Interreg
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NWE-REGENERATIS
European Regional Development Fund

# D. T1.3.2. Benchmark report on excavation technics for potential resource extraction for reuse, on a PMSD

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Laurie Lommel , Renaud De Rijdt,
Laura Lamair, Iqra Aziz

*Atrasol*

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# SUMMARY

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# Acronyms

AAS: Atomic Absorption Spectroscopy
BOFS: Basic oxygen furnace slag
EAFS: Electric arc furnace slag
EDS: Energy-Dispersive X-ray Spectroscopy, used in conjunction with SEM
EMI: Electro-Magnetic Induction
EPMA: Electron Probe Micro-Analyser
ERT: Electrical-resistance Tomography
GPR: Ground-Penetrating Radar
GSI: Geological Strength index
IPCC system: In-Pit Crushing and Conveying system
IR: Infrared spectroscopy
LIBS: Laser-Induced Breakdown Spectroscopy
LFS: Ladle furnace slag
LOM: Light Optical Microscopy
MS: Mass Spectroscopy
NIR: Near-Infrared
OES: Atomic Emission Spectroscopy
PCS : Potentially Contaminated Sites
PMSD : Post Metallurgical Sites and Deposits
RFID: Radio frequency identification
REE: Rare earth elements
REGENERATIS: Regeneration of Past Metallurgical Sites and Deposits through innovative circularity for raw materials
SEM: Scanning Electron Microscopy (FESEM: Field Emission SEM)
SRF: Simple Research Framework
STEM: Scanning Transmission Electron Microscopy
TEM: Transmission Electron Microscopy
UWB: Ultra wideband
Volvo CE: Volvo Construction Equipment
WDS: Wavelength-Dispersive Spectroscopy
XRD: X-Ray Diffraction
XRF: X-Ray Fluorescence (EDXRF: Energy Dispersive XRF, WDXRF: Wavelength Dispersive XRF)
XRT: X-Ray Transmission

# 1 INTRODUCTION

With the increase in the world's population and the global standard of living, the need for ferrous and non-ferrous metals is on the rise (MULTIPICK, 2021). At present, Europe is heavily dependent on foreign countries for its mineral raw material needs. The largest import comes from China, which supplies a total of 98% of the EU's rare earth elements and is also the world's largest producer of aluminium (Simon, 2020). Imports of flat rolled aluminium from China into Europe increased from 171 kilotonnes in 2016 to 330 kilotonnes in 2020, which is a doubling of aluminium imports compared to five years ago (European Aluminium, 2021). In addition to the dependence on China, Turkey supplies 98% of the EU's borate needs and South Africa covers 71% of the EU's platinum needs (Simon, 2020). The European Commission has recently pointed out the drawbacks of this situation. Aluminium production in China is up to three times more carbon-intensive than aluminium made in Europe (Keating, 2019). In addition, many of the mineral materials currently imported could be produced or recycled in Europe, provided that Europe develops extraction, refining and recycling capacities in order to ensure its self-sufficiency (Simon, 2020).

In 2011, EU soil contamination was estimated at 2,5 million potentially contaminated sites (PCS), with metallurgical industries reported as significant sources of contamination (13 %) (EEA, 2019). This is also the case in Wallonia, where, born of its rich industrial and metallurgical past, 5,600 brownfield sites still need to be rehabilitated, representing a total surface area of 22,047 hectares (SPW, 2020). In France, there are approximately 6,800 polluted sites, which need immediate attention and resolution, with about 1,290 in the Rhône-Alpes, 963 in the Nord-Pas-de Calais regions respectively (BASOL 2018). Payá *et al.* (2018) report that about 19% of registered and identified contaminated sites in the EU needs some level of intervention. It further indicates that some about 35,000 sites in Germany, 9,031 sites in Czech Republic amongst others need urgent remediation.

Old metal waste deposits (aggregate materials with a high content of ferrous metals, scrap metal, other metals, white and black slag and other fluxes[1]) are commonly found on site, which represents a source of pollution. The environmental stability of metal waste can be altered by changes in pH, interaction with water and the influence of the atmosphere, potentially leaching toxic metal elements into the environment (Pan *et al*., 2019).

Since 2001, regulations[2] have been introduced to allow the treatment and minimise the landfilling of metal waste streams, which still represent 22% of the total annual waste

[1] Substances added to a furnace during metal-smelting or glass-making which combines with impurities to form slag.

[2]Since 14 June 2001, Walloon Government decree allowed the use of BOFS, EAFS and LFS in road and civil engineering works (road pavements, sub-base work,...) (SPW, 2001). On 18 March 2004, Walloon Government decree prohibited the disposal of some wastes in landfill sites, including BFS, EAFS and LFS (SPW, 2004).

volume in Wallonia. These include residues from thermal operations (58%, slag, sand and dust), ferrous metal waste (22%, scrap, straw and shavings, off-cuts) and acid, alkaline or saline waste (8%) (ICEDD asbl, 2016). However, despite the high metal recovering potential of metal waste streams, current valorisation tracks do not focus on raw material recovering. The main reason being that recycling costs remain in many cases higher than other alternatives such as incineration, use in civil engineering works and landfilling (ICEDD asbl, 2016; SPW, 2007). Thus, to move towards a circular economy policy that is not only zero waste but also profitable, Wallonia is investing massively to improve recycling processes and provide more recovery opportunities for by-product stocks.

It is in this context (which is common to many NWE regions) that the Interreg NWE-REGENERATIS project takes place, which is dedicated to the extraction and re-use of raw materials from Past Metallurgical Sites and Deposits (PMSDs). In this framework, a bibliographic study has been carried out to define the current and innovative excavation techniques that can be applied for the treatment and recovery of waste streams on PMSDs.

This report is divided into three parts:

1. The first part precisely describes the excavation techniques currently used to remove soils, rocks and anthropogenic backfills.
2. The second part provide a review of modern and most innovative civil engineering excavation techniques, to take recent progresses into account when designing the SMARTIX AI tool and the NWE-REGENERATIS methodology.
3. The last part summarizes the pre-processing[3] techniques, which are supposed to facilitate the work of the metallurgists and to reduce negative externalities as transportation, by preparing the metallurgical waste on site before applying mineral processing techniques.

This report will allow the construction of the desk data set regarding the excavation and pre-processing techniques to be used for PMSD, which is the basis of the learning process for the SMARTIX tool.

[3] By “pre-processing”, we mean the on-site preparation of the materials to 1° directly eliminate not valuable parts and unwanted impurities before their transportation to mineral processing and/or metallurgical plants, and 2° adjust the grain size distribution and other parameters to the requirements of the downstream plants

# 2 Current techniques for the excavation of metallurgical waste

**Definition:** Excavation is the process of moving earth, rock or other materials using tools, equipment or explosives, usually for further use or processing. The areas of application involving excavation are significant, including exploration, mining, soil remediation and construction.

## 2.1 Parameters determining the most appropriate type of excavation and equipment

### 2.1.1 Characteristics of the materials to be excavated

According to Nichols & Day (2005), material to be excavated are roughly divided between three classes: (1) rock, (2) hard digging and (3) easy digging. Hard digging can be defined as compacted, cemented, or rocky dirt, clay, soft shale, and rotten rock, that can be dug directly by heavy machinery, or loosened readily by rippers whereas easy to medium digging is any soft or fine, firm or loose deposit.

Excavation equipment include blasting, hammer, ripping, digging or manual excavation. The choice of the type of equipment to be used for excavation depends on the characteristics of the material to be excavated, e.g. its hardness.

**Rock masses** are composed of rock materials separated by discontinuities, or families of discontinuities. Strength of the rock material can be quickly determined by measuring the point load strength index (Is), which is well correlated with the unconfined compressive strength (UCS) (Verbrugge & Schroeder, 2018; **Table 1**). "Is" refer to the uncorrected point load strength index measured with the Franklin test, which must be corrected to the standard equivalent diameter of 50 mm. The correction is not necessary for $Is_{50}$, as it refers to the point load strength index measured on NX core whose diameter approach 50 mm (54mm to be precise). More information about these tests are available in Rusnak *et al.* (1977) and Singh *et al.* (2012).

*Table 1- Uncorrected point load strength index (Is), unconfined compressive strength (UCS) and field estimation of strength of the main types of rocks (Verbrugge & Schroeder, 2018).*

| Term | UCS (MPa) | Is (MPa) | Field estimate of strength | Examples |
|---|---|---|---|---|
| Extremely strong | >250 | >10 | Can only be chipped with a geological hammer. | Basalt, chert, diabase, gneiss, granite, quartzite |
| Very strong | 100-250 | 4-10 | Requires many blows of a geological hammer to fracture it. | Amphibolite, sandstone, gabbro, gneiss, granodiorite, |

| | | | | |
|---|---|---|---|---|
| | | | | limestone, marble, rhyolite, tuff |
| Strong | 50-100 | 2-4 | Requires more than one blow of a geological hammer to fracture it. | Limestone, marble, phyllite, sandstone, schist, shale |
| Medium strong | 25-50 | 1-2 | Cannot be scraped or peeled with a pocket knife, but can be fractured with a single blow of a geological hammer. | Claystone, coal, concrete, schist, shale, siltstone |
| Weak | 5-25 | NA | Can be peeled with a pocket knife with difficulty, shallow indentation made by a firm blow with a point of a geological hammer. | Chalk, rock salt, potash |
| Very weak | 1-5 | NA | Crumbles under firm blows with a point of a geological hammer, and can be peeled with a pocket knife. | Highly weathered or altered rock |
| Extremely weak | 0.25-1 | NA | Can be indented by thumbnail. | Stiff fault gouge |

*NA: Point load tests (Is) on rocks with uniaxial compressive strength <25 MPa are likely to give ambiguous results.*

Several indexes have been created to classify fractured rock masses, for example the Rock Quality Designation index, the Tunnelling Quality Index, the Rock Mass Rating, the Geological Strength Index (GSI) and the modified GSI. If the first indexes are based on direct measurements (e.g. drilling, uniaxial compressive strength), the GSI can be determined either through calculations or via an empirical approach. Indeed, Vásárhelyi *et al.* (2016) suggested that the best way of estimating the GSI was by visual observation (direct observation of surface conditions, discontinuities and the structure of the rock mass) by an experienced engineering geologist, and not by any of the calculation methods that they tested.

Even if the GSI methodology is subject to inaccuracies, it is much easier to apply on site because it does not require special measurements. In their work, Tsiambaos & Saroglou (2010) suggested to link the GSI measurement with the excavatability, i.e. the ease with which the material can be excavated. High GSI values are associated with greater strength of the rock mass, and will therefore require the use of blasting or hammer to break up the rock. The direct use of a shovel or in addition with a ripper will suffice for a more fractured or disintegrated rock mass, illustrated by lower GSI values (**Fig. 1**).

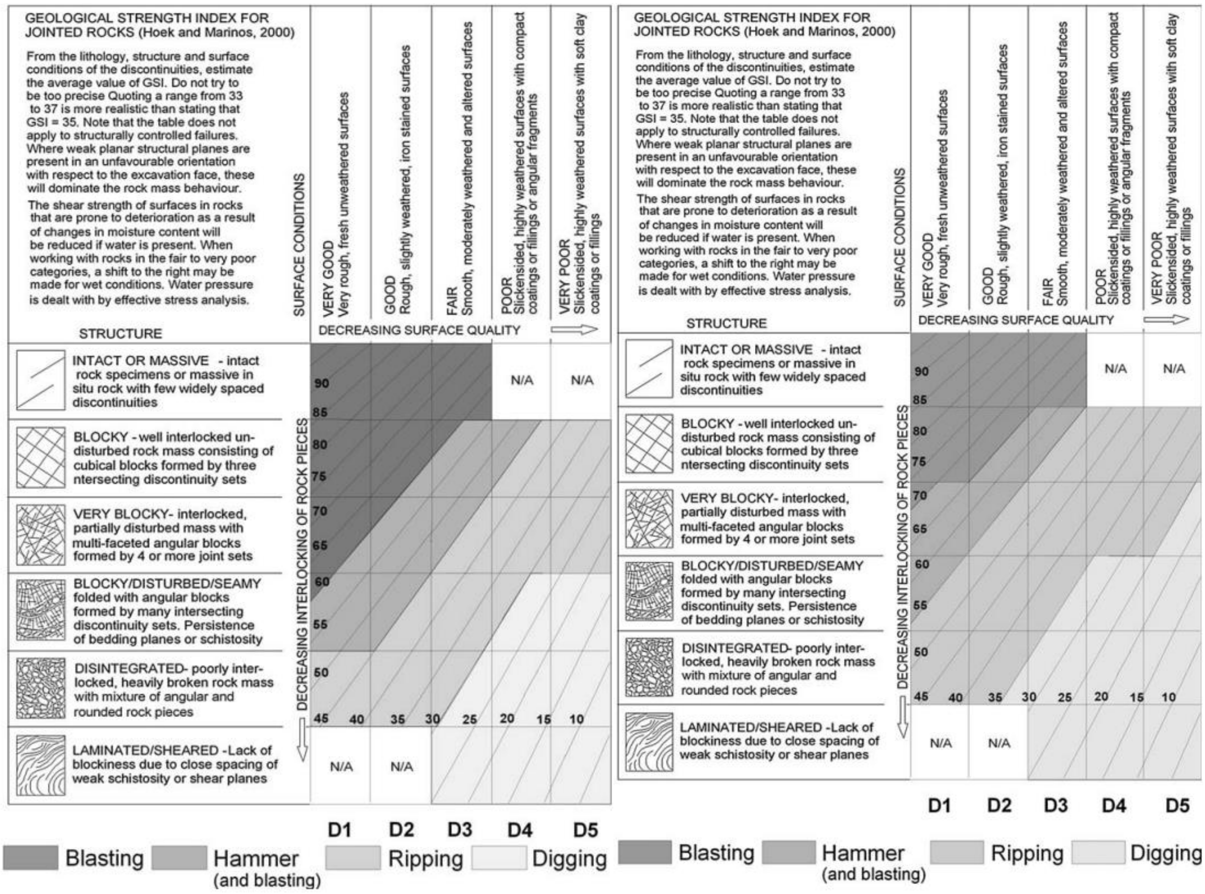


*Figure 1- GSI chart for the assessment of excavatability of rock masses, left: $Is_{50} \geq 3MPa$, right: $Is_{50} < 3MPa$* (Tsiambaos & Saroglou, 2010)

Apart from the GSI, other indicators are also used to classify the ease of excavation of a material, such as (Nichols & Day, 2005):

- the digging resistance, i.e. the resistance that must be overcome to dig a formation (made up largely of hardness, coarseness, friction, adhesion, cohesion, and weight);
- the weight of the material, and especially its density;
- the rippability, i.e. the measure of the ease or difficulty with which a rock can be broken by heavy rippers into pieces that can be economically moved by other equipment, usually scrapers. It involves three factors: the resistance to breakage of the rock material itself, the extent to which it is weakened by bedding layers (lamination) or by joint cracks or fault movement, and the degree to which the rock has been softened and weakened by weathering.

The procedure defined by Bilgin *et al.* (2014) for the investigation of the site before an excavation is shown in **Figure 2**. Please note this procedure already integrates geophysical imaging, as considered in NWE-REGENERATIS project. However, the proposed geophysical imaging is here for excavation purposes only and not related to the metal content of the materials.

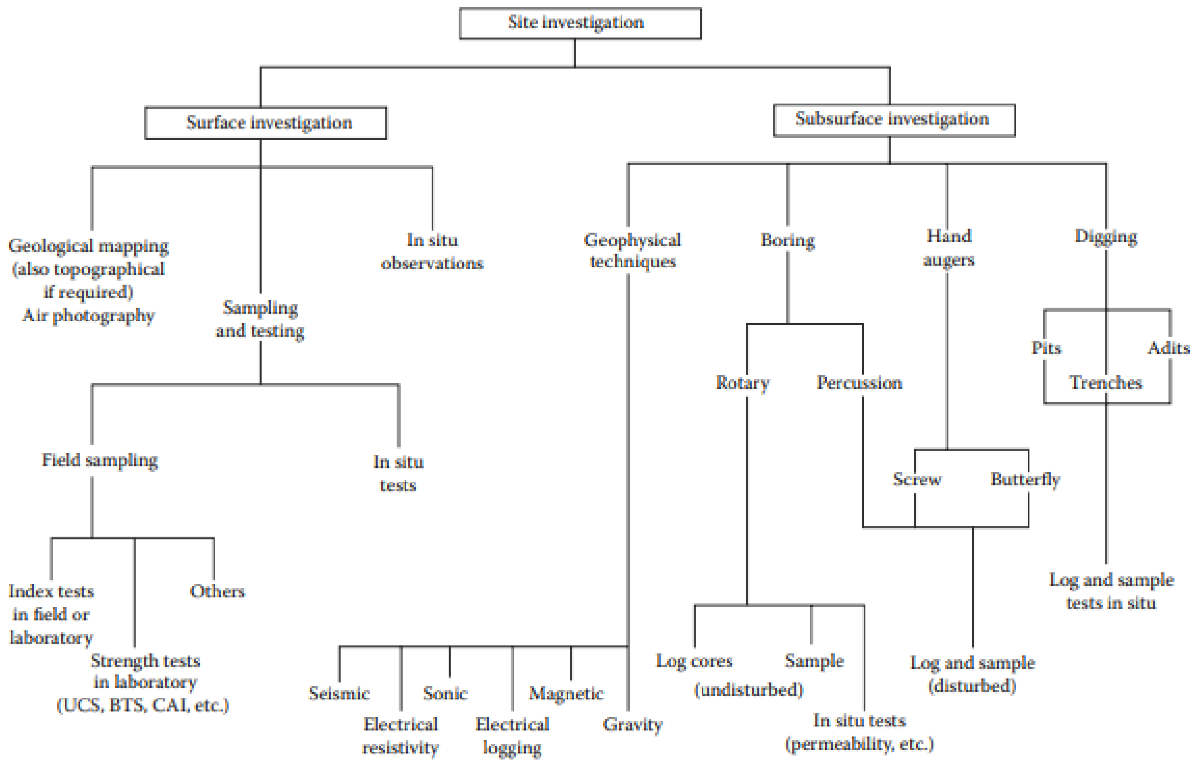


*Figure 2- Site investigation organisation tree* (Bilgin et al., 2014)

## 2.1.2 Workload

In addition to the characteristics of the material to be excavated, the quantity (volume and total weight) of the material, the accessibility of the site as well as the type of work that is required are also important parameters to consider when choosing the most appropriate machine. It is believed that bigger and more powerful machines are synonymous with better performance as these machines can excavate a larger quantity of material and therefore reduce excavation time, but this is not always the case. Larger and more complex machines are bulky and often not cost-effective if they are under-exploited, as they have higher owning and operating cost (Gregory Poole, 2019; Muth, 2019; Warren CAT, 2019).

In general, the weight of the excavator can be taken as an indication of the size of the machine and its bucket capacity, but it is also important to ensure that the arm can reach the maximum distance (digging depth and reach) it will be required to work. Most manufacturers provide a graph in their technical documentation showing the kinematics of the arm and therefore the maximum heights and depths it can reach (DirectIndustry, 2021). Mini or compact excavators approximately weight 2-7 tonnes, standard excavators range between 7 and 45 tonnes and large excavators weight up to 80 tonnes (Warren CAT, 2019).

The estimated number of days of excavation is calculated by dividing the number of tonnes to be excavated by the number of tonnes per day that all the machines can excavate.

### 2.1.3 Machine workspace

Soils differ greatly in their capacity to support and permit movement of vehicles. For example, soils characteristics and conditions determine the tractive efficiency, which is a measure of the proportion of the weight resting on drive wheels or tracks that can be converted into movement of a machine. The choice between wheels and tracks will therefore depend on the comparison between their traction efficiency depending on the type of soil and its water content, the closer the traction efficiency is to 1, the easier the movement is (**Fig. 3**).

| | | Tractive Efficiency | | | |
|---|---|---|---|---|---|
| | | Wheel Factor* | | Track Factor (Grousers) | |
| Standard Tables | Type of Surface | Dry | Wet Surface | Dry | Wet Surface |
| | Smooth blacktop | .8 – 1.0 | .6 – .9 | – | – |
| .88 – 1.0 | Rough concrete | .9 – 1.0 | .8 – 1.0 | .3 – .6 | .3 – .6 |
| | Hard smooth clay | .6 – 1.0 | .1 – .3 | .4 – .7 | .2 – .4 |
| .40 – .58 | Hard clay loam | .5 – .8 | .15 – .4 | .6 – .9 | .4 – .9 |
| | Firm sandy loam | .4 – .8 | .25 – .8 | .6 – 1.0 | .6 – 1.0 |
| | Spongy clay loam | .4 – .6 | .15 – .3 | .7 – 1.0 | .6 – .9 |
| .40 – .44 | Rutted clay loam | .3 – .5 | .15 – .3 | .7 – 1.0 | .6 – .9 |
| .20 – .35 | Rutted sandy loam | .3 – .4 | .2 – .5 | .7 – 1.0 | .7 – 1.0 |
| .36 | Gravel road, firm | .5 – .8 | .3 – .9 | .7 – .9 | .7 – .9 |
| | Gravel, not compacted | .3 – .5 | .4 – .6 | .5 – .9 | .6 – 1.0 |
| | Gravel, loose | .2 – .4 | .3 – .5 | .4 – .7 | .5 – .8 |
| .20 to .35 | Sand, loose | .1 – .2 | .1 – .4 | .3 – .5 | .4 – .7 |
| .20 | Snow, packed | .1 – .4 | .0 – .3 | .2 – .6 | .2 – .6 |
| .12 | Ice, roughened | .1 – .3 | .0 – .2 | .1 – .4 | .0 – .3 |
| | Ice, smooth | .0 – .1 | .0 – .0 | .0 – .1 | .0 – .1 |

*May be increased by extra wide or extra soft tires.

