 embankments.

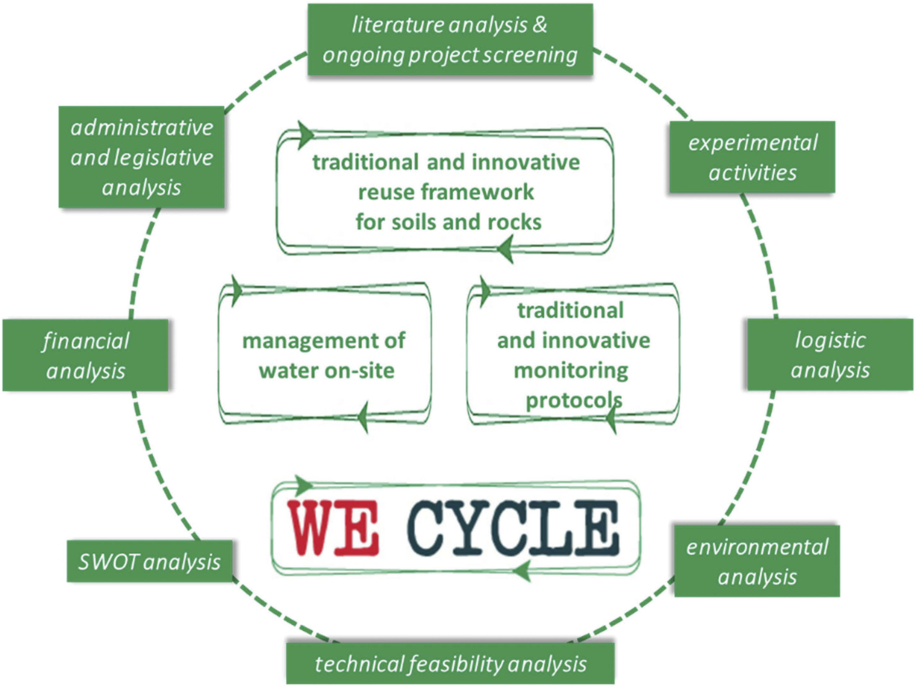


Figure 2. Framework of the WE CYCLE research project.

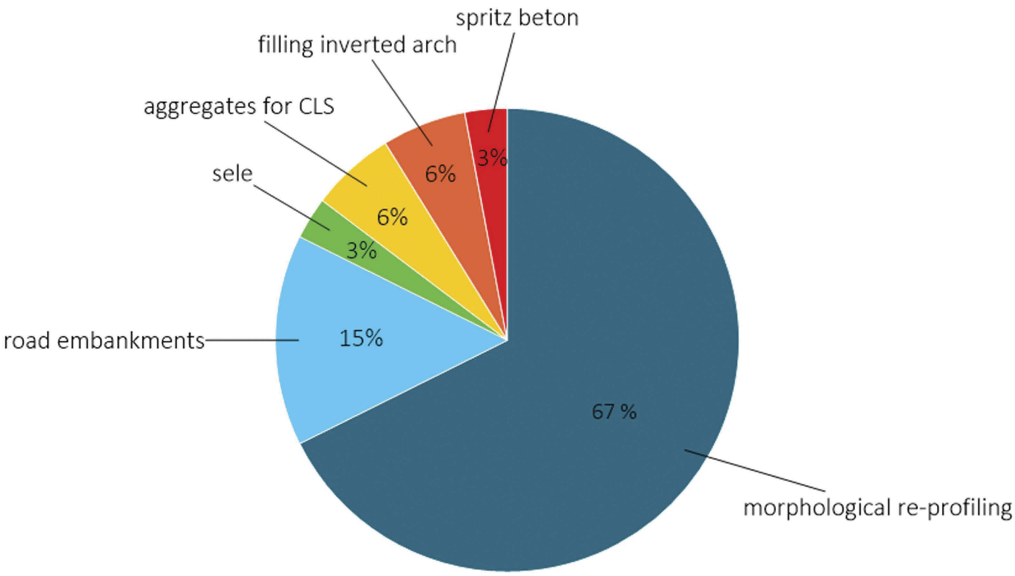


Figure 3. Results of bibliographic analysis, different reuse from tunneling project.