*Figure 3- Tractive efficiency on surface* (Nichols & Day, 2005)

As can be seen in the **Figure 3**, moisture content is also an important variable influencing traction efficiency. For deep soft and wet soil (mud), tracks are preferred to wheels, as the latter can get bogged down, or slip in the case of a film of mud on firm footing. Once frozen, it can lock together and immobilize the most powerful machines. However, even when using tracks, the presence of mud is still a major problem in excavation and can cause work delays. Mud sticks to shovel buckets and truck bodies instead of dumping, and builds up in chains and tracks until they jam. Its powerful suction force holds objects lying on it so that they become difficult or impossible to lift. In order to reduce the inconvenience of the mud and to allow the movement of the machines, at least one geotextile track must be laid, otherwise infrastructure must be built such as corduroy roads, pole tracks, plank roads or platforms (Nichols & Day, 2005).

## 2.2 Mechanical excavation

### 2.2.1 Digging and ripping

Mechanical excavation is the most widely used type of excavation in the case of non-indurated materials (e.g. soil, gravel), possibly supplemented by manual excavation in the case of rough terrain or terrain that is inaccessible with conventional machinery. In the 1900s, cable-operated excavators were dominant, but their use has declined greatly in favor of the easier to operate hydraulic excavators. In the case of very large works (e.g. in open-cast mines), they are still very often used, in the form of draglines, clamshells, big cranes and dipper models (Nichols & Day, 2005). Usually, excavation machines are classified based on digging capacity, bucket volume and transport configuration (Chacko *et al*., 2014). The mechanical excavation equipment is summarised in **Table 2** and commonly includes (Meuser, 2013):

- Crawler or wheel excavators, which are equipped with a bucket in the front for excavating soil and rocks and then loading it onto transport vehicles. They are suitable for heavy lifting, digging trenches and moving piles of debris from sites. They allow large scale movement of soil, rock and rubble. Wheeled excavator can move quickly but are less suitable than crawler excavator for uneven grounds or loamy/clayey sites (Meuser, 2013; Truck & Trailer, 2016).
- Wheel or crawler-type loader are very similar to excavators but differ from them because they have rear and front axles that can bear vast amounts of weight, making it ideal for use with heavy materials. Their front mounted square wide bucket can carry a greater volume of material than the excavator (Meuser, 2013; Truck & Trailer, 2016).
- Bulldozers (or dozers) use a broad steel blade or plate to push large quantities of soil or rocks, rather than lift it (Meuser, 2013).
- Backhoe excavators are equipped with both a front loader made of a bucket attachment and, on the backside of the machine, with a digging tool, composed of an articulating arm with a backhoe at the end. The operator can use the controls for both attachments if necessary, making it possible to move tons of material to make deep and extensive holes and trenches.
- Vacuum excavators are the only non-hydraulic machines among those mentioned in this section. This technique will be chosen if the soil is soft and when a non-invasive excavation technique is needed, for example when some utilities should not be damaged (pipelines) or when the environmental protection agency objects to the cutting of certain trees. The withdrawal of the soil in the vicinity of the truck

is performed by suction (using pressurised water or pressurised air), so that the roots are not damaged (De Rijdt *et al*., 2018).

The technical characteristics of hydraulic machines can vary greatly. As introduced in the section 2.1.3. Machine workspace, wheel excavator can move quickly but are less suitable than crawler excavator for uneven grounds or loamy/clayey sites (Meuser, 2013). In addition, some machines, such as excavators, are very versatile machines that can be fitted with different attachments to suit the desired use, i.e. digging, ripping or breaking (**Fig. 4**):

- Crane, clamshell, front shovel, backhoe and draglines are all attachments that can be used for digging or lifting materials.
- A ripper is a tooth, or set of teeth that are pulled through rock or hard soil to break and loosen it. It can be mounted either directly on excavation equipment (excavator), or in a frame hinged to the back of a crawler tractor, with hydraulic hoist.
- A breaking hammer is a device that, when used properly, can crack almost any sound rock. For example, it is used to break up boulders or to loosen and reduce solid rock pieces before loading them.

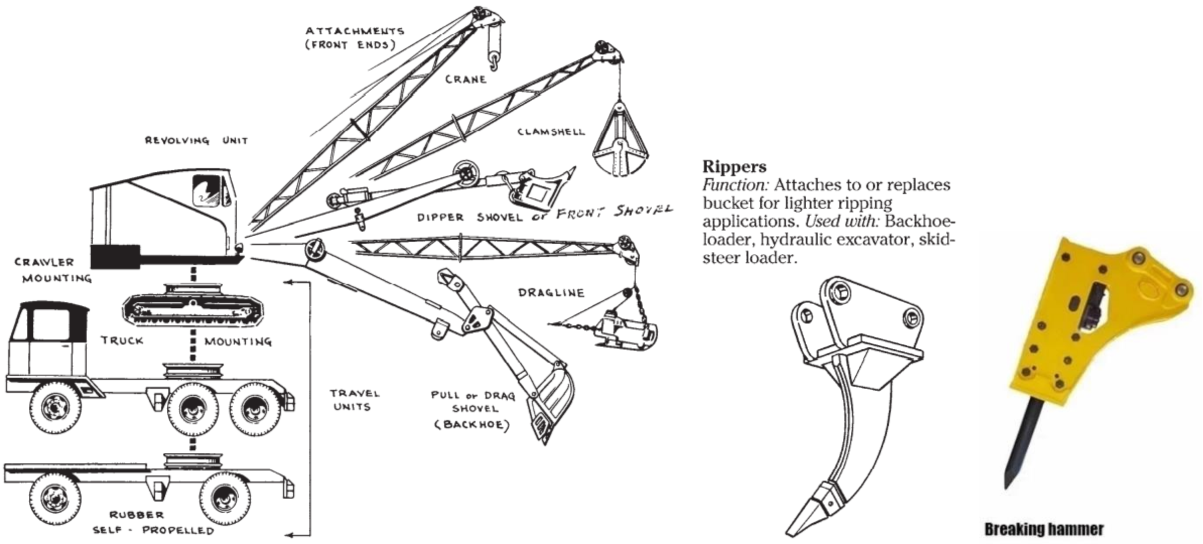


*Figure 4- Attachments for hydraulic excavators (Nichols & Day, 2005)*

*Table 2- Summary table of equipment used in excavation work* (Caterpillar, 2021c; iSeekplant, 2019; Meuser, 2013; Muth, 2019; Nichols & Day, 2005; Pon Cat, 2019)

| **Equipment** | **Advantages** | **Disadvantages** |
|---|---|---|
| Excavators  | • Complete rotation (360°)<br>• Suitable for demanding job (digging and mining operation)<br>• Versatile | |
| Dragline excavators  | • Long reach<br>• Ability to dig below the tracks | • Low digging force |
| Loaders  | • Suitable for use with heavy materials | |
| Hydraulic shovels  | • Most powerful type of excavator | • High power more than necessary in many cases |
| Backhoe loaders  | • More versatile than excavators: a larger number of tasks can be performed.<br>• Smaller than excavators so can operate in confined areas or at smaller working sites | • Can only rotate up to 200 degree<br>• Less large and powerful than excavators |

| | | |
|---|---|---|
| | | |
| Bulldozer  | ● Powerful | ● Not versatile |
| Vacuum excavators  | ● Non-destructive<br>● Suitable for precise and careful excavation | ● Not applicable for large scale projects (the diameter of the suction pipe is usually 30 cm) and only for shallow excavation (approximately 20m depth)<br>● Cost intensive<br>● Takes a long time |

### 2.2.2 Trucks and haulers

Dump trucks are the most familiar machines used to transport soil or other materials after excavation (**Figure 5**). Depending on the model and size of the truck, the design remains more or less the same, except that the heavier the truck, the stronger and heavier the parts have to be, and the transmission contains more gears. Engines are either petrol or diesel. Dump bodies may be mounted on semitrailers and trailers, with either standard or special constructions. Dumping can be done in the standard way (by tipping the bucket backwards), through a full-length bottom opening (bottom dumpers) or by side dumping.

There are restrictions on the size and weight of trucks when they are to be used on highways. In Belgium, the maximum width is fixed to 2,55 to 2,6m, the maximum height can be 4m and the maximum length can vary from 12 to 15,5m. There is also a maximum weight limit, which can change depending on the country you are in. The maximum weight allowed is 19 tonnes for 2-axle trucks, 26 tonnes for 3-axle trucks and 32 tonnes for 4-axle trucks. This legislation varies slightly from country to country (**Table 3**).

*Table 3- Permissible maximum weights of trucks in some NWE-countries* (International transport forum, 2019)

| Permissible maximum weights of lorries in Europe (in tonnes) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Country | Weight per non-drive axle | Weight per drive axle | Lorry 2 axles | Lorry 3 axles | Road train 4 axles | Road train 5 axles and + | Articulated vehicle 5 axle and + |
| Belgium | 10 | 12 | 19 | 26 | 39 | 44 | 44 |
| France | 12 | 12 | 19 | 26 | 38 | 40/44 | 40/44 |
| Germany | 10 | 11.5 | 18 | 26 | 36 | 40 | 40 |
| Ireland | 10 | 11.5 | 18 | 26 | 36 | 42 | 44 |
| Luxembourg | 10 | 12 | 19 | 26 | 44 | 44 | 44 |
| Netherlands | 10 | 11.5 | 21.5 | 21.5-30.5 | 40 | 50 | 50 |
| United kingdom | 10 | 11.5 | 18 | 26 | 36 | 40/44 | 40/44 |

A two-axle truck can be equipped by an extra axle in the rear, allowing to distribute both weight and driving strains over twice as many units. The resulting double-axle unit is called a tandem or bogie, and permits carrying much heavier loads in proportion to tire size and axle strength. Trucks equipped with this system are called a tandem, a six-wheeler or a ten-wheeler.

Around the 1950s, Volvo introduced articulated dump trucks, which are designed to be more maneuverable and more capable of working on poor soil conditions. This was made possible by a tractor-trailer combination with the tractor part on one axle and the trailer on another, with an articulated joint between the two. Today they are produced by many manufacturers (Nichols & Day, 2005).


*Figure 5- Left: on-highway dump truck (Nichols & Day, 2005), center: off-highway dump truck* (Caterpillar, 2021a), *right: articulated dump truck (Nichols & Day, 2005)*

### 2.2.3 Transport of excavating machines

Most excavating machines are not designed to travel on their own power on highways, especially for long journeys, and are transported from job to job on machine trailers.

The deck or carrying space of the trailer should be large enough to support and hold the machine to be carried, and the power must also be adapted to the machine being transported. If these characteristics are not carefully defined, sagging beams may occur in the case of excessive overloads, which are very expensive to repair. The size and weight of the ramps is another factor to be carefully selected, as higher decks require longer and heavier ramps or more dependence on loading from a bank. In terms of manoeuvrability, semi-trailers are often preferred, as larger trailers may find themselves in difficulties in country roads and residential districts.

The main types of trailers that exist are deck trailers, girder or I-beam trailers, low-bed semi-trailers and tilt trailers (**Fig. 6**). Low-beds trailers are available in lighter models, with the machines being able to carry machines weighting 10 tons or less, and girder trailers are the most suitable type of trailer to carry shovel (Nichols & Day, 2005).

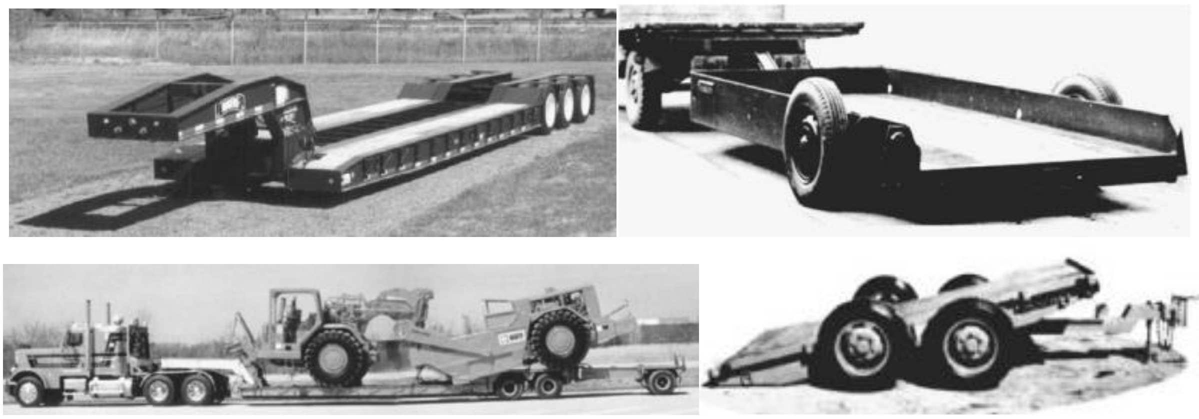

*Figure 6- Top left : deck trailers, top right: low-bed semi-trailers, bottom left: loaded girder trailer, bottom right: tilt trailer (Nichols & Day, 2005)*

## 2.3 Survey and monitoring

### 2.3.1 Stability

#### *2.3.1.1 Maximum digging depth*

Trenching and excavation works present hazards to workers due to the risk of cave-ins. Thus, in order to ensure the safety of workers, in practice, it is possible to calculate a digging depth beyond which the ground collapses (Lemdani, n.d.):

$$H_{crit} = (\pi + 2) \times \frac{C}{\rho}$$

With C being the cohesion of the soil in tonne/m² and ρ referring to the density of the soil in tonne/m³. The lower the cohesion of the soil (e.g. sandy or saturated soils), the less resistant it is to shear and the more likely it is to collapse.

#### *2.3.1.2 Classification of soil according to their stability*

In USA, the Occupational Safety and Health Administration's (OSHA) created standards related to excavation and trenching operations (OSHA, 2015). The International Organisation for Standardisation (ISO) also published international standards concerning geotechnical monitoring, stability and excavation, but these are not always freely accessible (ISO, 2015).

OSHA categorize soil and rock deposits into four categories in decreasing order of stability: Stable rock > Type A > Type B >Type C. The classification is based on the strength of their cohesive forces, site conditions, environmental conditions and the structure and composition of soil and bedrock. The precise definitions of the classes are described in the following lines, and the densities of some textures are available in Appendix A (OSHA, 2015):

- "Stable rock is a natural solid mineral substance that can be excavated with vertical side and remain intact during exposition."
- "Type A soil are cohesive soils with an unconfined compressive strength of 14.6 tons/m² (144 kPa) or greater. Examples include: clay, silty clay, sandy clay, and clay loam. Certain conditions preclude soil from being classified as Type A. For example, no soil is Type A if it is fissured, has been previously disturbed, is subject to any type of vibration or has seeping water"
- "Type B soil are cohesive soil with an unconfined compressive strength between 4.89 tons/m² (48 kPa) and 14.6 tons/m² (144 kPa) and granular cohesionless soils (such as angular gravel, similar to crushed rock, silt, silt loam, sandy loam, and, in some cases, silty clay loam and sandy clay loam. Soil that meets the unconfined compressive strength of type A soil but subjected to vibration is fissured also belong to type B soil, as well as unstable dry rock, previously disturbed soils (not classified as type C soil), soil that is the part of a sloped, layered system with layers dipping into the trench at a slope less steep than 4H:1V
- "Type C soil are cohesive soil with an unconfined compressive strength of of 4.89 tons/m² (48 kPa) or less, granular soils (including gravel, sand, and loamy sand), submerged soil or soil from which water is freely seeping, submerged rock that is not stable, or material in a sloped, layered system where the layers dip into the excavation or with a slope of four horizontal to one vertical (4H:1V) or steeper"

#### *2.3.1.3 Usual and specific methods for soil stabilisation*

Most often, the stability of a trench is ensured by sloping or benching it, as it is easy to implement and low cost. The real slope of the trench must be less than the maximum allowable slope, which is the steepest incline of an excavation face that is considered acceptable (Bruxelles Environnement, 2018). The maximum allowable slope is either expressed as the ratio of horizontal distance to vertical rise (H:V), or in angles, and depend on the soil type (**Table 4**). In layered soil, the maximum allowable slopes change according to several criteria (see Appendix B for more information).

*Table 4- Maximum allowable slopes for different types of soils* (OSHA, 2007)

| Maximum allowable slopes (H:V) for excavations less than 6.10 m depth[4] | | |
|---|---|---|
| Soil/rock type | Angle[5] | Horizontal distance/vertical rise |
| Stable rock | 90° | Vertical |
| Type A | 53° | ¾:1 |
| Type B | 45° | 1/1 |
| Type C | 34° | 1½:1 |
| Type A* (Short-term) | 63° | ½:1 |
| *Short-term trench excavation is defined as an excavation open for 24 hours or less | | |

Sometimes it is not possible to carry out sloping and benching, either because of a lack of space or because of the shape of the trenches required (this is especially the case in construction, where different types of trenches can be built depending on the type of work required: see Appendix C). In that case, shoring can be used before or during earthworks. Shoring system during construction works consists of posts, wales, struts, and sheeting, with the two most common types of shoring being timber and aluminum hydraulic shoring. In the case of large, deep excavations or excavation in soils with low cohesion, the shoring system will be implemented before the earthwork is done, by using sheet piling, pile/diaphragm or soil mix wall (Bruxelles Environnement, 2018).

## 2.3.2 Specific monitoring instruments

Despite the most comprehensive geological investigations and soil analyses, the soil, rock mass and terrain are heterogeneous and anisotropic and show a large dispersion of parameters. Excavation theories are based on many hypotheses that can hardly cope with the many uncertainties of geological condition. Therefore, excavation has to be carried out along with monitoring instrument, which is part of an effective risk management during the construction and operation phases. Geotechnical monitoring instrument provide direct information on stress changes and displacement generated by excavation. These measurements are supervised by engineers in charge of checking the stability and safety of the excavation at all times and can change the excavation plan accordingly (Golser & Steiner, 2021; Ou, 2006).

[4] Sloping or benching for excavations greater than 6.10 m deep should be designed by a civil engineer.
[5] Angles have been rounded off.

Instrumentation for short-term monitoring generally differ from long-term monitoring. Indeed, in the case of long-term monitoring, instruments permanently placed in boreholes, such as rod extensometers or pore pressure transducers, must be suitable for maintenance. Extensometers appropriate for long-term use should have an exchangeable rod and for piezometers, a special construction of a pipe with filter and transducers with a packer or a docking station with a conical tip can be applied, which allows the transducer to be exchanged or re-calibrated (Golser & Steiner, 2021).

In recent years, electronic measurement techniques have developed and proved to be more accurate and capable of providing good frequency and data transmission. However, experiments proving their long-term efficiency do not really exist, and some technical problems can be identified, such as the sensitivity of electronic systems to power surges, the risk of damage to cables due to unanticipated ground deformation and the risk of random drift of electrical signals. Similar interest has been shown in fibre optic measurement for distributed system, which can determine a lot of parameters like deformation, settlements, temperature and force along the measuring line. As fibre optic technology is insensitive to lightning and over voltage, this technique is more frequently used in power plants and may fulfil the requirements for long-term monitoring. However, the readout devices remain very complex and expensive and are still under continuous development. For all these reasons, mechanical and hydraulic measuring systems that can be directly measured, such as hydraulic or pneumatic piezometers or stress cells with measuring gauges, are preferred to electronic or fibre optic measurements (e.g. in concrete and earth dams) (Golser & Steiner, 2021).

In recent decades, potentiometric sensors (or piezoresistive sensors) have been replaced by transducers based on the vibrating wire system. The electromagnet inside excites a taut steel wire (string), which vibrates, producing a certain resonant frequency. This is then detected by the coil and transmitted to a reading device. The change in the deformation of the wire causes a change in the resonance frequency, which is then converted into displacement or pressure with appropriate calibration. The great advantage of these sensors is that there are no electronic parts and the technique is simple, robust, and suitable for long-term monitoring and for use with other transducers (Golser & Steiner, 2021).

## 2.4 Specific excavation cases in polluted areas: in situ neutralisation

Some precautions relate specifically to the presence of polluted soils. For example, in order to avoid the spreading of pollution, unpolluted soil must be excavated separately from polluted soil. In case of presence of surficial pollution or pollution in a specific area of the site, it can be neutralize on-site by using the different kinds of neutralizers according to the types/nature of pollutants before starting the excavation operations.

### 2.4.1 Acid tar

In case of presence of acid tar on site, firstly, the analysis of initial pH of the tar should be done and neutralization agent would be applied according to the pH of tar. It should be applied in required quantity to avoid the environmental issues after the neutralization. An effective process consists of the application of a bulk neutralizing agent having specific gravity more than acid tar. It should be sufficient enough to accomplish the neutralization. After spreading the neutralizing agent on acid tar, it would start to sink into the tar, the sinking rate depends upon the tar viscosity, specific gravity of neutralizing agent and tar and temperature. As the neutralizing agent sinks, it initiates the chemical reaction and increase the pH of the soil and make it easy to handle. Depending upon the sinking rate of neutralizing agent into acid tar, the depth and entire mass of the tar can be neutralized.

The mixing of paper chalk mixture with soil comprising acid sludge can surprisingly transform acid sludge into a neutral, solidified, stabilized, immobilized easily handled product with chemically bounded sulphur dioxide (European Patent Specification, 2016).

### 2.4.2 Acid sulfate soils

In acid sulfate soils, aglime also called agricultural lime is used for neutralization. Aglime refers to the substance which is ≥ 98% calcium carbonate by weight particle size of < 0.5 mm. Studies improved the effectiveness of aglime in treating the acid sulfate soils. It should be noticed that, use of aglime as a neutralizing agent produce $CO_2$. Thus, its application on a large area/site needs a proper management strategy (Dear et al., 2014).

# 3 RECENT PROGRESS IN MACHINERY

## 3.1 EQUIPMENT

Since 1960 and the appearance of hydraulic machines, there have been no revolutionary innovations concerning excavation equipment (Chacko *et al*., 2014). Moreover, due to the high competitiveness in the field of excavating machines, innovations created by one company spread quickly to the whole market.

Some contractors are imaginative when it comes to designing more sophisticated equipment, but these inventions are not widely used. Examples include the appearance of huge walking excavator for steep slope use (TGM, 2017) or excavators with four articulated independent crawler suspension (Doosan, 2010, 2020; Volvo CE, 2009) (**Fig. 8**).

*Figure 7- Walking excavator (left)* (Kaiser, 2021) *and excavator with four independent crawler tracks (right)* (Doosan, 2010)

Another example of sophisticated machines are the excavators with a fully tiltable telescopic boom, which were developed some seventy years ago by the Gradall company (**Fig. 9**). The telescopic, tilting boom provides greater versatility as it allows full length rotation without losing power at any boom angle. This design also allows the machine to work at low profile (under trees, bridges signs, ground floors and multi-story buildings and other challenging job locations) (Gradall, 2021).

*Figure 8- Gradall excavators (Gradall, 2021)*

## 3.2 Fuel efficiency

In recent years, much progress has been made in fuel efficiency. World first hybrid excavators were launched in 2009 by Komatsu, reducing fuel consumption up to 40 percent (Komatsu, 2019). Then electric excavators and loaders have appeared on the market (Pon Cat, 2019; Volvo CE, 2021b). The search for zero-emission vehicles continued with JCB's creation of a world-first hydrogen-powered fuel cell excavator in 2020. This fuel cell reduces nitrous oxide ($NO_x$) emissions by 97%, soot particles by 98% and carbon dioxide ($CO_2$) emissions by half compared to a conventional system (JCB, 2020). However, even if hydrogen seems to be a promising energy source, research must continue in order to solve the remaining difficulties regarding the production and storage of hydrogen and to ensure its large scale development (Balat, 2008; Shusheng et al., 2020). Right now, improvements are being considered, such as the design of on-board hydrogen-producing fuel cell vehicles, which eliminates the problems associated with high-pressure hydrogen storage and the hydrogenation process. The fuel cell works as the main power source to drive the engine, and the lithium battery is used as an auxiliary power source to accelerate and recycle energy to meet the specific requirements, such as energy recovery, power and dynamic characteristics (Shusheng *et al*., 2020) .

## 3.3 SMART EXCAVATION

Current innovation is also very much focused on the development of smart and autonomous excavators, as onboard telematics and remote connectivity is on the rise. It can be expected that the automation of excavating machines will increase in the coming years.

### 3.3.1 Connectivity and fault prevention

As connectivity on excavation machines increases, manufacturers try to offer a personalised user experience, improve worker protection, increase productivity and prevent faults. More or less similar monitoring systems exist in all manufacturers, among them DoosanCONNECT® Telematics and Equipment Monitoring, CAT® CONNECT and CareTrack (Caterpillar, 2021d; Doosan, 2021b; Volvo CE, 2019a).

In particular, CareTrack was developed by Volvo CE (2019a) in 2017, which works by capturing data points from the machine using Volvo's telematics system. These points are transmitted to the Volvo Uptime Center and remotely monitored by Volvo experts. When a fault on the machine is detected, the dealer is informed of the fault diagnosis. He can in turn inform the customer of the problem and plan the right time to perform the corrective action (**Fig. 10**). The advances expected from this system include head and eye movement monitoring to avoid fatigue-related accidents, people detection, machine-to-machine communication and real-time production data. The aim is to provide a personalised user experience and improve worker protection. Now, Volvo Construction Equipment (Volvo CE) has 150,000 connected machines, which is 140,000 more than 10 years ago (Volvo CE, 2021a).

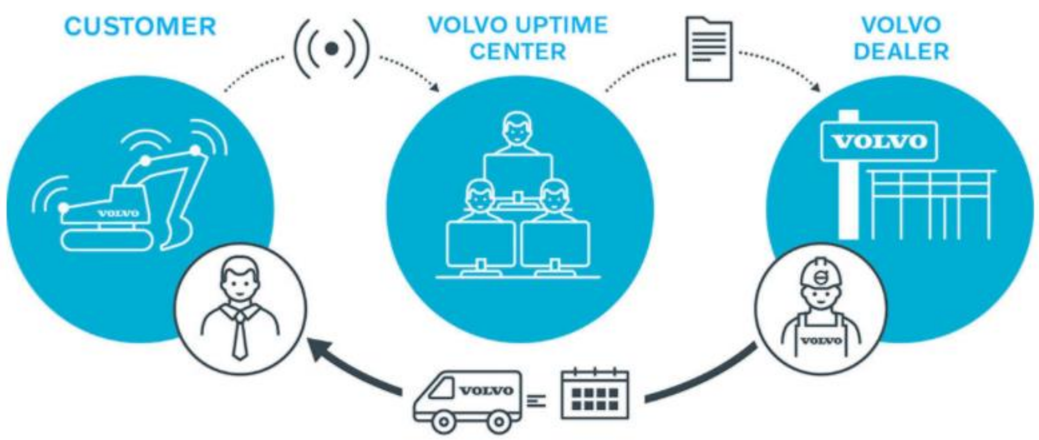


*Figure 9- Volvo CareTrack proactive monitoring system*

### 3.3.2 Automation

**Automation** is a set of function performed automatically by equipment and that reduce human intervention in processes. The operator performs requirements before or after the automated sequence whereas **autonomy** refers to an equipment which can perform programmed operations under defined conditions without human guidance. Multiple automation sequences are required to enable equipment to work semi-autonomously or autonomously (Caterpillar, 2021b).

Remote control is one of the processes of automation that has been made possible, especially with the advent of 5G. In 2019, Telia, Ericsson and Volvo CE have launched Sweden's first 5G network for industrial use at Volvo CE's facility in Eskilstuna. According to the contractors, using connected machine can create added value for the customer, such as greater efficiency, cutting costs (including fuel costs) and reducing risk in hazardous environment (Volvo CE, 2016, 2019b).

New semi-autonomous wheel loaders have been launched by Caterpillar, which is one of the most advanced contractors in the field of autonomous mining as they have invested in automation development for more than 30 years. Caterpillar has been operating autonomous mining trucks in full production use for 20 years. Up to date, 282 autonomous trucks are in operation, and they accumulated more than 72,4 million kilometres of autonomous driving (Caterpillar, 2020; World Highways, 2020). With "Cat Command", one operator can control several machines, one at a time, delivering semi-autonomous technologies and remote fleet management tools (World Highways, 2021). Volvo CE has also started to market remotely controlled machines such as its autonomous haulers, but fully automated worksites are not yet the norm (Volvo CE, 2020a, 2020b).

Some examples of automated machines can be seen in **Figure 11**.


*Figure 10- Some examples of automated machines developed by LIEBHERR and Volvo*

### 3.3.3 Sensors used in automation

Many sensors are used to enable excavators and other construction machines in order to detect faults or to work autonomously. Stentz *et al.* (1999) believed that they created the first fully autonomous system to load trucks for mass excavation by using two scanning laser rangefinder to recognize the truck, measure the soil on the dig face and in the truck and detect obstacles in the workspace. In 20 years, significant progress has been made and the quality of control systems has greatly improved. According to the reviews published by Azar & Kamat (2017) and Jiang & He (2020), earthmoving equipment automation includes:

- Condition monitoring systems are used to predicts faults occurrence.
  - *Oil contamination and leakage* fault is responsible for 70% of the failures in hydraulic systems. On-chip impedance sensors, mobile embedded particle contamination sensors or multifunctional sensors can be used for online detection of oil contamination. Leakage can be avoided by using an in-pipe fibre optic pressure sensor array.
  - *Vibration monitoring* is made by using sensors to transform vibration into electric signals. A data-driven fault diagnosis method based on Symbolic Perceptually Important Point and Hidden Markov Model as well as vibration monitoring system based on the uniform charge structure fibre Bragg grating vibration sensors have been proposed. The full vector spectrum is a tool used for homogeneous multi-sensor data fusion and is particularly suitable for hydraulic components with rotary parts.
  - *Emission monitoring:* The ZigBee sensor can be used to configure a wireless network, conduct greenhouse gas emission trading and accurately measure greenhouse gas emissions.
  - *Whole system monitoring:* Fault diagnostic methods should be primarily based on adequate and accurate sensor data and can be realised through four steps: 1) feature selection, 2) case retrieval, 3) case matching and 4) case updating. The collected sensor data are encapsulated in three electronic control units, which communicate with each other through a controller area network bus.
- Motion control
  - *Linear motion*: linear motion sensors (stroke transducers) are commonly used to measure the stroke of cylinders.
  - *Rotary motion*: rotary motion sensors are used to measure the angle, angular velocity and angular acceleration. Rotary encoders can very precisely convert a rotation position or quantity into an analogue or digital signal. They can be distinguished between two types, according to their output: absolute and incremental. The output of the first one provides information about the current

axis, making it an angle sensor, whereas the second one indicates the axis's motion, usually processed elsewhere as position, speed and distance.

As rotary motion is difficult to measure directly, indirect measurement, realised by measuring the tilt angle, is the predominant choice adopted. Tilt sensors are acceleration sensors that perform their measurements by using the principle of inertia. They can be divided between three kinds of inclination sensors: solid pendulum, liquid pendulum and gas pendulum.

- Integrated fleet management system and equipment tracking: a series of built-in sensors and onboard diagnostic systems are used to provide data about the condition and output of the fleet. These systems are used to track the fuel consumption, working and idle hours and location (mainly for security) of the equipment.
  - It generally involves *radio-based technologies*, such as global navigation systems (GPS/ GLONASS) or local positioning systems such as radio frequency identification (RFID) and ultra wideband (UWB). However, spatiotemporal data might not be sufficient for activity recognition. Multimodal sensing system are then required, such as weight and angle sensors, together with a positioning system, to address the lack of productivity estimation data for payloads.
  - Beside radio-based technologies**,** *computer-vision based technologies* are also widely used. They generally work by combining visual sensors (e.g. 2D or 3D cameras) and computationally intensive algorithms in the aim of tracking or recognise object or action.
- Safety management:
  - *GPS-based systems* combined with smart sensors and wireless networks were developed to alert about potential dangers and to avoid accidents, however they unfortunately tended to produce false alarms. The creation of the Kalman filter allowed reducing the false alarm rate, when it is combined with the nearest-neighbour method.
  - Another system is to instal antennas on the equipment and then use radio frequency remote sensing (RF/ RFID**)** to alert the worker with a set of visual and audio alerts. Bluetooth system can also be used, as it detects proximity with RFID and magnetic field systems. UWB technology can also be used for collision avoidance.
  - Imaging methods such as *range-imaging cameras and laser scanners* (such as LIDAR) can also be suitable for safety management. Range-imaging cameras can generate a 3D model of the work environment and detect objects. Laser scanners can provide point clouds of the surrounding environment, which can be processed.

- Regular cameras have also showed relatively good performance in detecting dangerous proximities; however, they still needed to be improved because of technical limitations such as reliability, accuracy, and applicability.

- Equipment pose estimation and automated machine guidance technology: *Automated machine guidance and automated machine control* use accurate sensing technologies to provide real-time, accurate pose information about the end-effector so that operators can complete tasks more quickly and with higher precision.

**Figure 12** shows the extensive hardware changes and main components added to a standard walking excavator (Jud *et al*., 2021)

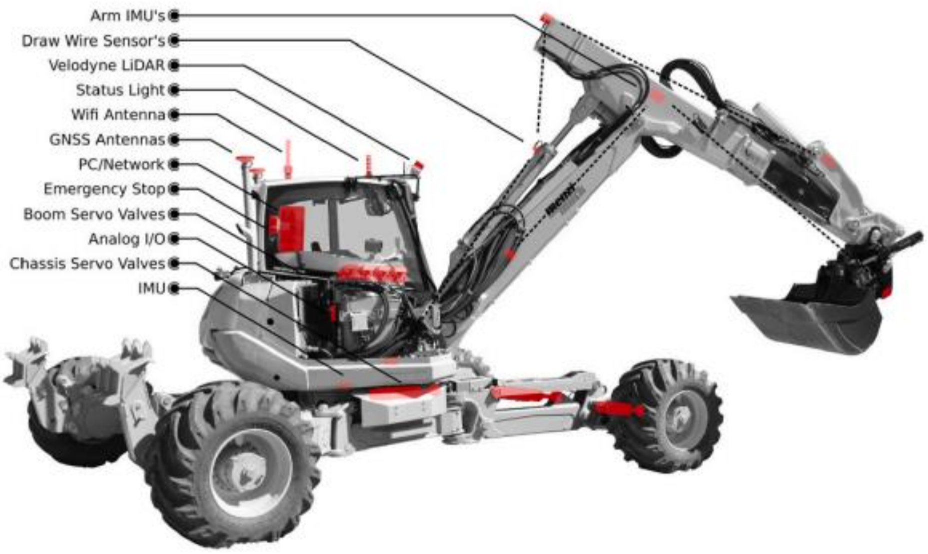


Figure 11- Extensive hardware changes and main components added to a standard walking excavator *(Jud* et al.*, 2021)*

## 3.3.4 Prospects

It is expected that the industry will move towards more and more automation of excavators, which will tend to be more and more autonomous, until they hardly need human control.

The autonomous walking excavator developed by Jud *et al.* (2021), has shown higher manipulation accuracy in various tasks than human operators. The spatialisation of work is also higher in the case of autonomous machines, as the machine always knows exactly how much soil it is moving, but also when and where. Future development is expected to improve the machine in various area, including upgraded sensors, which will allow for more precise handling of objects and better control of interaction forces to facilitate more difficult handling tasks. In general, it is expected that autonomous excavators will begin to be able to tackle more and more sophisticated excavation and construction projects soon.

According to Concept-X (**Fig. 13**), future job site operation starts with drones scan of field data and collection of topographic information. Data are then transmitted to the control centre, who will calculate the equipment needed to complete the job and design the most efficient workflow plan based on the soil distribution plan. The optimal work plan is the one which lower the construction/excavation period and cost. Each piece of equipment is then loaded with the work plan and will operate automatically. The equipment will be designed to reach optimal collaboration, thanks to auto recognition sensors made to recognise the surrounding environment (such as object detection system). The unmanned equipment will be constantly monitored, including real-time self-diagnosis and monitoring status, such as stress analysis of main parts and components and prediction of residual lifetime. The monitoring is realised by the control centre for the entire duration of the job site operation and the work plan will be constantly updated (Doosan, 2021a). Doosan estimates that commercialisation will be possible as early as 2025 (Infopro Digital, 2020).

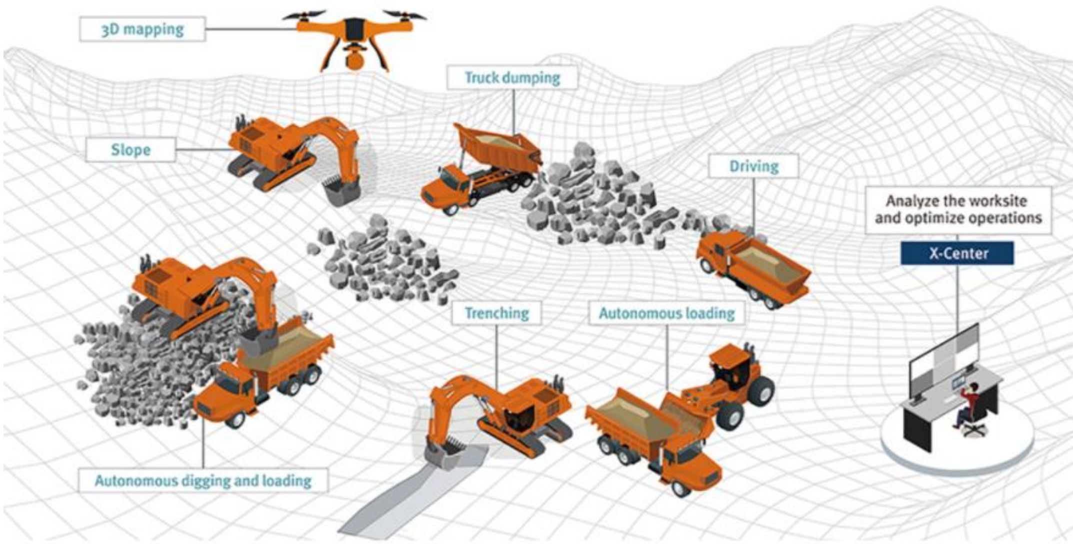


*Figure 12- Concept-X, designed by Doosan* (Doosan, 2021a)

However, despite the obvious progress made in automation, some technical barriers and concerns remain to be overcome. Although autonomous excavators show higher absolute accuracy in many tasks compared to human operators, it is only the case for repetitive and well-controlled tasks, e.g., digging a many kilometer-long pipeline trench. When a task needs constant adaptation and shows many unexpected events, a human operator can still reason and leverage his experience, which is not the case for a robot (Jud *et al.*, 2021). Moreover, environmental factors can cause elements defects and accelerate sensor failures. It represents a significant problem, as fully automated systems are entirely dependent on the proper functioning of a large number of sensors in order to be reliable and safe. In addition, autonomous machinery requires the intellectualisation of machinery, sensors, and workers. The future will surely see not only an increase in the number of sensors needed, but also the need for smarter sensors. This will also generate massive data to process and will initiate the need for qualified workers (engineers, computer scientists) to monitor and control the system (Jiang & He, 2020).

## 3.4 ESTIMATION OF EXCAVATORS' PRODUCTIVITY

Early detection of discrepancies between actual and planned performance helps project managers to take timely corrective action (Ibrahim & Moselhi, 2014). Lately, for the purpose of estimating the actual productivity of construction machinery at a construction site, researchers use a variety of methods and tools of fast-growing wireless technologies. For example, it includes (non-vision based) sensing and tracking technologies, and vision-based technology. Non-vision based technologies rely on GPS-data, possibly coupled with a variety of sensors (e.g. strain gauges to measure the hauling unit load weight, accelerometers, barometric pressure) whose data is processed by an algorithm (**Fig. 14**). Non-vision-based methods have difficulty categorising activities in detail when based on GPS data alone, and require the attachment of sensors to reduce inaccuracies (Alshibani & Moselhi, 2016; Ibrahim & Moselhi, 2014).