One of the activities developed downstream from the study of data acquisition from existing projects in Italy and abroad was to make a list of possible reuse for soil from excavations by dividing them into three categories (Table 2):

– Group 1: conventional modes of reuse characterised by low added value, extensive guarantees of technical feasibility, verified compatibility with the current set of laws and regulations and limited level of innovation;
– Group 2: reutilisation methods that have already been tested sporadically, are characterised by a certain added value, moderate guarantees of technical feasibility, overall good compatibility with the current set of laws and regulations and a good level of innovation;
– Group 3: rarely/never applied re-use methods characterised by a high potential added value, a number of aspects to be clarified regarding technical feasibility and compatibility with the current set of laws and regulations, and a high level of innovation.

The reuse modalities included in Group 1 are currently the most widely used in tunnelling projects and allow the reutilisation of large volumes of soil, as well as enabling the reuse of a wide range of soils/rock. In order to be able to reuse the excavated soil for the individual uses, design requirements must be guaranteed and adhered to, which in the case of Group 1 modes, are not particularly restrictive, which is also why the choice of reuse mode in many projects falls into this category.

In Group 2 we find several modes often employed within tunnel projects (or infrastructure projects in general) which, unlike the previous group, are aimed at fractioning the excavated volumes, they are in fact aimed at soils with particular geotechnical/ mineralogical and chemical characteristics.

The last Group 3 includes those modalities that have not yet been studied, tested and explored in depth, including the use of excavated soil as raw materials for the production of cement, re-use to make unfired earth bricks or the production of geopolymers.

Table 2. Classification of reuses of soils from tunneling.

Group 1	Group 2	Group 3
fillings quarries morphological re-profiling road embankments	aggregate/filler road pavements pea gravel	filler for backfilling grout cement production bricks and geopolymers

3.2 *Materials studied*

In order to acquire data and information on how to manage excavated soil and rock belonging to different lithologies, the research activity was developed by using samples of soil and rock from 22 different geological/geotechnical formations affected by the construction of tunnels and underground works in 8 major infrastructure projects in Italy and abroad.

The analysis of these formations made it possible to acquire, where possible:

– geotechnical characterisation (grain sizes, Atterberg limits, specific weight of grains, . . .)
– mineralogical composition by diffractometric analysis;
– chemical composition by fluorescence analysis;
– grain morphology (for sands and gravels) by process-imaging and electron microscopy;
– range of water content, void index (sands/gravels) and texture (clays/loams);
– range of characteristic conditioning parameters (WIR, Cf, FER, FIR, Tr, . . .).

3.3 *Activities performed*

3.3.1 *Group 1*

Regarding the reuse methods included in Group 1, as mentioned above, these are fairly well-established methodologies (Zuo et al., 2013) that do not require particular research developments to be applied. consequently, it was decided to analyze, in this case, only the most relevant elements in terms of (i) void index (extremely important for knowing volume changes due to the excavation process and subsequent in situ compaction processes); (ii) deformability and strength characteristics; (iii) treatment needs; and (iv) potential fit with respect to general civil engineering classification systems.

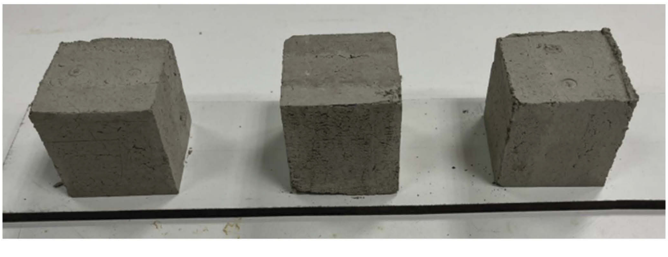
3.3.2 *Group 2*

Regarding all the reuse modes included in Group 2, these are modes that have some common elements related to the importance of grain size, mineralogy, and morphology of the grains of which they are composed. In addition to these elements, some experimental activities were developed in order to quantify the maximum reuse rates for each of the available soils and rocks and each of the reuse modes in order to be able to have quantitative elements to be included in the subsequent economic and logistic analyses.