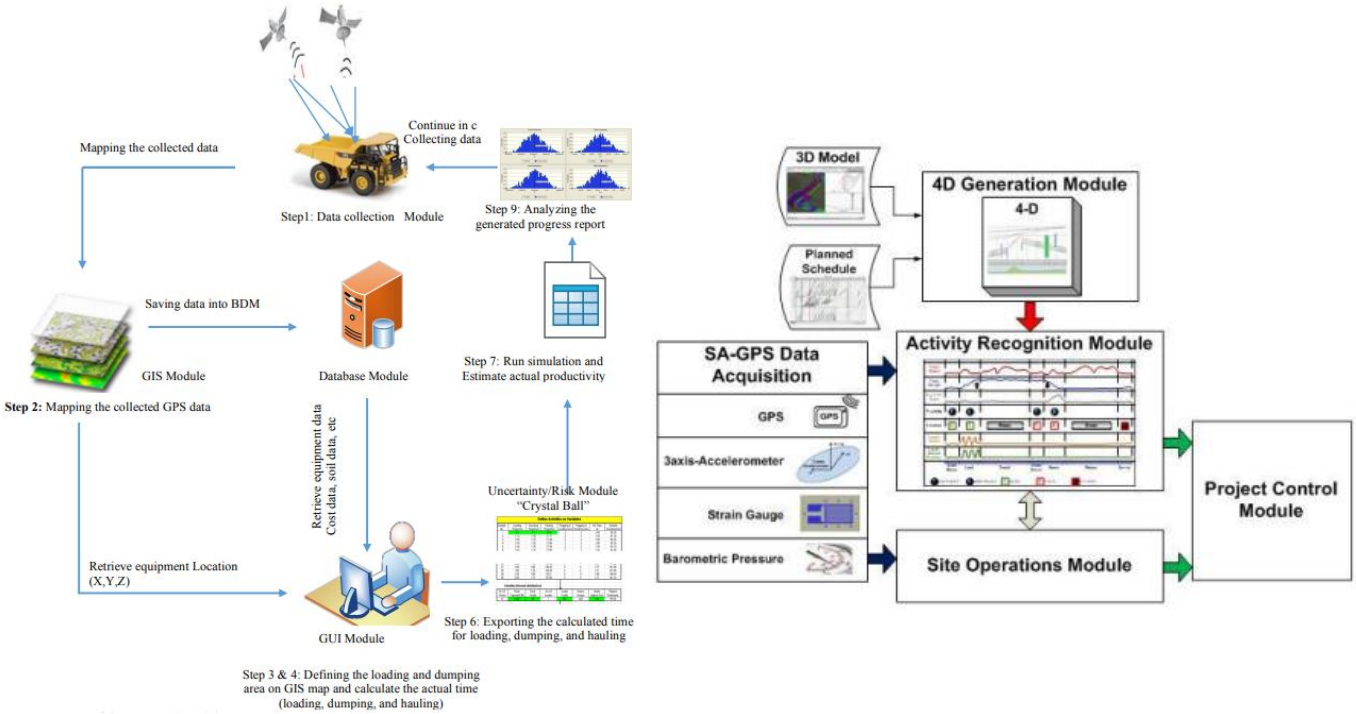


*Figure 13- Left: non-vision based technologies relying only on GPS-data* (Alshibani & Moselhi, 2016)*, right: non-vision based technologies relying on GPS-data coupled with a variety of sensors* (Ibrahim & Moselhi, 2014)

More particularly, the use of vision-based technologies to track construction equipment and workers gained significant interest in construction industries (Xiao & Zhu, 2018). They can visualise the equipment state directly from images and videos, so that it becomes easy to identify false recognition and analyse the reasons behind low productivity. Chen *et al.* (2020) developed a framework based on three convolution neural networks that automatically recognize activities and analyse the productivity of excavators. The algorithm had acceptable results, but still needs some issues to be resolved such as overlapping detection and tracking results, and the lighting conditions of the video (i.e. too bright or too dark). Such issues could be improved by using more than one camera and by adding a filter to pre-process the video. The work of Kim & Chi (2020) is based on equipment tracking from multi-camera monitoring, action and interaction recognition. Their model was able to recognize the individual actions of excavators (i.e. "digging", "swinging full", "dumping", "swinging empty", "moving", and "stopping") and dump trucks (i.e. "moving" and "stopping"). Thus, as there is currently no standardised methodology for determining the actual productivity of heavy construction site, Šopić *et al.* (2021) proposed a simple research framework (SRF) for quick and practical estimates of excavator actual productivity in real construction site conditions (**Fig. 15**). The main contributions of SRF are estimated values of an excavator actual, maximum possible, productivity and cycle time related to one of the stages of earthworks at a construction site. With an insight into the productivity it is possible to estimate the required time and cost of the activity.

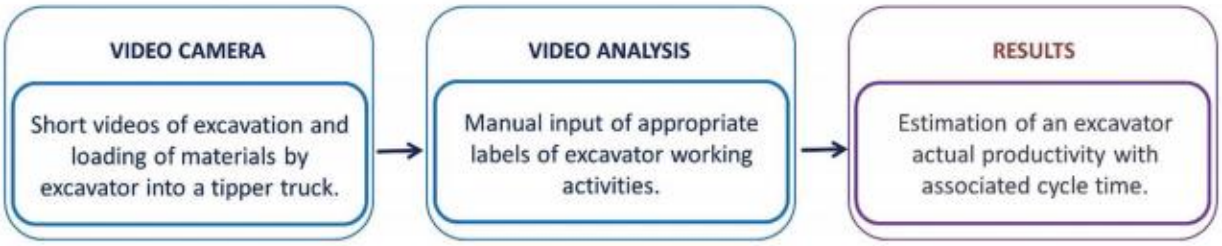


*Figure 14- SRF diagram with goals (Šopić et al., 2021)*

# 4 MATERIALS PRE-PROCESSING TECHNIQUES

Materials pre-processing techniques are defined in this report as the on-site preparation of the materials to 1) directly eliminate not valuable parts and unwanted impurities before their transportation to mineral processing and/or metallurgical plants, and 2) adjust the grain size distribution and other parameters to the requirements of the downstream plants.

The recovery potential of metallurgical waste is mainly determined from its chemical and mineralogical composition (Lim *et al*., 2016), which can be determined by characterisation techniques (see section 4.1). Based on these, industrial applications such as sensor-based sorting techniques can be developed, which are able to remove non-recoverable parts and impurities (see section 4.2.). The boundary between on-site material pre-processing techniques and mineral processing techniques may seem somewhat blurred as they are often the same processes and equipment as mineral processing, but smaller or sized to be suitable for on-site use. Section 4.3. describes these equipment and processes.

## 4.1 METALLURGICAL WASTE CHARACTERISATION

Materials can be characterised either by analytical tools, where the structure of the material is the sole determinant of the results, or by experimental tools, where the influence of the material on the environment is measured. Experimental tools includes leaching tests, dilatometry, among others, but these are not detailed in this work as the results depend as much on the environmental conditions as on the material itself (Heikkinen, 2021).

Many laboratory instruments and protocol exist to measure the chemical or mineralogical composition of minerals (**Table 5**), all of them require representative samples to be analysed.

*Table 5- Characteristics of analytical methods used to characterise metallurgical waste* (Heikkinen, 2021)*:*

| Analytical method | What is measured? | Pre-treatment? | Application and limitation |
|---|---|---|---|
| Light Optical Microscopy (LOM) | Microstructure: main and minor phase, grain size and morphology | Require polished samples | Often used as a pre-examination before electron microscope analysis |
| Electron microscopes, e.g. SEM, FESEM, TEM, EFTEM, STEM, EPMA, EDS, WDS | • Microstructure: phases and grains<br>• Chemical composition of the measured point (small area) | Require dry and polished samples in the form of solid/ powder particles | • It does not recognize the lightest elements<br>• Pre-examination with LOM is recommended |
| Mineral Liberation Analysis (MLA) | Identification of minerals/crystal phase in each particle | Require prior phase identification (XRD,EDS/WDS) on the | Often used in mineral processing (e.g. |

| | | | | |
|---|---|---|---|---|
| | | | basis of their chemical composition (SEM-EDS/WDS) and composition limits for phase identification | upgrading REEs from iron oxide-silicate rich tailings) |
| X-Ray Diffraction (XRD) | | Semi-quantitative identification of minerals and crystal phases | Usually require samples in the form of fine powder | ● It has difficulties recognising amorphous / non-crystalline phases (e.g. slag solidified as glass) |
| Atomic spectroscopy | Atomic Absorption Spectroscopy (AAS), e.g. F-AAS and GF-AAS | Quantitative analysis of the chemical composition | Require liquefied samples | ● High sensitivity and suitable for 60 metal elements analysis<br>● Time intensive, expensive analysis |
| | Atomic Emission Spectroscopy (OES) , e.g. ICP-OES and LIBS | Quantitative and qualitative analysis of the chemical composition | Samples can be solid, liquid or gaseous | ● High sensitivity and suitable for measuring a large number of atoms<br>→ ICP-OES: can measure all elements between Li and U except noble gases, halogens, O, N and C<br>→ LIBS: all elements can be measured |
| | Mass Spectroscopy (MS), e.g. ICP-MS and LA-ICP-MS | Quantitative and qualitative analysis of the chemical composition | Require ionisation (by plasma) before analysis:<br>→ ICP-MS: samples are dissolved in liquid solution<br>→ LA-ICP-MS: solid material can be analysed thanks to the vaporisation by laser beam | ● High sensitivity: very small amount can be measured<br>● In practice, the resolution is not good enough to separate all elements from each other |
| | X-Ray Fluorescence (XRF) | Quantitative and qualitative analysis of the chemical composition | No | Analysis is sensitive to matrix: it might need separate calibration from different type of samples |
| Infrared spectroscopy (IR) | | Qualitative and quantitative identification of phases/ compounds | No | IR and Raman complement each other: some compounds are only IR-actives and others only Raman-actives |
| Raman spectroscopy | | Identification of Raman-active phases | No | Sometimes it is difficult to identify peak |

Although all these analytical methods are perfectly suited for the identification of specific compounds, many of them require samples pre-treatment before they can be used. This is the case for example for atomic absorption spectroscopy (AAS), which require the sample to be liquefied. In addition, some equipment is not suitable for use in the field but rather requires laboratory handling due to its fragility. In general, while laboratory analyses remain the standard for providing the highest quality data possible, these measurements can be costly, and generally need intensive sample preparation and analysis time. In this way, the development of modern *in situ* techniques to analyse slag could be of considerable interest to contractors, as the metal recovery from slag depends mainly on its composition and mineralogy (Young *et al.*, 2016).

For all these reasons, the remainder of this section will focus primarily on a more comprehensive explanation of analytical methods that can be adapted on-site for rapid, cheap, non-destructive and accurate analysis (Brooks, 2020). According to Piatak *et al.* (2015), the most common method used in the literature to measure the mineralogy of slag is XRD, which is often combined with electron microscope such as SEM or EPMA. For total chemical composition analysis, it is reported that XRF is the most used technique, together with ICP-OES and AAS. However, as XRF and LIBS technologies have become particularly popular and have proven to be suitable for the development of portable devices, they are selected rather than ICP-OES and AAS. Thus, the analytical methods that have been selected and are explained in the following are Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF) and laser Induced Breakdown Spectroscopy (LIBS).

## 4.1.1 Scanning Electron Spectroscopy (SEM)

When an electron beam (with high-energy) strikes a sample, it can emit a range of signals, such as X-rays, light or electrons (**Fig. 16**). Two given electron microscopes will generally not capture the same signal as each is useful and provides different information about the sample.

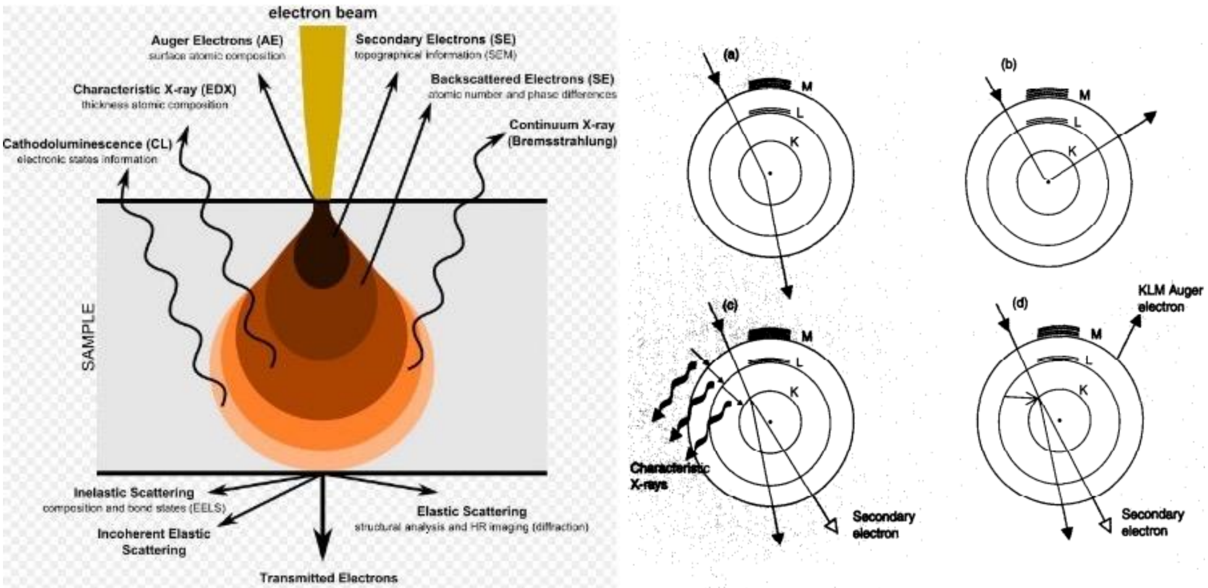


*Figure 15- Left: Types of signal generated caused by electron beam-sample interaction* (Thermo Fisher Scientific, 2021b).

*Right: Representation of the emitted signals according to the electronic layers of the atoms: (a) Low-angle scattering g - electrons scattered in this way pass to the next layer of atoms with very little loss of energy (b) Back (or high-angle) scattering; (c) Emission of a secondary electron and characteristic x-rays; (d) Emission of a secondary electron and an Auger electron* (Vernon-Parry, 2000).

Scanning Electron Microscopy is a powerful tool for capturing high-resolution images revealing the topography and crystalline structure of the sample surface (Hidayat *et al.*, 2018). In SEM, two types of electrons are collected by the detectors: the backscattered electrons (BSE) and the secondary electrons (SE) (Thermo Fisher Scientific, 2021b). The SE usually escape from the sample when an energy below 50 eV is applied, by being ejected from their orbits by an incident electron. The SE provide topographic information and some compositional contrast. The BSE are electrons that are scattered by incident electrons when they approach the nucleus closely enough. They are less numerous but have more energy than the SE and provide mostly compositional information and sometimes crystallographic information when electron channelling occurs (Vernon-Parry, 2000). The atomic number of the atom have a high impact on BSE imaging. The higher it is, the brighter the material will appear on the image.

### 4.1.2 X-Ray diffraction (XRD)

X-ray diffraction rely exclusively on the portion of an electromagnetic radiation of wavelength about $10^{-10}$m (X-rays) elastically scattered by electrons (Thomson scattering), to obtain information on crystalline structure at the atomic level (Bashir & Liu, 2015; Lavina *et al.*, 2014). Since the wavelength of an X-ray is similar to the distance between atoms in a crystal, the diffraction event, which is a consequence of an interaction between electromagnetic radiation and electrons, can be used to measure the distance between the atoms (Bruker, 2019; Lavina *et al*., 2014).

Elastic scattering occurs when x-rays are absorbed and then re-emitted by the electrons of an atom. At the scale of a crystal, the distance and alignment between the atoms will scatter the x-ray with a specific intensity and angle. An amplification of this signal (constructive interference) is produced by tilting the x-ray source and correspond to a specific angle (Bruker, 2019; Lavina *et al*., 2014).

In Bragg's law (**Fig. 17**) (1), diffraction is expressed as the reflection of X-ray by crystallographic planes defined by indices hkl (Lavina et *al.*, 2014):

$$n\lambda = 2d_{hkl} \sin\theta_{hkl} \quad (1)$$

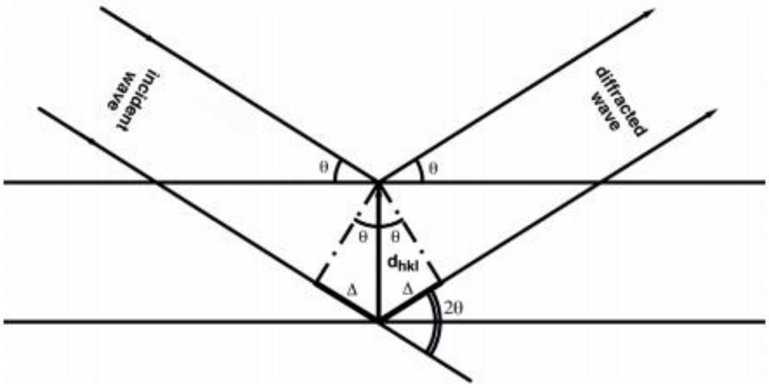


*Figure 16- Bragg's representation of the diffraction condition* (Lavina et al., 2014)

According to Bashir & Liu (2015), three XRD methods are mainly used: (1) X-ray synchronous diffraction, (2) single crystal X-ray diffraction and (3) X-ray powder diffraction.

#### *4.1.2.1 Single crystal X-ray diffraction (SXD)*

Single-crystal X-ray diffraction (**Fig. 18**) is used to determine the atomic arrangement and the structure of a crystal (e.g. minerals, alloys). When X-ray interacts with the crystal, it will diffract in directions of a certain angle and intensity. These directions and their characteristics will be used to construct a 3D image of the electron density, which reveals the average position of the atoms in the crystal. The length of chemical bonds between atoms, bond strength, their disorder and defects can then be determined (Bashir & Liu, 2015).

This method gives the most complete answer about the structure properties of ordered crystalline materials. However, SXD devices are cumbersome and the measurement is more time-consuming compared to other methods such as powder diffraction (Lavina *et al*., 2014). Moreover, it cannot provide reliable structural information for nanoporous materials, when the crystals or crystallites are too small or with highly polycrystalline morphologies (Logar *et al*., 2009). Sample crystals should therefore be carefully selected using a microscope in order to select crystals with a sufficient size (50-500 µm) and with the most homogeneous crystalline structure possible (Lavina *et al*., 2014).

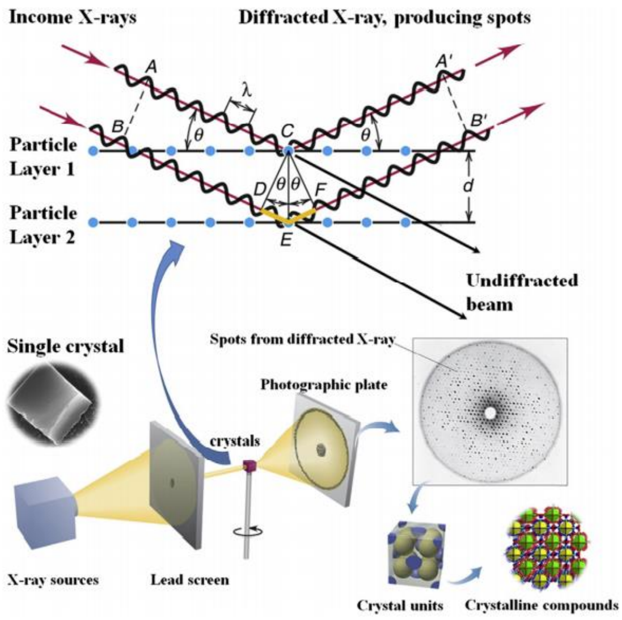


*Figure 17- Schematic presentation of single crystal X-ray diffraction* (Bashir & Liu, 2015)

#### *4.1.2.2 Synchrotrons soft X-ray synchronous diffraction*

The development of synchrotron radiation has led to advances in the field of microcrystallography, making it possible to analyse crystals measuring only a few microns. Moreover, synchrotron X-ray diffraction equipment (**Fig. 19**) allows *in situ* diffraction studies of the structural changes during crystallisation. Phase transitions and localisation of active metal sites in the structures are also made possible (Bashir & Liu, 2015; Logar *et al*., 2009; Sharma & Hesterberg, 2020).

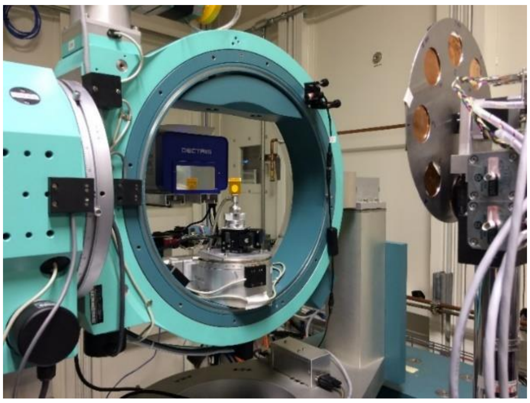

*Figure 18- Synchrotron X-ray diffraction* (NIST, 2019)

#### *4.1.2.3 X-ray powder diffraction*

X-ray powder diffraction is a rapid analysis of multicomponent mixture that can quicky identify its crystalline structure and provide information on phase identification, crystallinity, lattice parameters and physical strength. It is already used for material characterisation in metallurgy and mineralogy and can identify nanometals, metal oxides (such as $TiO_2$ and $Fe_3O_4$) and mesoporous materials (Bashir & Liu, 2015; Logar *et al*., 2009). In order to assure sufficient quality of powder diffraction results, satisfactory particle statistics are required, since powder cannot be reoriented as crystals for each diffraction event as done in single crystal experiments. In particular, $10^6$ micro grains of the sample in the X-ray illuminated volume are needed, with random/uniform distribution of grain orientations. If these are satisfied, then there exist grains that are randomly oriented into all the many diffracting conditions, and therefore diffraction from all of the lattice plane families is observed simultaneously. Powder diffraction performed with a polychromatic incident beam leads to a continuous diffraction signal without distinct spatially resolved peaks that can only be interpreted with an energy-resolving detector (Lavina *et al*., 2014).

### 4.1.3 Combination of XRD and Electron microscopy

Although several types of XRD analysers have been developed to meet various applications, XRD methods often fail to correctly describe amorphous/non-crystalline and mesoporous materials (Vernon-Parry, 2000). For this reason, many studies combine XRD analysers with SEM or EPMA in order to characterise the material completely (Herbelin *et al*., 2020; Steenkamp *et al*., 2018). However, according to Piatak *et al.* (2015), they can still fail to correctly represent the mineralogy in some cases, e.g. to determine the major and trace element composition of various phases or because the EPMA peak overlap for some elements, which can lead to erroneous measured concentration. Complementary analyses with Raman spectrometry or Transmission Electron Microscopy (TEM) are therefore recommended in order to supplement the characterisation with equipment that allows the representation of mineralogical and chemical variations on a nanometric scale.

### 4.1.4 X-ray fluorescence (XRF)

#### *4.1.4.1 How it works*

An electron can be expelled from a particular atom by x-rays interaction if the x-ray energy is higher than the binding energy of the electron in this atom. If this happens, the atom will be in an unstable energy state and will want to return to its initial energy level. To do so, the electrons in the outer layers will move to the inner layers, emitting secondary x-rays (fluorescence) (Brouwer, 2010). The energy of the emitted photons is equivalent to the energy difference between the shells. As each atom has its own energy levels, the energy of the fluorescent x-ray radiation produced is characteristic for each atom (Kalnicky & Singhvi, 2001). In practice, a material is composed of many elements. Fluorescent X-rays emitted by some of them after interacting with primary x-ray radiation can sometimes in turn eject electrons from other elements in the sample, a process called secondary fluorescence. Both primary and secondary fluorescence are measured by a spectrometer, and are impossible to be differentiated (Brouwer, 2010). **Figure 20** shows the x-ray fluorescence process and the difference between primary and secondary fluorescence.

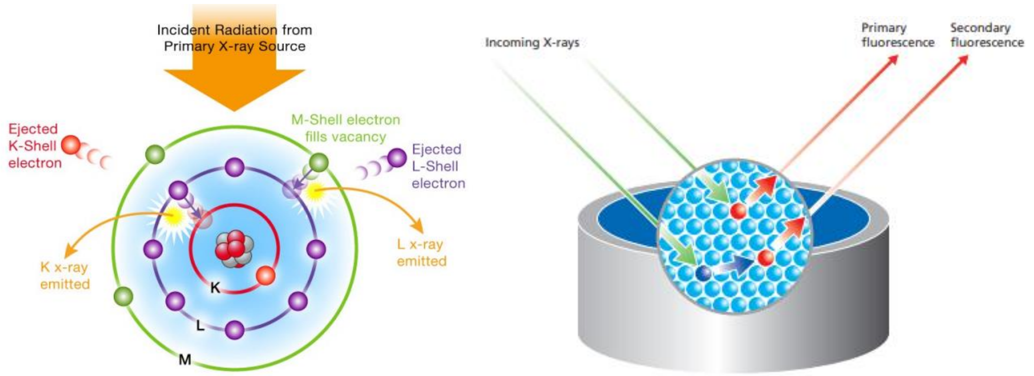


*Figure 19- Left: X-ray fluorescence process* (Yerly, 2014)*, right: primary and secondary fluorescence* (Brouwer, 2010)

Typical XRF spectrometers consist of a photon source for the excitation of incident X-rays, a sample support, a fluorescent X-ray detection unit and a data evaluation unit (figure 21). Even if some special application use Synchrotron radiation or charged particle accelerators, the source is usually an x-ray tube or radionuclides. Spectrometers are generally divided into two main groups according to their difference in the detection system: either the wavelength (wavelength dispersive X-Ray Fluorescence WDXRF) or the energy of the radiation (energy dispersive X-Ray Fluorescence EDXRF) is determined (Brouwer, 2010; Kramar, 2016). WDXRF uses crystals to disperse the fluorescence spectrum into individual wavelengths of each element and is based on Bragg's law, which states that crystals will reflect x-rays of specific wavelengths and incident angles when the wavelengths of the scattered x-rays interfere constructively (Yerly, 2014). The XRF spectrum (intensity (count per second) in function of energy (keV)) represents a qualitative and quantitative elemental analysis. Indeed, the energy (EDXRF) or wavelength (WDXRF) is characteristic of the element in the sample and the intensity of the peak can be directly related to the concentration of the element in the sample (Brouwer, 2010; Kramar, 2016).

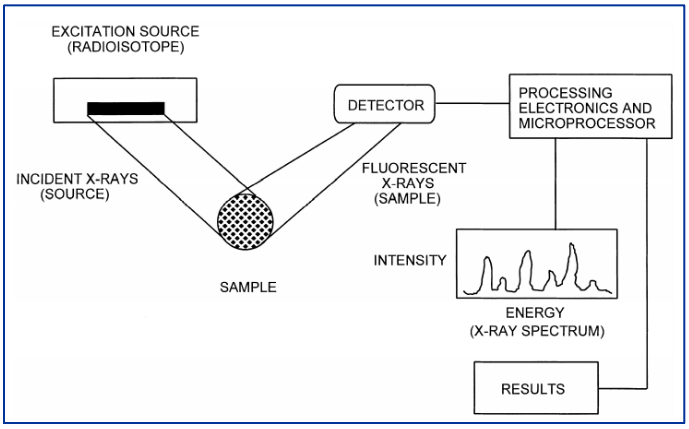


*Figure 20- Block diagram of a typical (ED)XRF spectrometer* (Kalnicky & Singhvi, 2001)

### *4.1.4.2 Characteristics and applications*

X-ray fluorescence is one of the simplest, most economical and accurate methods for determining the chemical composition of a wide range of materials, whether in solid, liquid or powder form (Spectro, 2021). XRF results are generally highly precise and reproducible and measurement time varies between seconds to 30 minutes, depending on the number of elements detected and the required accuracy (Brouwer, 2010).

WDXRF and EDXRF have their own specific characteristics, and the choice of one or the other technique depends on the purpose:

- **Energy dispersive X-ray fluorescence (EDXRF)** can be used to measure elements from sodium to uranium in concentrations ranging from (sub) ppm to 100% (table 6).
- **Wavelength dispersive X-ray fluorescence (WDXRF)** can analyse an even wider range of elements, from beryllium to uranium.

A comparison of these two methods is shown in **Table 6**.

*Table 6- Comparison of EDXRF and WDXRF, adapted from Yerly* (2014) *and Brouwer* (2010)

| | **EDXRF** | **WDXRF** |
|---|---|---|
| Elemental range | Na to U | Be to U |
| Sensitivity | Good for heavy elements analysis, less optimal for light elements | Good for heavy elements, reasonable for light elements and rare earths |
| Energy resolution | Poor in general (~150eV): good for heavy elements and less optimal for light elements | Better in general (15~150eV): less optimal for heavy elements and good for light elements |
| Costs | Lower operating costs (relatively inexpensive) | Higher operating costs (relatively expensive) |
| Power consumption | Energy efficient (from 5 to 1000W) | Less energy efficient (from 200 to 4000W) |
| Measurement | Simultaneous | Sequential/ simultaneous |
| Practical information | No moving parts and fewer optical components<br>More compact | Moving parts under vacuum (crystal, goniometer) |
| Sample size | All | Powder or liquid samples in a sample loading system |

Due to its wide range of elements analysed and its ease of use as solids requires no sample preparation, applications are very broads and include metal, cement, polymer industries and mining or geological use. While WDXRF are generally suitable for laboratory instrumentation, EDXRF is the technique of choice for field instrumentation as it is easier to use and more portable (**Fig. 22**) (Brouwer, 2010; Young *et al*., 2016). A wide range of XRF can be found on the market with several options available (Bruker, 2021; Olympus, 2020; Spectro, 2021; Thermo Fisher Scientific, 2021a).


*Figure 21- Left: General element range for EDXRF equipment (Hitachi, 2018), Right: Configuration of a typical hand-held EDXRF-analyser (from Thermo Fisher (2021), cited by Analytical Committee (2019))*

### 4.1.5 LIBS

LIBS is a type of atomic emission spectroscopy (AES or OES)[6] that uses a highly energetic laser pulse to excite the sample. Typical OES techniques requires (i) to vaporize the (solid, liquid or solution analyte form) sample into a free gaseous atom; (ii) Then, atoms are electronically excited to provoke optical emissions at discrete wavelengths which are characteristics of the atoms; (iii) Finally, the optical emission is collected, recorded and analysed (Cremers *et al*., 2016). In LIBS, OES steps (i) and (ii) are satisfied by the interaction between the high energy laser and the sample, which generates a hot plasma whose constituents can reach a temperature of 15,000K (14,726°C) (Noll, 2012). Light is emitted from the elements inside the plasma, which is then directed to a spectrograph for detection and analysis of atomic emission lines (Yañez *et al*., 2018). Although in reality the contact with the laser causes the vaporisation of part of the sample (Anabitarte *et al*., 2012), this method is still considered non-destructive, as this loss of sample is very small. However, it must be considered carefully in the context of archaeological analyses or in art, otherwise irreparable damage may be caused. **Figure 23** illustrates a typical LIBS setup and the impact of a laser pulse on the sample.

[6] Atomic emission requires a means for converting a solid, liquid, or solution analyte into a free gaseous atom, usually by applying a source of thermal energy as the excitation source. The most common methods are flames and plasmas, both of which are useful for liquid or solution samples. Solid samples may be analysed by dissolving in a solvent and using a flame or plasma atomizer (Khandpur, 2006).

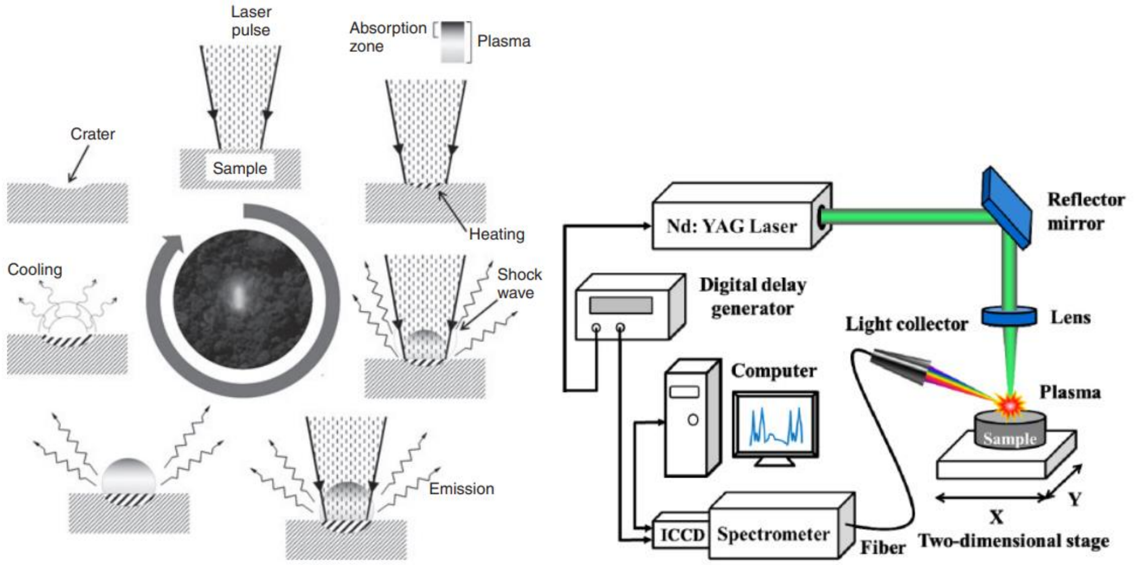


*Figure 22- Left: Interaction between a solid surface and a laser pulse during a LIBS (Cremers et al., 2016), right: LIBS spectrometer device (Zou et al., 2014)*

### 4.1.6 Comparison between XRF and LIBS

Recent advances in XRF and LIBS techniques in recent years have made them ideal candidates for the rapid analysis of the chemical composition of materials on site. The LIBS technique is more versatile than XRF as it is not limited by the atomic mass of the elements. The range of elements detected therefore also includes elements with an atomic weight lower than Na (Elias, 2021). However, according to Weiss (2017), LIBS is not yet cost effective on an industrial scale. Currently, LIBS is multiple times more expensive than XRF or XRT in terms of costs per tonnage and only a very few prototype installations exist worldwide. Sorting therefore starts primarily with the use of cheaper methods such as XRF, although it is possible that in some specific cases the need for further separation justifies a higher investment and the application of LIBS. A further comparison between XRF and LIBS can be seen in **Table 7**.

*Table 7- Comparison between XRF and LIBS (Anabitarte et al., 2012; Chen et al., 2015; Cremers et al., 2016; HORIBA, 2021; Portable Spectral Services, 2020; Quantum RX, 2021; Yañez et al., 2018) *For LIBS measurement, doing repeated measurement will ablate the outer layer of a few µm for each measure.*

| | (ED)XRF | LIBS |
|---|---|---|
| Elemental range | Na to U | All |
| Speed analysis | Few seconds to minutes depending on the case (5s/element | <100ms (or 1s for all elements) |
| Detection limits | ppm to high % | ppm to high % |
| Penetration depth | Few millimetres to few micrometres | Few micrometres (up to 10-20µm), except for repeated sampling* |
| Destructive method | No | Quasi non-destructive |
| Distance analysis | No | Yes |
| Sample preparation | Little: need a representative sample | |
| Moisture influence | Yes: as the humidity increases, the concentrations are diluted proportionally | |
| Costs | Relatively non expensive | Very expensive as it is very energy consuming |

LIBS and XRF techniques, although very useful for characterising the chemical composition of a predefined material, do not penetrate deeply into the sample. Indeed, their penetration depth varies from a few micrometres to a few millimetres depending on the material. For instance, if one wants to characterise the homogeneity in the metal composition of a heap at depth, geophysical techniques such as electromagnetic induction (EMI), electrical resistivity tomography (ERT) or ground penetrating radar (GPR) could be used.

## 4.2 Metal pre-concentration and sorting techniques: industrial installations and case studies

Even if the recycling of mining waste is not strictly speaking a new topic of interest, many challenges needed to be overcome to allow the economic profitability and viability of the industrial facilities. This business has seen a resurgence of interest in recent years, given the increased value of certain rare metals (Wimmer, 2021). This section focuses on the innovative industrial facilities that have been created by operators in recent years to sort minerals and metallurgical waste. In these installations, sorting is generally carried out based on on-line analysis of chemical and mineralogical composition. The sorting is completed by further steps to concentrate the metal (see section 4.3.2.)

### 4.2.1 Leading companies in the sorting and recycling of metal waste

- Sensor-based sorting systems

REDWAVE was the first company to create sorting machines based on XRF technology. Thanks to its 12 years of experience in the field, it is now the world leader. Although the facilities were originally intended more for the waste recycling sector (glass, plastics, aluminium alloys), a wide range of facilities is now available on their website. The modular plants are a real advantage for scrap recyclers as they can be easily adapted to the project and the material to be recycled (REDWAVE, 2021h; WtERT, 2017). The XRF analyser allows rapid analysis of the chemical composition and sorting can be done according to a desired concentration limit or ratio between different elements, e.g. Mn/Fe.

The functional principles of the REDWAVE XRF 2-way belt type and REDWAVE XRF/C 2-way free fall system is shown in **Figure 24**. The technical characteristics of the REDWAVE facilities that are suitable for the sorting of metallurgical waste are described in **Tables 8 and 9**.

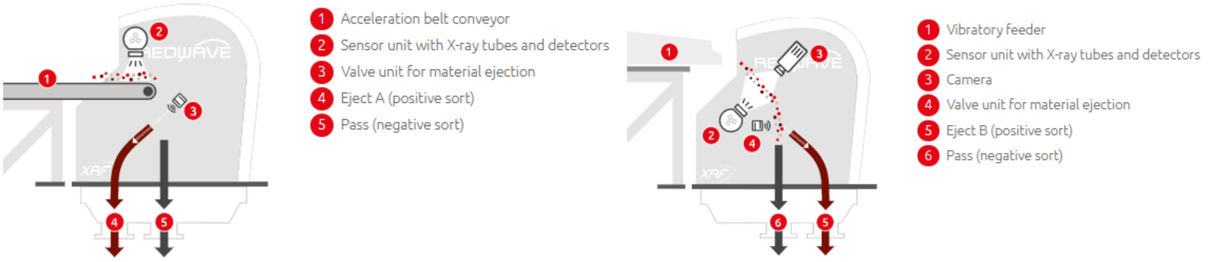


Figure 23- Functional principle of REDWAVE XRF 2-way belt type (left) and REDWAVE XRF/C 2-way free fall system (right) *(REDWAVE, 2021h)*

*Table 8- Technical characteristic of some REDWAVE facilities adapted to metallurgical waste sorting (Environmental XPRT, 2021; REDWAVE, 2021g, 2021h)*

| | REDWAVE sorting installation | | |
|---|---|---|---|
| | XRF-M | XRF/C | XRF-ROX |
| Technology | EDXRF | combination of EDXRF and camera | simple or combined technology (e.g. C, NIR, XRF) |
| Detection and sorting based on | chemical composition | chemical composition, colour | colour, brightness, transparency, chemical composition |
| Execution | Chute system<br>2-way or 3-way | 2-way belt or free-fall system | single/double-side detection, 2-way system |
| Sorting width | 900-1370mm | | up to 2000mm |
| capacity | up to 28-30 t/h (depending on the sorting width) | | up to 200t/h (depending on grain size and bulk density) |
| Sortable fraction | 15-120 mm cullet size | see table 9 (case studies) | 2-300mm |
| Sortable materials | Zorba, Zurik, IBA, Heavy metals, Ores (mining) | | minerals, ores and stones |
| Influence of water content on sorting quality | sort wet and dry material | | sort wet and dry material |

*Table 9- Companies that have used a REDWAVE XRF-C machine for sorting operations, case studies (REDWAVE, 2021d, 2021c, 2021e, 2021b, 2021a, 2021f)*

| | Case studies | | | | | |
|---|---|---|---|---|---|---|
| | VA ERZBERG GMBH: mineral sorting/processing of ore | CFO & FILHOS SA: sorting of various non-ferrous metals | MAYER RECYCLING GMBH: sorting of various non-ferrous metals | STENA RECYCLING: sorting of various non-ferrous metals and ZURIK | RMBSpA: sorting of various non-ferrous metals and IBA | SDI LA FAGA LLC: Sorting of Birch/Cliff-copper scrap |
| Type of machine | REDWAVE 1370 XRF-C G36 2-way | REDWAVE 900 XRF-SDD/C 2W easy upgrade | REDWAVE 900 XRF-SDD/C 2W | REDWAVE 1370 XRF-SDD/C2W | REDWAVE 1370 XRF-SDD/C 2W | REDWAVE 1370 XRF-SDD/C2W |
| Input material | Carbonate iron ore deposit | Sorting of ZORBA in aluminium (TWITCH) and heavy metals (ZEBRA) Sorting of ZEBRA in high purity products of copper, brass, zinc, stainless steel, aluminium, etc. | Various non-ferrous metals from ZORBA or incinerated bottom ash; Sorting of copper, brass, zinc, stainless steel, aluminium, etc. | ZEBRA (heavy metals) from dense media and ECS ZURIK (stainless steel) from dense media and ECS Sorting of ZEBRA and ZURIK into high purity products of copper, brass, zinc, stainless steel and stainless steel alloys, aluminium, etc. | Various non-ferrous metals from ZORBA or incinerated bottom ash; Sorting of copper, brass, zinc, stainless steel, aluminium, etc. | Birch/Cliff- copper scrap |
| Capacity (t/h) | 100 t/h | Depend on sorting step: 1 or 5-6 t/h for one sorting machine | Depending on sorting step: 4-8 t/h | Depending on sorting step: 5-10 for one sorting machine | Depending on sorting step 2-8 t/h; for one sorting machine | 10-15 t/h |
| Sensor system | XRF in combination with colour recognition | Combination of XRF and camera | | | | |
| Grain size | 30-100 mm | 8-30 mm, 30-70 mm and 70-120 mm | 15-45 mm, 45-120 mm | 20-60 mm, 60-120 mm | 10-20 mm, 20-50 mm, 50-100 mm | 10-150 mm |
| Working width | 1,370 mm | 900 mm | 900 mm | 1,370 mm | 1,370 mm | 1,370 mm |

Note: *ZORBA: shredded and pre-treated non-ferrous scrap metals, ZEBRA: non-ferrous heavy metals ZURIK: concentrate of metals produced by separators that recognize the presence of a metallic element within a stream of material, IBA: Incinerated bottom ashes, TWITCH: floated, fragmented scrap stream derived from a dry or wet density separation technique that must be dried after processing and may contain no more than 1% free zinc, 1% free magnesium, 1% of free iron.*

Similar sorting systems have also been developed by other companies such as:

- TOMRA is an active company and a trusted supplier for dry beneficiation of ores and minerals (TOMRA, 2021a). The sensor-based sorting equipment that they develop and are based on various detection technologies: colour, Near-Infrared (NIR), X-ray Transmission (XRT), EM and laser (TOMRA, 2021b). Their installations are mainly used in the mining industry, e.g. for ore and minerals sorting but dry sensor-based metal slag sorting system have also been created. Their sorting algorithm can be easily adapted and is thus able to separate different types of slag and/or metals (TOMRA, 2021c).
- Steinert is a company that also develops sorting plants for various applications (recycling of waste, metals, slag and ash and for the mining industry). They accompany their customers in their project and offer the possibility to include modules for the preparation (e.g. zig-zag classifier, cyclone) or separation (e.g. Eddy-current, electromagnetic drums) of materials (STEINERT, 2021b, 2021a). This year they created the UniSort machines, which is a fully automated sorting system that uses high-speed delta robots (60 picks per minute) (STEINERT, 2021c)
- The MULTIPICK project aims to build a robotic installation for sorting metals from dismantled vehicles or used household appliances. Sorting will be carried out using a combination of different sensors: XRT, hyperspectral and a 3D-scanner. The intelligent system is able to learn automatically from the data collected by the sensors, which makes it possible to classify each waste according to different categories (zinc, copper, brass, lead, stainless steel) (MULTIPICK, 2021). In the end, the installation that will be built is very similar to the UniSort machines created by Steinert.