3.3.3 *Group 3*

Finally, in group 3 are collected the reuse modes that required a higher experimental effort to acquire the necessary elements to make some technical and economic evaluations, as:

1) The Research activity aimed to evaluate a possible inclusion in the mix design of backfilling grouts portions of the soil excavated during drilling included several tests carried out on different mix designs of the two-component mortar at varying i) mineralogical characteristics of the soils used and ii) the percentage of filler in the mix design. Evaluations were made on the needs to rearrange the other components in order to achieve the proper features on fresh and hardened grouts and about the influence of fillers in strength, stiffness or durability Figure 1.
2) On the possibility of reusing part of the soil volumes produced by the excavation of tunnels in building materials as bricks, tiles, panels or plasters with relevant benefits from economical and environmental point of view several laboratory tests were performed on different mix design, compose of clay – sand – cement – water and including fibers at different curing time (7 – 14 – 28 days).
3) On the possibility of reusing part of soils and rocks as raw material for cement production, dedicated tests were performed. Cement is one of the most important and traded building materials worldwide; for its production, synthesising a complex and articulated production process, three phases can be identified: *i*) crushing the raw materials; *ii*) *clinker* production and *iii*) mixing and final crushing. The effectiveness of the process, and consequently the focus of the experimental tests, depends on the chemical composition of the raw materials and on several parameters of the process such as the thermic treatment (i.e. max temperature and cycle duration).



a)

b)

Figure 4. a) samples backfill grout; b) samples of raw-soil bricks.

3.4 *The management of water on-site*

During the construction of a tunnel, wastewater may originate from the drainage behind the excavation, from the collection of rainwater and the discharge of industrial water serving the works. The runoff water from the excavated material spoil will have quality characteristics that are conditioned by the substances used for excavation, consequently the more eco-friendly these substances are, the less effort required for purification, both in terms of time and type of treatment.

Wastewater must be subjected to adequate purification processes that allow it to be reused on site and discharged into the receiving body afterwards.

On-site reuse responds to the logic of the circular economy and mitigates the site's impact on the territory by reducing the need to supply new volumes of water.

The purification systems must be designed and modulated to make the purification process efficient and guarantee the quality of the water to be reused and/or discharged. The more effective and efficient this process is, the greater the volumes of water re-used, the more adequate the quality of the water leaving the treatment plant (in terms of residual concentration of pollutants based on the expected use), the shorter the timescales of the various phases: water analysis, water treatment, discharge. The project is exploring the possibility of increasing the automation of treatment plant through the analyses of the correlation between treatment and pollutant reduction and the possibility to distinguish the features of the treatment plant to better face the different chemical composition of the water with specific references to the residual surfactants related to soil conditioning process in EPB-TBM.

3.5 *Controls and test protocols*

A key aspect of the proper management of excavated materials on site is a calibrated and effective monitoring and control program. Alongside new ways of managing soils and rocks, equally efficient ways of monitoring their geotechnical and chemical/environmental characteristics are needed (Sebastiani et al., 2019). In recent years technological development has also made available increasingly advanced and powerful tools and methodologies (Bavasso et al., 2020) capable of being interconnected with other monitoring tools. To evaluate whether the residual foaming agents used during drilling processes produce significant eco-toxicological effects into the soil, it is necessary to provide specific protocols to validate the effective reuse of the conditioned material.

The WeCycle project also included an analysis of traditional monitoring procedures and an analysis of possible integrations with advanced technological tools potentially capable of acquiring more analyses on more representative samples in a short time frame and directly on site. Analyses were initiated to correlate the results of chemical and ecotoxicological analyses in order to define limit values with regard to the total amount of surfactants in the soil. This comparison should be seen as an additional tool for the evaluation and interpretation of eco-toxicological results, which now form the basis for subsequent optimizations.

4 CONCLUSIONS AND FUTURE DEVELOPMENTS

The WeCycle project, developed by Webuild and GEEG was initiated for the purpose of approaching the topic of mechanized tunnel excavation management and the management of soils and rocks from excavation in a unified and multidisciplinary way by fostering innovative, green, and circular modes of management, use, and control.

The project, which is still in progress, involved a relevant number of real gallery projects in Italy and abroad that involved the analysis of over 22 different geological/geotechnical formations from several major infrastructure projects of tunnels and underground works.

The research activities developed have made it possible to quantify the importance of some important parameters for more traditional modes of reuse. On the other hand, it has allowed to verify the feasibility of some reuse modes less known in the literature, allowing to acquire quantitative data on the most relevant parameters regarding economic, logistical and environmental implications. In the continuation of the Research project, some of the most promising ways to manage, treat and reuse on-site soils and rocks from excavation and water and some ways to analyze and monitor geotechnical and environmental characteristics will be validated in real TBM tunnelling projects. The belief is that the results will enable the introduction of guidance and best practices on virtuous reuse of soils and rocks from excavation with a view to reducing emissions and environmental impacts in mechanized tunnel excavation.

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