### 4.2.2 Qualities, defects, and challenges of some industrial innovations

#### *4.2.2.1 On-line industrial XRD-XRF analyser*

In general, it has been seen that the mining industry relies mostly on XRF technology combined with XRD to characterise minerals (CSIRO, 2021). However, XRD analysis has long been largely confined to punctual analyses (in laboratory or on-site thanks to compact instruments) but has not yet been adapted on a large scale to analyse a continuous stream of material. In the early 2000s, in-line XRD analysers were invented (**Fig. 25**), initially for use in Portland cement manufacture (Madsen & Nikolov, 2002; Scarlett *et al*., 2001; Summit *et al.*, 2003). At first, the sample feed system was first limited to dry feed materials. Since then, these facilities have improved, but they are still not widely used by companies.

A major advance in the development of in-line XRD devices have been achieved by CSIRO and FCT ACTech. These companies have succeeded in developing systems that are not only suitable for slurries, but which combine XRF and XRD technologies. In this way, it is capable of measuring both mineralogy and ultra-low-elemental composition directly in the process stream.

The XRDF, developed by CSIRO, is at first sight more suitable for suitable analysis and the flow rate can be adapted up to 100 litre per minute (CSIRO, 2021). The $CMX_{\beta}$, developed by FCT ACTech can also be adapted for slurries and realise ultra-fast analysis. Twenty complete analyses of the material chemistry and composition are done every hour (FCT ACTech, 2021).


*Figure 24- Left: continuous XRD analyser applied to cement (Summit et al., 2003) , right: $CMX_{\beta}$ dual XRD and EDXRF analyser (FCT ACTech, 2021)*

Despite all these innovations and widespread use of XRD technology, as stated in Wills & Finch (2016) and as already explained above (see section 4.1.3.), quantitative XRD analyses can be erroneous for non-crystalline and too small material (<100nm) or due to matrix effects.

XRF technology is not exempt from its own shortcomings. As the analysis of the chemical composition is only carried out on a thin layer, it is essential that this layer is representative for the analysis to be valid. Furthermore, light elements are not analysed by XRF, which can fortunately be corrected by using LIBS analysis in combination.

As analysers with combined technologies have emerged, it is hoped that scientists will investigate the creation of XRD/XRF analysers coupled with other complementary techniques to compensate for the shortcomings of XRD and XRF.

#### *4.2.2.2 On-belt analysis*

Scantech has created GEOSCAN-M (**Fig. 26**), which is an on-belt, non-contact elemental analysis system specifically designed for mineral application and material recycling (Scantech, 2015b). It works via a radiation source (Cf-252) placed under the belt, which generates neutrons that pass through the material. They will interact with the element nuclei and allow the emission of gamma ray emissions characteristic of the elements (Wills & Finch, 2016). The measurement is typically performed every two to five minutes and the elements that can be analysed include calcium, silicious, aluminium, copper, zinc, nickel, iron, potassium, titan, manganese , sulphur, chlore, magnesium and sodium (Scantech, 2015a). The moisture is also measured using the microwave transmission technique, and the elemental analysis is corrected by taking into account the moisture content (in order to obtain elemental analysis on a dry basis) (Wills & Finch, 2016).

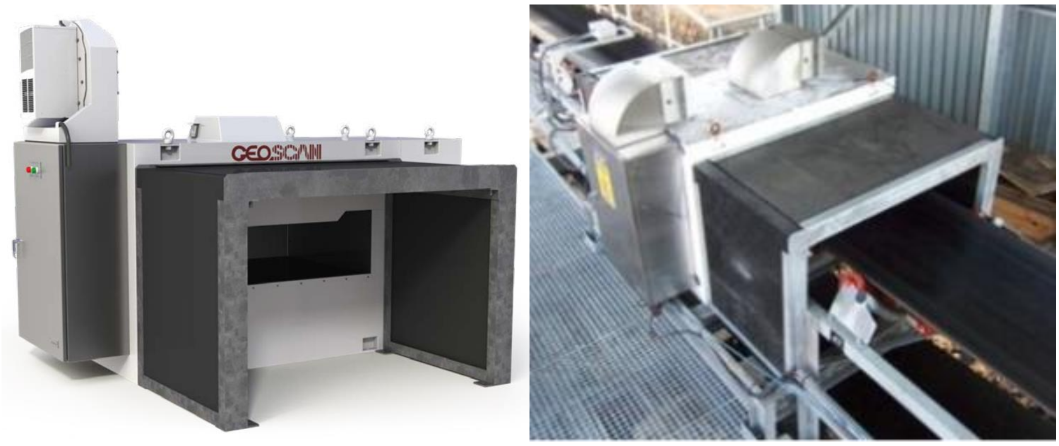


*Figure 25- Geoscan-M, developped by Scantech (IndustrySearch Australia, 2021)*

The LIBS technology has also been developed for on-belt analysis, but as it has been reported section 4.1.6, LIBS is not yet widely used due to high costs.

## 4.3 Mobile mineral processing equipment

The methods for separating and concentrating metallic elements from metallurgical waste are often identical to the ones for mineral processing. However, some adaptations still need to be made to make these processes appropriate for use on site. What is sought to be used in the NWE-REGENERATIS project are either mobile or semi-mobile plant, suitable for assembly and disassembly after a few months or years of treatment. Semi-mobile plants are often called "portable" by equipment manufacturers because they are usually modular and can be transported on a low-bed truck or in truck-mounted containers. Sometimes containers that can be stacked together and contain heavy equipment requiring a crane are described as "portable" or “mobile”, but they are not mobile in the true sense of the word (AT mineral processing, 2019b). It may require a few weeks (i.e. 4 to 10) to transport, install, test and begin to operate a semi-mobile plant on site.

Currently, only size reduction processes (screening and crushing) are used on a large scale in portable devices but this is not yet always the case for other mineral treatment processes. According to AT mineral processing (2019a, 2019c), processes identified for potential conversion to mobile applications, although not limited to, include grinding, ore sorting, high intensity leaching, froth flotation, dewatering technologies, magnetic and Eddy current separation. Some of these methods have been successfully developed for on-site physico-chemical treatment plant for polluted soil. These will be briefly explained in the following lines but we recommend to consult the *Deliverable WP T1. T1.3.3 Benchmark report on mineral processing for potential resources extraction for reuse on a PMSD* written by Mignon *et al*. (2021) for more detailed information.

## 4.3.1 Size reduction and control

Size reduction is (by tonnage) the largest process operation in mineral processing. It must be properly carried out, as mis-grinding can lead to severe performance losses in separation, sedimentation and dewatering.

### *4.3.1.1 Crushing and grinding*

Size reduction starts by crushing rocks and minerals as finely as possible, the ideal particle size to reach being usually between 11 and 32 mm, where the product value is at its highest (**Fig. 27**).

Once the mineral reaches a size <100 mm, grinders need to be used instead of crushers. Grinding is carried out by tumbling, stirring or vibration, until the size is reduced in the interval 100-10 micron.

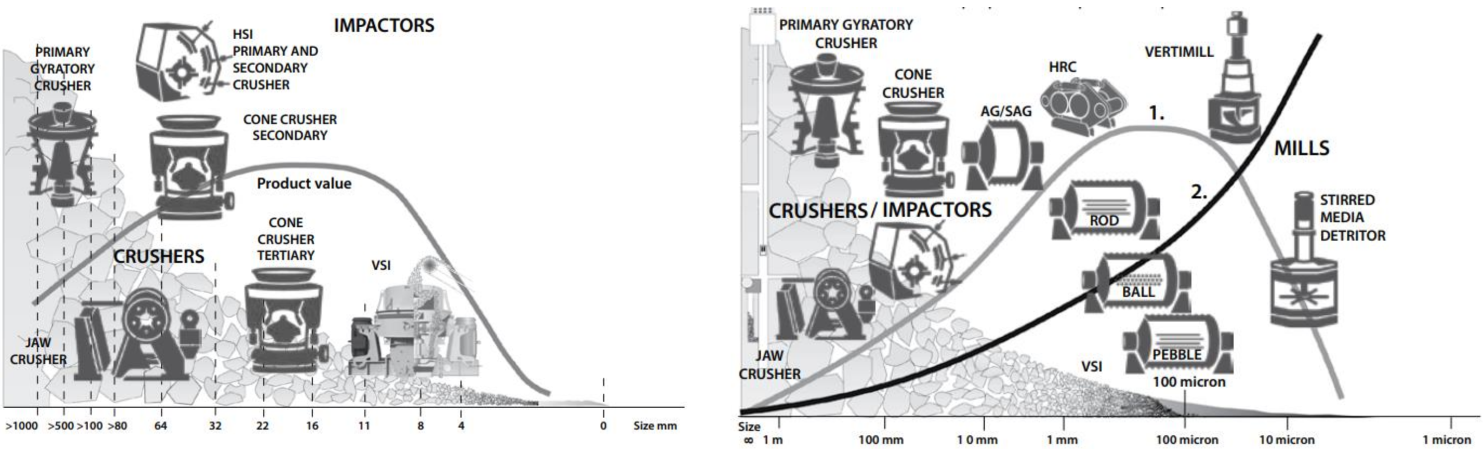


Figure 26- Left: crushing of rock and minerals, right: crushing and grinding of ore and minerals (Metso, 2015)

The crushing and grinding circuit is composed of a succession of crushers and grinders selected according to the material being ground and the reduction ratios of the crushing/grinding machines used. Crusher and grinder generally have limited reduction ratio, as large reduction ratios are inefficient in most of the case. It is therefore recommended to set several grinding/ crushing stages. A couple key parameters need to be known about the feed material: its "crushability or grindability" (work index $W_i$ kWh/sh.ton) and its "wear profile" (abrasion index $A_i$) (Metso, 2015).

#### *4.3.1.2 Size control: classification*

As crusher and grinding are generally not very precise in reducing to a homogeneous size, screens are used to control the size for the coarser part of the process (above 1-2 mm). Spiral classifiers are then used in the finer part (<1 mm) of the process (Metso, 2015).

Screens, or direct grading, use a geometrical pattern for size control, whereas classification (indirect grading) uses particle motion for size control.

In addition to the objective of selecting oversize particles before regrinding, another objective of the particle size control equipment may be to select a specific particle size in case the ore content differs according to particle size and needs to be separated accordingly (Metso, 2015).

#### *4.3.1.3 Some examples of mobile equipment for size control*

**Table 10** shows examples of mobile crushing and size control equipment produced by the most well-established crushing manufacturers.

*Table 10- Some example of mobile crushing equipment* (AT mineral processing, 2019b, 2019c; FLSmidth, 2021b; Joy Global, 2012; Machineryline, 2021; Metso Outotec, 2019, 2021b, 2021a; Mignon, 2021; Mining Life, 2021; Truck1, 2021)

| Manufacturer and range of products | Mobile equipment manufactured | Use and strength | Notes |
|---|---|---|---|
| Metso | Lokotrack jaw crusher range  | ● Suitable for primary crushing of hard rock and recycling products. | ● Designed to be used with the Lokolink conveyor system. |
| | Cone crusher  | ● Suitable for secondary crushing and screening application. ● Some models are suitable for multistage crushing. ● Can produce up to three end products. | |
| | Impact crusher  | ● Suitable for softer rock such as limestone, or for asphalt and concrete crushing. ● Some models are suitable for multistage crushing. | |
| Atlas Copco (AC) "Powercrusher" range | Jaw crusher | ● Increase throughput, minimise blocage and produce a uniform product | ● Powered by CAT engines and include pre-screening. |

| | | | |
|---|---|---|---|
| |  | | |
| | Cone crusher<br> | ● Accept most sizes of feed including abrasive rocks. | |
| | Impact crusher<br> | ● Adapted to primary and secondary crushing of soft to medium hard material. | ● The position of the swing beams which carry the hammer allows for a wide gap. |

| | | | |
|---|---|---|---|
| | Mobile vibrating screens | | ● Can be operated in tandem with a mobile crusher or fed separately by a loader or excavator. |
| FLSmidth | Fully mobile products designed for mining use: Dual Truck Mobile Sizer (left) and the Triple Track Mobile Sizer (right) or PF series crushing station (below)   | ● PF series crushing station are tailored and customisable to specific application, upstream and downstream plant capabilities and unique circumstances. | ● Triple Track Mobile Sizer is tailored to overburden removal and waste stacking. |

<table>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>Reflux Classifier plant (RC)<br>
</td><td>● Suitable when the quantities does not justify the building of a dedicated fixed plant.<br><br>● Allows a capacity of about 100 t/h.</td><td>● Fine particle gravity based separation technology, which incorporate the “Laminar high shear rate” mechanism.</td></tr>
</table>

| | | | |
|---|---|---|---|
| Joy Global Inc. | Heavy duty tracked mobile crusher, designed to be loaded by face shovels  | ● Can handle 9000 t/h and produce a finished product size of 360-400 mm. | ● Comprise an apron feeder, a double roll crusher and a discharge conveyor. ● Can be equipped with a breaker hammer. |

In addition to these examples, other companies can also be mentioned, such as (AT mineral processing, 2019b):

- The Swiss company Sandvik, which produces a variety of tracked and wheeled mobile (cones and impact) crushers, along with a range of one, two or three deck screen models. Their crushers have mining applications and are also suited for quarries, civils and recycling markets.
- The German company "ThyssenKrupp" produces a range of mobile and semi-mobile crushers that can achieve outputs of up to 14,000 t/h.
- The subsidiary Kleenmann (Wirtgen group), also offers a range of jaw, impact and cone mobile crushers, as well as mobile screens.
- The company BHS-Sonthofen supplies mixing technologies (mixers), crushing technologies (impact mills, impact crushers) and filtration technologies for mining industry. Their vertical-shaft impact mills (BHS Rotor Impact Mill) is suitable for crushing low to moderately abrasive mineral and it represents a potential solutions where selective crushing processes are required. BHS-Sonthofen offers also Rotor Centrifugal Crusher, which is a high-performance crusher, suitable for all types of minerals, with a vertical shaft for throughput rates of 30–400 t/h. Finally, BHS-Sonthofen also supplies rotot impact mills (type RPM) and rotor centrifugal crushers (type RSMX). They use a combination of impact and shear forces, which allow them to selectively crush composite materials.
- Maschinenfabrik Köppern Gmbh &Co. KG developed the high-pressure grinding roll (HPGR), which is emerging as an important comminution technology in the mineral processing industry.
- The company TAKRAF also produces HPGR as well as flotation cells, roll crushers and fully mobile crushing plants.
- Terex corporation's range of products comprises jaw crushers, cone crushers, vertical/horizontal shaft impactors, and screening equipment. Their size reduction and screening technologies are available in a variety of size, in a modular or mobile format, and have been employed for mineral processing operations around the world.
- The British company Parker Plant offers crushing and screening plants for primary, secondary and tertiary applications. Parker's range of crushing equipment and vibrating screens are available in any configuration of tracked, wheeled or static unit.
- Hewitt Robins International Ltd. supplies mobile screens on tracks, wheels or skid mounted frames. The mobile range is available as inclined, horizontal or high-energy screens and in multi-deck configurations.

Mobile grinding circuits are less predominately feature in the minerals industry than mobile crushing circuits. The Loesche company produced a mobile grinding mill since 1928 but it is not a mobile plant in the true sense of the word, as it comes in three or more containers. This plant is called the ore grinding plant (OGP), and it can grind down to 90 μm, with an output limited to 2-4 t/h of soft rock. Otherwise, the Sepro Tyre Drive Mill developed by Sepro Mineral Systems Corp. is suited for small capacity application and can be adapted and integrated into modular mobile grinding circuit. It has a variable frequency drive system that allows the operator to fine tune the operation to suite the mining application (AT mineral processing, 2019b).

### 4.3.2 Preconcentration and beneficiation

Ore concentration is the process of removing gangue and other impurities from the ore and beneficiating it. Before considering the use of any separation technique, washing can be performed using wet screens, scrubbers, attrition cells or gravity beds. Those allows to simply remove surface impurities like clay, dust, organics or salts (Metso, 2015). Pre-concentration techniques, such as the sensor sorting technologies described above (see section 4.2.) are well suited to rejecting significant portions of impurities before going further in separation. Although none of the optical and X-ray sorters described in section 4.2 appear to be strictly mobile, this technique looks promising and mobile or semi-mobile installations could be developed in the future.

The main separation techniques used in mineral processing for beneficiation are described in **Table 11**. The choice of a particular separation method is based on the nature of the ore. The separation methods that can be adapted for mobile or semi-mobile use are explained below. They include dense media separation, gravity separation, froth flotation, magnetic and electrostatic separation.

*Table 11- Selection of separation techniques, adapted from Mignon et al.* (2021) *and Metso (2015)*

| Separation based on | Selection criteria for the separation technique | Example |
|---|---|---|
| Density | The materials to be separated have a large difference in density. | • Gravity concentration: in water or in dense media<br>• Differential acceleration<br>• Flowing film concentration method |
| Magnetic susceptibility | The elements to be separated have magnetic properties. | • Low intensity magnetic separation<br>• High intensity /gradient magnetic separation |
| Electrical conductivity | There are both conductors and non-conductors to be separated. | • Eddy current separation<br>• Electrostatic separation |
| Water affinity/ hydrophobicity | | • Flotation |

#### *4.3.2.1 Separation based on density*

Gravimetric methods are wet techniques that allow separating components based on their difference in density (Dd) (**Table 12**). The higher the Dd, the easier it is to separate the constituents.

It can be classified in two categories (Metso, 2015):

1) **Separation in water (gravity concentration)**:

$$Dd = \frac{(D_{heavy\ mineral} - 1)}{(D_{light\ mineral} - 1)}$$

2) **Separation in a heavy medium (dense media separation (DMS))**:

$$Dd = \frac{(D_{heavy\ mineral} - D_{heavy\ media})}{(D_{light\ mineral} - D_{heavy\ media})}$$

*Table 12- Possible separation according to the Dd value* (Metso, 2015; Mignon, 2021)

| Dd value | Separation | Applicable |
|---|---|---|
| >2,5 | Easy | Down to 74-100 µm and lower |
| 1,75-2,5 | Possible | Down to 150-212 µm |
| 1,5-1,75 | Difficult | Down to 1,7 mm |
| 1,25-1,5 | Very difficult | Only for gravel and eventually sand |
| <1,25 | Not possible | No |

- Gravity concentration

The differential acceleration principle is a gravity concentration method that is realised in jigs. The periodic oscillation applied to the liquid generate a differential sedimentation between the heavy and light particles: the heavy particles group together and settle faster than the light particles. Jig separators are composed of a frame with an opening grid, a discharge device, a container to collect the particle passing through the grid and a mechanism to apply pulse and suction cycles.

The wet flow film concentration method, realised either in spiral concentrators or in shaking table, consists of distributing the solid-water mixture to be separated in a thin layer over an inclined surface. The difference in size, density and shape of the particles gives them a variable falling speed and resistance to movement, thus allowing them to be separated.

Jigs and shaking tables are identified for the recovery of minerals containing metals such as gold, tungsten and tin in a mobile processing environment.

Centrifugal separators such as the Knelson and Falcon concentrators are often found in stationary plants to recover liberated gold ahead of cyanide leaching circuits. The units have a small footprint and can be used to concentrate a variety of minerals, with a throughputs range from 1-1000 t/h. These units could potentially be used in a mobile setting.

- Dense medium separation

Dense media separation takes place in fluid media with a density between that of the light and heavy fractions that are to be separated. Separation depends only on the density of the particles and the density of the fluid so the fluid must be chosen according to the material to be separated (**Table 13**). If this condition is satisfied, the lightest particles float to the surface while the heaviest particles fall to the bottom. Ferrosilicon powder (for higher density separations) or magnetite-based medium (for coal applications) is commonly used to adjust the density of the medium.

*Table 13- Density of some fluids and solids*

| Nature of the fluid or solid | Density |
|---|---|
| Water | 1 |
| Zinc chloride | 1 - 1,3 |
| Calcium nitrate or chloride | 1 – 1,3 |
| Clay | 1,3 – 1,6 |
| Barite | 1,8 - 2,5 |
| Magnetite | 2,2 – 2,4 |
| Ferro-silicon | 3,1 – 3,3 |

Sepro Mineral Systems offers customizable and transportable Dynamic Dense Medium Separator Plants for a wide variety of application, e.g. the dynamic, multi-stage Condor Dense Medium Separator (DMS). This unit has a minimum of two separation stages, which result in high product separation efficiency in rougher/scavenger or rougher/cleaner dense medium multi-product applications. Sepro's standard two product (concentrate, tailings) Dense Medium Separator Plant requires a two stage Condor DMS and single density medium circuit, while the three product (concentrate, middlings, tailings) Dense Medium Separation Plant uses a three stage Condor DMS and two medium circuits at high and low density.

Modular, relocatable and mobile drum dense media separator were also produced by some manufacturers. As an example, FLSmidth supply the Wemco® Heavy Media Separation, which is a dense media separation for coal and minerals in the size range of 300 – 6 mm.

#### 4.3.2.2. Separation based on magnetic susceptibility and electrical conductivity

##### Separation based on magnetic susceptibility

Magnetic separation allows separating magnetic particles from non-magnetic and diamagnetic particles by creating an environment combining magnetic forces (Fm), gravitational forces (Fg) and drag forces (Fd) (**Fig. 28**):

$$F_m = V.\chi.H.\ \mathrm{grad}\ H$$

Where V and $\chi$ are characteristic of the particle and correspond respectively its volume and its magnetic susceptibility. H and grad H depend on the magnet system design, where H is the magnetic field created (in milliTesla (mT) or kilogauss (kG)[5] ) and grad H is the magnetic field gradient (in mT/m) (Fears, 2018; Metso, 2015).

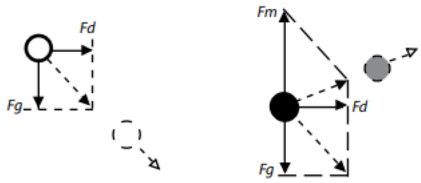


*Figure 27 - Magnetic separation (Metso, 2015)*

Magnetic susceptibility is defined by the ratio of the intensity of magnetisation produces in the material to the magnetic field which produces the magnetisation (Wills & Napier-Munn, 2006). Minerals can be classified according to their magnetic susceptibility into four groups (Metso, 2015; Mignon et al., 2021):

- **Non-magnetic:** minerals that have no magnetic properties
- **Diamagnetic:** minerals that are weakly repelled by the application of a magnetic field, due to the development of a magnetic opposite moment through induction. They have a low magnetic susceptibility ($10^{-9}$ $m^3$/kg).
- **Paramagnetic:** minerals slightly attracted by an applied magnetic field. Their susceptibility ranges from 0,5x $10^{-6}$ to $10^{-7}$ $m^3$/kg and is independent of field strength and temperature.
- **Ferromagnetic:** minerals characterised by a high magnetic susceptibility ($10^{-2}$ to $10^{-4}$ $m^3$/kg), dependent on the field intensity, the temperature and, in some cases, on the crystallographic structure of the particle.

Non-magnetic and diamagnetic ores cannot be concentrated magnetically because the forces involved are very small.

- **Low intensity magnetic separation** is specifically designed to recover ferromagnetic constituents.
- **High intensity magnetic separation** is designed to separate paramagnetic minerals from diamagnetic and non-magnetic constituents.

For both methods, wet and dry equipment is available.

### Separation based on electrical conductivity

When conductive particles pass along a row of permanent magnet of alternating polarity or by the rotation of a pole wheel inside a conveyer drum, repulsive forces are developed in response to the alternating field generated by the poles. The **Eddy current separator (ECS)** use this phenomenon to physically repel non-ferrous metals, which enables a separation from non-conductive material (Bunting, 2021; Mignon et al., 2021). The ECS is often part of an entire module where a preliminary separation is first performed by a drum magnet to remove ferrous particles (**Fig. 29**). Generally, ceramic-type high-field magnet are used to generate an alternative magnetic field.

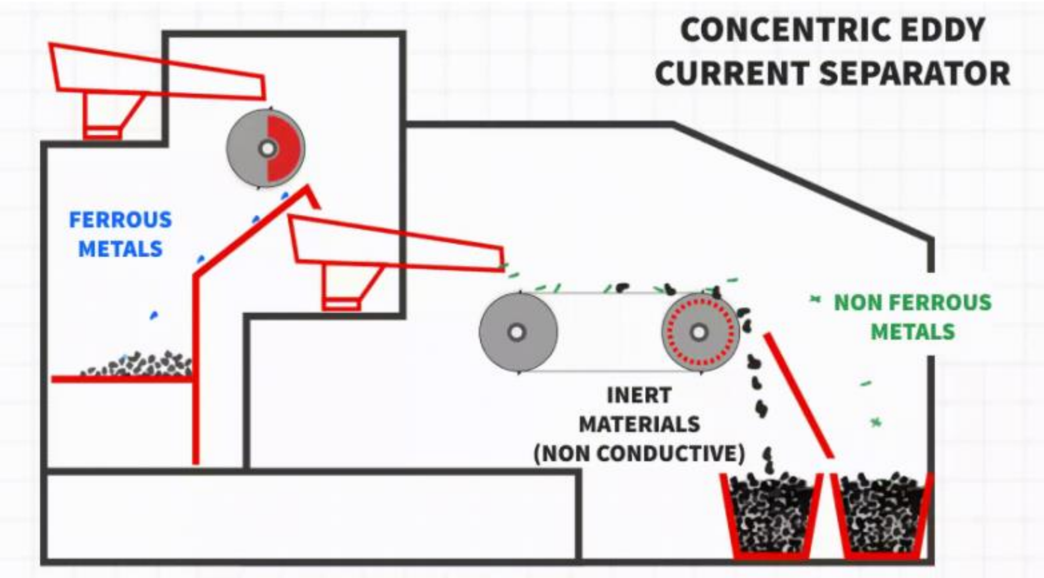


*Figure 28- Eddy current separator (Fears, 2020)*

The greater the ratio between the electrical conductivity and the density of the particle, the greater the intensity of the repulsive force that is developed. When a high voltage is applied between two electrodes, the gas ionizes and forms a continuous flow of gaseous ions, which is called a corona discharge. In **electrostatic separation devices**, when particles pass through the corona, they are bombarded with ions and develop a surface charge (positive). After ionisation, the charged particles pass over a negatively charged roll. The particles will then behave differently on the roller depending on their conductivity. Non-conductive particles will be attracted by the roll as they tend to lose their charge slowly. On the other hand, conductive particles lose their surface charge relatively rapidly and are therefore ejected from the rotor due to the combination of centrifugal, gravitational and frictional forces. Electrostatic separators (**Fig. 30**) are very useful to separate particles that Eddy current separator did not manage to process. It is particularly suitable for finer grain size mixture (60-500 µm) (Fears, 2020; Mignon et al., 2021; Wills & Finch, 2016).

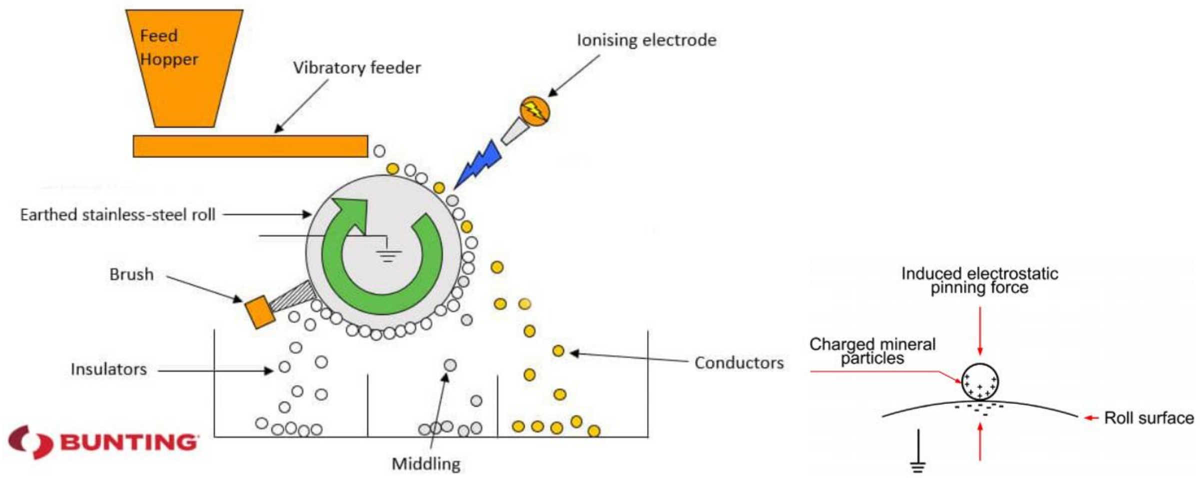


*Figure 29- Left : Electrostatic separator (Fears, 2020) and right: representation of forces (Wills & Finch, 2016)*

#### Mobile equipment

Most of the magnetic and electrostatic separators that are currently being developed in the mineral industry can already be included in a mobile plant. This is therefore not perceived as very challenging (AT mineral processing, 2019b).

#### 4.3.2.3. *Separation based on water affinity (froth flotation)*

Froth flotation is a method that separate hydrophobic materials from hydrophilic, thanks to the difference in wetting characteristics of the gangue and the ore with water and oil. The slurry (crushed ore along with water) is put in a floatation cell with additives chosen depending on the nature of the ore. Additives help the ore to become water repellent, allowing it to bind to the air bubbles injected into the cell and float (askIITians, 2021; D. Michaud, 2021; Mishra et al., 2018)

The size of the cell chosen for a project is dependent on feed rates and residence times required. The size and designs of froth flotation cells therefore vary among manufacturers, even if they all share the same methods of separation. The main suppliers in Europe are Metso, FLSmidth and Outotec and froth flotation cells have already been included in some mobile plants (see section 4.3.4).

### 4.3.3. Dewatering equipment

#### *4.3.3.1. Drying techniques*

Most mineral separation processes end with a dewatering step to separate the water from the solid matter. Dewatering is usually performed by a combination of three different methods: sedimentation (gravity and centrifugal), filtration, and thermal drying.

## Sedimentation

Gravity sedimentation (also called thickening) is very widely used in mineral processing, as it is a cheap and high capacity technique. It is usually carried out in thickener (**Fig. 31**), which are open cylindrical tanks, or more rarely in centrifuges. In thickener, after sedimentation, the clear liquid is pumped at the top (thickener overflow) and the suspension is transported by rotating rakes to be discharged from the bottom (underflow). The diameter of the thickener determine the clarifying capacity for a given throughput. The surface area must therefore be large enough so that the upward velocity of liquid is at all times lower than the settling velocity of the slowest settling particle that is to be recovered. The thickener depth control the residence time of the particle and hence the degree of thickening produced.

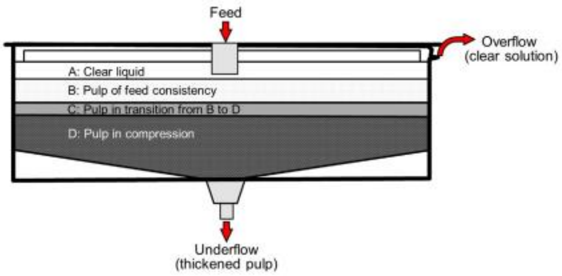


*Figure 30- Concentration zones in a thickener* (Wills & Finch, 2016)

## Filtration

Filtration usually follows thickening in mineral processing, and consists of separating the solids from the liquid via a porous medium (the filter). The filtration process involves five steps: (1) cake formation (which is the solid matter trapped by the filter), (2) moisture reduction, (3) cake washing (if required), (4) cake discharge and (5) medium washing. The filtration rate varies directly with the pressure drop across the filter and the area of the filter, and inversely with liquid viscosity, cake resistance (reciprocal of cake permeability), and slurry solids contents. The function of the filter medium is to act as a support for the filter cake, while the initial layers of cake act as the true filter. The filter medium should be chosen on basis of its ability to retain solids without blinding, its high strength, its resistance to corrosion and its low resistance to filtrate flow. Usually, cotton fabrics are used because of their low costs and their availability, but many other fabrics are also available, such as wool, linen, jute, silk, glass fibre, porous carbon, metal, ceramic, nylon and other synthetics (Wills & Finch, 2016).

### Types of filter

In the case of very coarse particles, for which capillary pressures would be negligible, it would be possible to employ gravimetric drainage, e.g. dewatering screens in dense media recovery. In the case of recovery of large quantities of fine solids (e.g. 100 µm) from fairly concentrated slurries (50-60% solids), pressure or vacuum types cake filters are most often used, with batch or continuous modes of operation (**Fig. 32**).

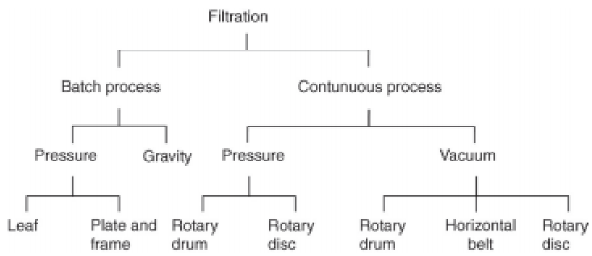


*Figure 31- Classification of filtration processes* (Gupta & Yan, 2016)

### A) Gravity filters

Gravity filters consist of a semi-permeable membrane forming a circular or rectangular vessel into which the slurry is pumped. The liquids flow through the membrane, are collected before being treated or returned to the natural environment. Once the vessels are full and dewatering is complete, the solids can be collected. The Geotube® technology (**Fig. 33**), developed by the company TenCate Geosynthetics Europe, is a gravity filter with a membrane that recovers 99% of the solids while providing a volume reduction of up to 90%. Sometimes, chemical conditioning, i.e. the addition of polymers such as coagulants and flocculants, is required to obtain the fastest dewatering time. Although this technology does not dry the material as effectively as filter presses or belt filters, it is probably the greenest of all dewatering methods. In all aspects of transport, manufacture, use and end of life, it is very low energy intensive and very low cost (TenCate, 2021).

*Figure 32- Photo taken by Renaud De Rijdt (2011) in the context of a project to extract and dewater materials from industrial sludge pond in Tilly (Belgium)*

### B) Pressure filters

Filter presses are available as plate and frame filters, or as chamber filters which are an improved version of the former (Gupta & Yan, 2016). They can be in horizontal (e.g filter press used in the Bioterra NV plant) and vertical form, which is defined by the direction of the pressure applied (**Fig. 34**). Although they are infamous for their high cost, filter presses are convenient in some cases. They are suitable to filter slurries with high moisture content (8-10 wt%[7]) and containing very fine particles. The latter is an important feature for mineral concentrates as typically 80% of Cu, Zn and Pb are <30 µm. Compared to vacuum filtration, the filtration of fine particles under pressure has higher flow rates. They also offer better washing and drying results from the higher pressures that can be used (Wills & Finch, 2016). For example, in the BELGARENA NV plant, they were able to produce a cake with a moisture content of 25%, compared to 45% with the belt filter.

In **horizontal filter press**, an hydraulic piston allows to hold the plates together and to open and close the press. The slurry is first pumped into the press to fill each chamber. As the chambers fill, the membranes are pressurised to hold the cake in place and squeeze out water. When they are full, pressures up to 8 bar are applied in order to force pressurized air through the cake. Once the cycle is completed, the press is opened, allowing the cake to be dumped below by gravity. The press is then cleaned if necessary by e.g. vibrations, sprays and the cycle can be repeated. **Vertical filter press** use the same process except that the chambers are stacked vertically on top of each other and, at the end of the cycle, the cake is discharged by advancing the filter cloth. One cycle takes about 10 min to be completed (Wills & Finch, 2016).

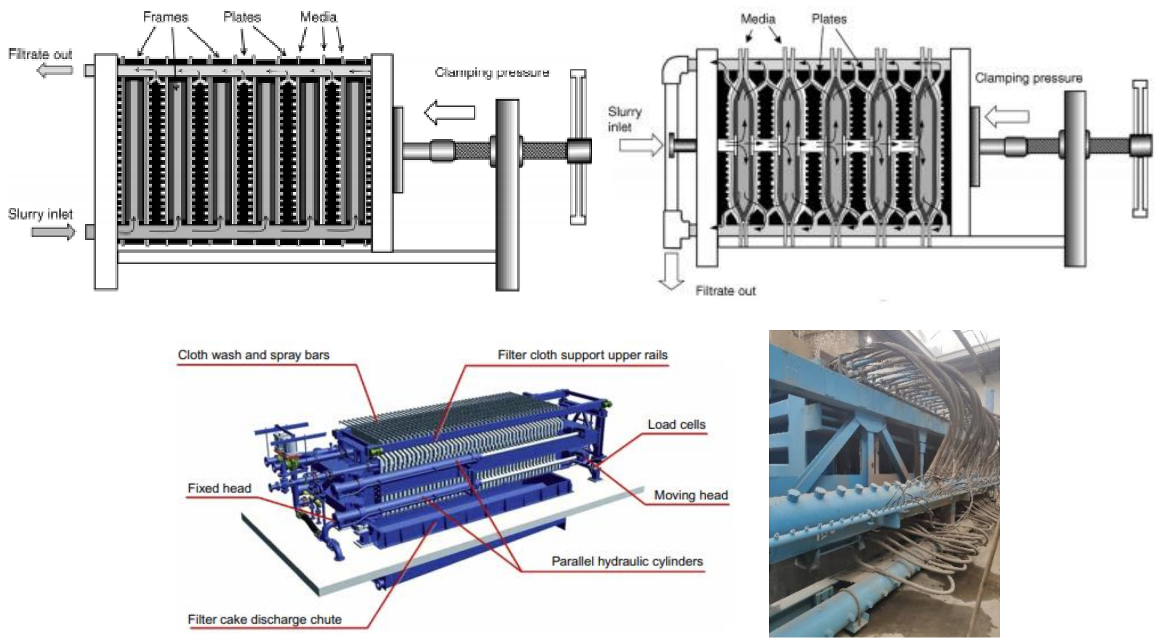


*Figure 33- Above: left: plate and frame filter press, right: chamber press filter* (Gupta & Yan, 2016)*.*
*Below: left: horizontal pressure filter scheme* (Wills & Finch, 2016)*, right: horizontal pressure filter picture, taken in the BIOTERRA NV plant*

As ultra-fine materials (<10 µm) have higher capillary forces, they required higher air pressures and thus special equipment to be drained. Thanks to the **tube press** (**Fig. 35**), filtration takes place in a tube, where pressures of up to 100 bars can be applied.

[7] % of water content.

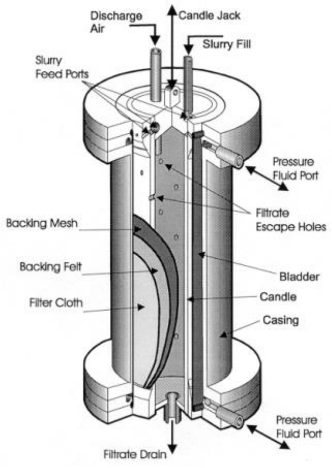


*Figure 34- Tube press* (Metso, 2015)

### C) Vacuum filters

Vacuum filter all include a filter media supported on a drainage system, beneath which a reduction of pressure is applied by connection to a vacuum system.

The **vertical leaf filter** (**Fig. 36**) and the **horizontal leaf/ tray filter** are very similar devices except for the orientation of the leaf. In Gupta & Yan (2016), they are classified as pressure filter as they operate at pressures of up to 600 kPa but in Wills & Finch (2016), they are classified as vacuum filter. Although very simple to operate, they require considerable floor space and are now only used for clarification.

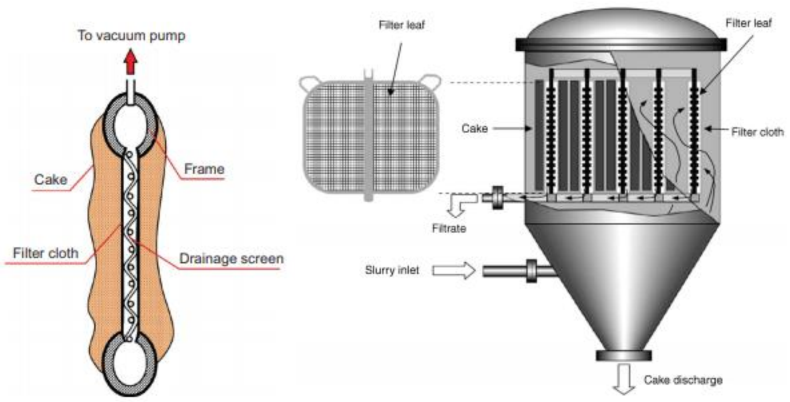


*Figure 35- Left: cross section of a vertical leaf filter* (Wills & Finch, 2016)*, right: sketch of a pressure leaf filter* (Gupta & Yan, 2016)

Continuous vacuum filters are very widely used for the filtering process in mineral operation. They are generally divided into three categories: drum, discs and horizontal (belt) filters.

**Rotary drum filters** (**Fig. 37**) are composed of a horizontally mounted drum immersed in a vat where the slurry is maintained in suspension by agitators. The periphery of the drum is a filter inside which the vacuum is created, which allows to retain the solids while drawing liquids through the filter medium. As the drum rotates, solids stuck around the drum (cake) come out of the liquid, can eventually be washed and dried before being discharged (HASLER Group, 2021; Wills & Finch, 2016). The common discharge method is to place a knife or a scraper against the cake but other devices also include continuous string discharge, continuous belt discharge and roller discharge. The latter is particularly suitable for sticky clayey cake (Gupta & Yan, 2016). According to HASLER Group (2021), optimal filtration is ensure by setting a low speed of rotation (0.6 min/revolution to 5 min/revolution). The final moisture content is as low as 4% and the drum filters offered by this company can filter a pulp of 10%w/w to 0.01%w/w.

The principle of operation of **disc filters** (**Fig. 37**) is like rotary drum filters except that the solids cake is formed on both sides of the disc and when the cake is lifted by the disc above the slurry, the cake is suction-dried and is then removed by a pulsating air blow (of 20-250 kPa) with the assistance of a scraper. The cost per unit area for disc filter is lower than for drum filters, but it is impossible to wash the cake when disc filters are used. A filtration unit consists of 1 to 15 discs each providing a porous cake of 6.5 to 65 mm thickness, which represent a deposition rate of 1.7–12 kg/m$^2$/min, depending on the specific gravity of the mineral (Gupta & Yan, 2016; Wills & Finch, 2016).

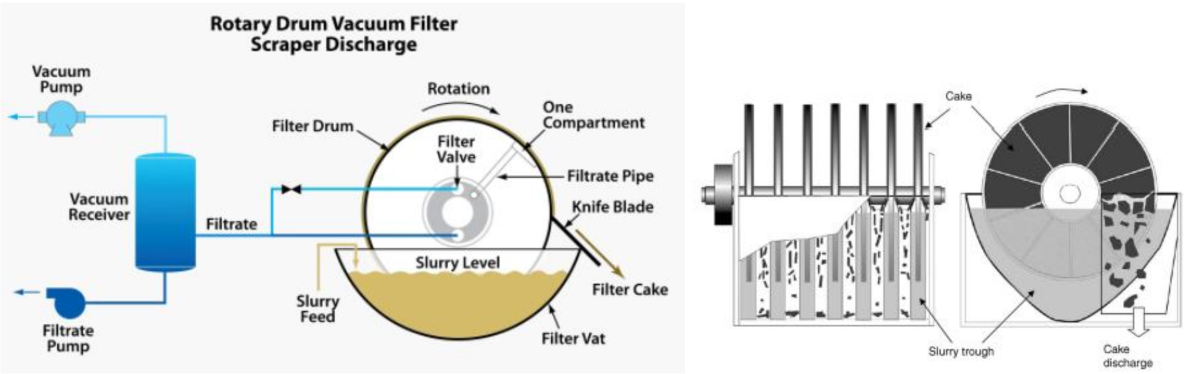


*Figure 36- Left : rotary drum filter* (Komline-Sanderson, 2021)*, right: schematic diagram of a disc filter* (Gupta & Yan, 2016)

**Horizontal belt filters** (**Fig. 38**) are suitable for use when the main objective is to produce solids that can be handled or stored and when the ultimate cake moisture content is not a critical parameter. For example, in the BELGARENA NV plant, they were able to reach 45% ultimate moisture content in the cake. They initially have been designed for fast settling and fast filtering slurries and to maximise water recovery. Belt filters consist of an endless, perforated rubber drainage tray on which the filter cloth is supported. Vacuum is applied by a series of suction boxes placed under the belt. Their number can be varied in order to adjust the length of the filtration, drying and (eventually) washing stages. The cake is discharged as the belt reverses over a small diameter roller. The belt speed varies between 5 and 100 mm per second and the cake thickness goes from 6 to 203 mm depending on the belt speed (Gupta & Yan, 2016; Wills & Finch, 2016).

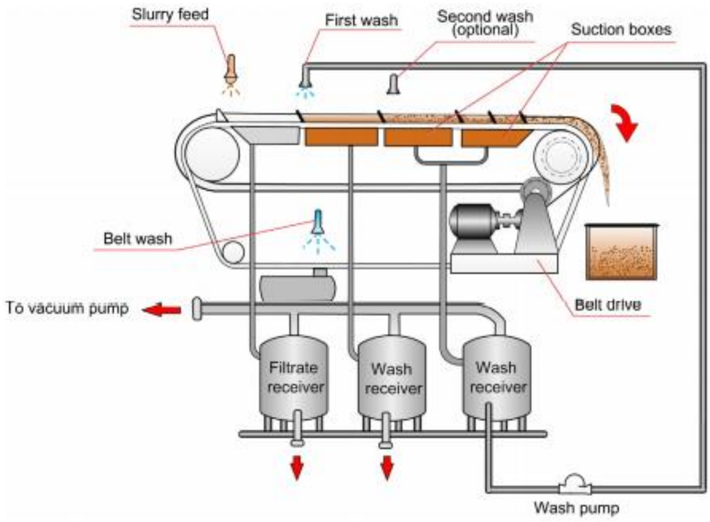


*Figure 37- Horizontal belt filter (Wills & Finch, 2016)*

### D) Summary table of the main filters used to dry slurries

**Table 14** provides an overview of the main slurries filtration techniques used on an industrial scale and their characteristics. According to the sources used to build this table, the most expensive technologies (both in terms of investment and operating costs) are, in ascending order, Geotube, disc and belt filter, drum and then press filter. However, each filtration technology has its own characteristics and the choice of the appropriate filtration technology is not only limited to the cost, but also to the characteristics of the slurries to be filtered (e.g. particle size) and the desired output characteristics. For example, even if the filter press is the most expensive technology, it allows to obtain a very low moisture content in the cake.

*Table 14- Comparative table of existing filtration techniques for slurry dewatering : Geotube* (Layfield Group, 2019; Mastin & Lebster, 2008; TenCate, 2021)*, Horizontal filter press* (ChemREADY, 2021; LennTech BV, 2021; Wills & Finch, 2016)*, rotary vacuum drum filter* (ANDRITZ, 2021; HASLER Group, 2021; L. Michaud, 2016)*, disc* (Gupta & Yan, 2016; Hahn, 2019)*, Belt* (Goud et al., 2003)

| Filter type | Gravity | Pressure | Vacuum | | |
|---|---|---|---|---|---|
| Equipment | Geotube® | Horizontal filter press | Rotary drum | Disc | Belt |
| Filtration capacity and dewatering time | 900 $m^3$/unit and each unit take several days to complete filtration | 1.5-10 kg solids/$m^2$ filtering surface per cycle (1 cycle takes about 10 min) | Up to 3,500 kg solids/$m^2$ per hour | From 1,7-12 kg/$m^2$/min (depend on the specific gravity of the mineral) | Higher than disc and filter press |

| | | | | | |
|---|---|---|---|---|---|
| Costs | low (+/- 5 $ per m³) | High investment costs (from 15,000$ to 250,000$ per plant) and very high operating costs | High (higher than disc filter) | Moderate (lower than drum filter) | High costs even if the capital costs are low |
| Size of the filtered particles | not too fine | Suitable for very fine particles (30 µm) | 50-300 µm | >30 µm and not too coarse | All particles size settle on filter |
| Ultimate moisture of the cake | Up to 99% solids in the best cases, usually 60% | 25% water content* | From 4 to 12% water content | 19 to 22 % water content | 45% water content* |
| Advantages | Cheap, minimal technical assistance, low energy consumption (as it uses sun and wind energy) | Allows a very low cake moisture to be achieved, suitable for the filtering of very fine particles | - | Cheaper than pressure filter, drum filter and belt filter | Suitable for all particle size |
| Disadvantages | The membrane can get clogged by fine particles, does not produce a cake with a very low water content. Membrane can be physically damaged by machines, so precautions must be taken. | Expensive | Expensive, only suitable for moderate particle size: clays can clog the filter and coarser particles will settle at the bottom of feeder box (and cause overflow of feed) | Only suitable for moderate particle size: clays can clog the filter and coarser particles will settle at the bottom of feeder box (and cause overflow of feed) | Does not produce a cake with a very low water content |

**source: personal communication from the BELGARENA NV plant*

## Thermal drying

The dewatered material usually still contains a significant amount of water. Thermal drying is therefore used in plants to remove this residual water and can produce a material with a water content approaching 5%, which allow to reduce the cost of transport. The rotary thermal dryer is the most commonly used industrial drier (Wills & Finch, 2016). A complete review of industrial dryers was carried out by Mujumbar (2014). It can be seen on **Figure 39** that, although efforts have been made to reduce the energy impact of industrial dryers, the energy required to dry one kg of $H_2O$ is still very high.

| Dryer Type | Typical Evaporation Capacity (kg $H_2O$/h m² or kg $H_2O$/h m³) | Typical Energy Consumption (kJ/kg of $H_2O$ Evaporated) |
|---|---|---|
| Tunnel dryer | — | 5,500–6,000 |
| Band dryer | — | 4,000–6,000 |
| Impingement dryer | 50/m² | 5,000–7,000 |
| Rotary dryer | 30–80/m³ | 4,600–9,200 |
| Fluid bed dryer | | 4,000–6,000 |
| Flash dryer | 5–100/m³ (depends on particle size) | 4,500–9,000 |
| Spray dryer | 1–30/m³ | 4,500–11,500 |
| Drum dryer (for pastes) | 6–20/m² | 3,200–6,500 |

*Figure 38- Capacity and energy consumption for selected dryers (Mujumdar, 2014)*

#### *4.3.3.2. Mobile dewatering and auxiliary equipment*

Many companies provide drying equipment for mineral processing but few of them are really suitable for mobile use. Overall, drying techniques that could be adapted for mobile use include thickening and gravity filters. On the contrary, thermal drying and other types of filters (vacuum filters, pressure filters) seems not really appropriate for mobile processing.

FLSmidth developed high-rate thickeners units that have a smaller footprint than conventional thickening technology and are more suited to mobile processing (FLSmidth, 2021a). Lamella thickeners are also often used in the minerals industry (as part of water treatment circuits) and have considerably smaller footprint compared to conventional thickeners (AT mineral processing, 2019b).

### 4.3.4. IPCC systems and other mobile plants

In-Pit Crushing and Conveying system (IPCC) (**Fig. 40**) is a modular installation that can be relocated, in which mobile crushers and screens are used. IPCC systems intend to decrease the use of shovel and truck operations, which in turn induces the reduction in operating costs, a more environmentally friendly behaviour, higher safety for workers and higher life expectancy of equipment.

An IPCC system is generally composed of crushers and screens close to the pit face, feeding conveyors that may lead to secondary or tertiary crushers, or to a heap leach pad. A fully mobile IPCC system uses tracked or wheeled crushers and screens, while a semi-mobile system is located close to the pit but generally outside the blasting radius. The mobile type does not require the use of dump trucks, as the digging unit feeds the hopper of the crusher, but the semi-mobile type still needs trucks to operate between the face and the crusher. The output of fully mobile units are limited to under 7000 t/h and, even if it tend to improve, they generally cannot deal effectively with hard rocks, while the semi-mobile systems have higher productivities on harder rock (AT mineral processing, 2019c; Metso Outotec, 2021a).

Although technological advances will make IPCC systems cheaper and more productive, they are not exempt from their own disadvantages. Indeed, fully mobile systems have to be relocated every time a new face is worked or moved for protection during blasting, and the relocation period can last between two and ten years. Consequently, they require a high degree of expert mine planning and design in order to ensure rapid relocation and avoid a loss of productivity. The works required for locating and stabilising semi-mobile plant can even be nearly as significant and expensive as that for fixed plant. Moreover, they are not suitable for irregular shaped ore-bodies and deep pits but work best in strip mines, large bulk deposits and during overburden removal (AT mineral processing, 2019c).

*Figure 39- Metso IPCC system* (Metso Outotec, 2021a)

In addition to the IPCC system developed by Metso, other mobile plants have been developed by companies (AT mineral processing, 2019c):

- The Westpro company designs customized modular pilot plants, built for specific applications such as base metals, gold and industrial mineral recovery. For example, they have manufactured a 400 kg/hour processing plant designed to fit into two shipping containers for transport. The plant includes units processes of crushing, grinding, gravity, flotation and dewatering.
- Resources Gold Technology developed a complete turnkey modular gold processing plant, with an output from 500 to 2,000 ton/day. The plant include a mobile crushing and screening plant, variable speed ball mill, tailings thickener, concentrate treatment filter and process return tank
- Sepro Minerals System Corp produces modular process plants suitable for specific applications. The Sepro's modular plant developed in 2014 for gold recovery has achieved an estimated 92% gold recovery, with an output of 200 t/day.

- Kappes, Cassiday and Associates (KCA) supply portable or modular carbon adsorption plants and Merrill-Crowe plants. Their modular plants can be built for gold operations processing up to 4000 t/day.
- APT provides flexible and modular equipment, which have been used in many applications such as tailings retreatment, alluvial gold and separation technologies (e.g. gravity and froth flotation).
- The Outotec cPlant is a pre-fabricated modular flotation plant equipped with Outotec FloatForce® mixing mechanism and Outotec TankCell® technologies. It is a low capacity plant, that has been designed to handle projects up to two million tons of ore per year. The plant can be easily transported and connected to processes.
- The Python processing plant system created by Gekko is designed for low energy processing in a narrow 2.3m-wide and 5m-high portable facility. The reduced size of the plant allow it to operate not only above ground, but also underground (**Fig. 41**) or close to the deposit. The majority of the ore is therefore processed underground and only the pre-concentrated ore is transported to the surface for further processing, which allow to reduce transport and waste processing costs and equipment footprint. It is composed of crushing system as well as inline pressure jigs and flotation cells (**Fig. 42**). The Python is suited to gold mining and is also adaptable to other minerals that can be separated by gravity and/or flotation, such as diamonds, tin and coal.

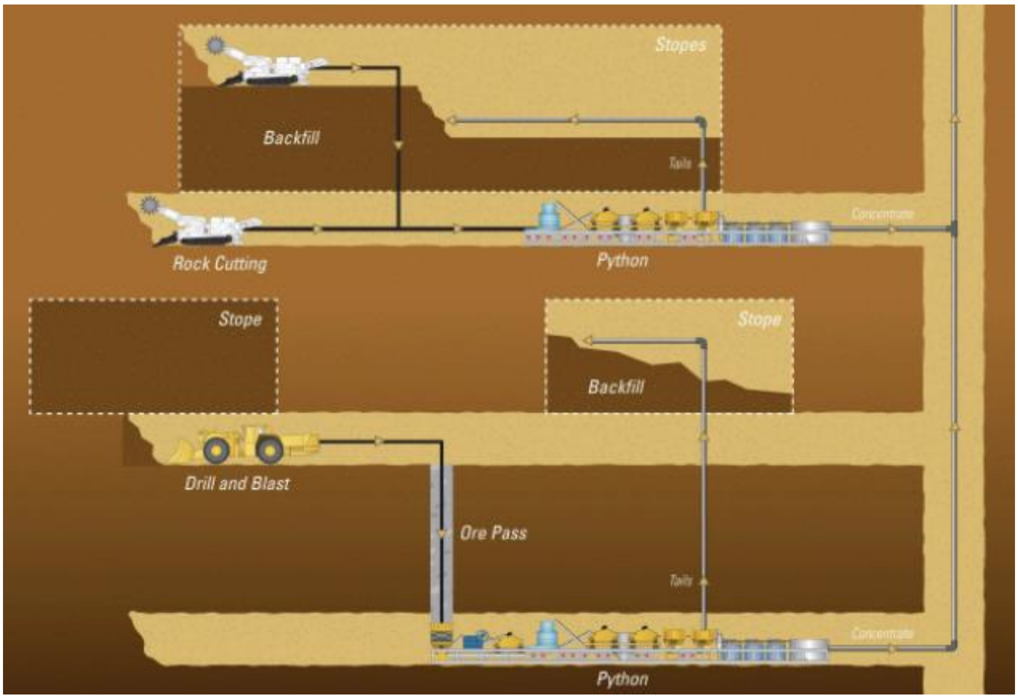


*Figure 40- Underground processing concept based on the Gekko Python modular system* (Dominy et al., 2010)

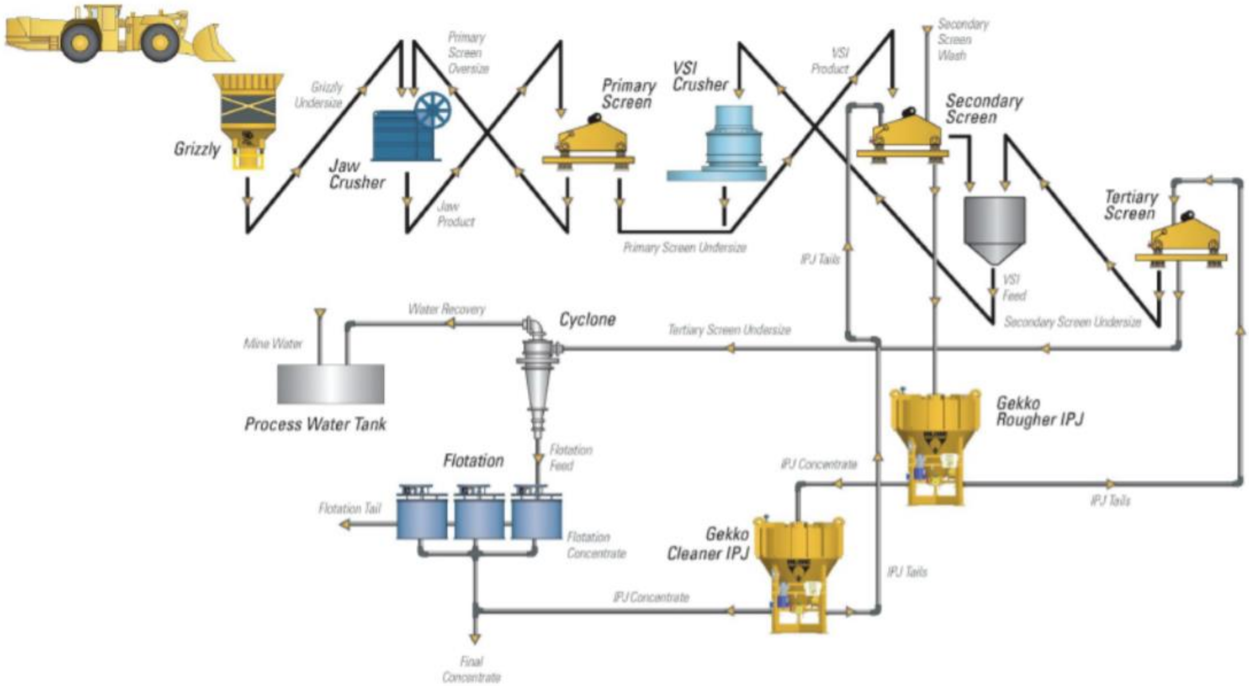


*Figure 41- Process flow diagram for the Python plant (Dominy et al., 2010)*

# 5. CONCLUSION

This report was intended to provide a comprehensive overview of current and innovative excavation and pre-processing techniques, which is crucial for the next phases of the NWE-REGENERATIS project. The useful excavation and pre-processing information provided will be considered in the NWE-REGENERATIS methodology to select the most relevant parameters to feed the SMARTIX AI tool. Besides, it will be used (in WP I1, I2 and I3) to propose a list of technologies to be implemented in the three project's pilot sites and to define business models and business plans.

As described, mechanical excavation equipment is varied and the choice of a particular machine is based on the answer to the following questions, which help define certain parameters and the machine characteristics:

- The **excavation characteristics of the material** to be excavated, such as its hardness, its GSI, its density, its water content, its digging resistance and its rippability. These make it possible to quantify the excavability (i.e. ease of excavation) and determine the machines that will be used to break/dig the material.

- The **workload** will allow to determine the type and the characteristics needed in a machine. The exact dimensions of the deposit to be excavated and the project planning are required to determine the excavation depth of the machine and the size of the bucket. The number of loaders (trucks and dumpers) will also be considered regarding the storage area, the capacity of the pre-processing plant and/or the evacuation of materials off site.
- A precise description of the **machine workspace** must be provided. On one hand, the **ease of access to the site and to the deposit** must be determined. The question to be asked is whether access to the site by heavy equipment is possible to the site and within the site? Are there any facilities nearby and possibilities of transporting the materials? Are there any buried or above ground infrastructures that must be removed before accessing the deposit? On the other hand, the **type of surface** on which the machines will move, and its water content must be known, which will make it possible to determine if the machines must be equipped with wheels or tracks.

Once the machine has been selected and the work has begun, measurements and evaluation of the stability of the excavation (settlements, landslides, cracks, apparition of leachates, etc.) must be constantly monitored.

Although excavation equipment has remained more or less the same in models recent years, much progress has been made in fuel efficiency and smart equipment. In the future, it is expected that the industry will move towards more and more autonomous equipment, until they hardly need human control. However, there are still some technical barriers to overcome, such as the inability of machines to perform tasks that require constant adaptation and the increased probability of machine failure due to the large number of sensors required to ensure their operation. Within the framework of the NWE-REGENERATIS project, it is necessary to determine whether it is worth investing in such automated and sophisticated equipment, which currently costs more than conventional hydraulic equipment and still needs to be improved.

Regarding pre-processing techniques, it has been seen from this this report that although not strictly speaking a new concept, the industrial development of optical sorting machines and mobile mineral processing equipment is on the rise.

Sensor-based sorting equipment is strictly based on cheap, on-line and fast metallurgical waste characterisation techniques such as XRF technology, which is currently proving to be the cheapest method of analysing the chemical composition of a material. Such industrial equipment is proving to be a good way of sorting and eliminating rejects before mineral processing and have allowed to improve the productivity of the installations for some case studies.

The development of mobile mineral processing equipment and entirely mobile plant is expected to develop further in the coming years. In particular, processes identified for potential conversion to mobile applications include grinding, ore sorting, froth flotation, magnetic separation, electrostatic separation and dewatering technologies. Currently, mobile crushing equipment can be marketed by suppliers as being mobile, but it is not the case for beneficiation and dewatering operation. Those could be adapted for mobile or semi-mobile applications (several modular installations have indeed been developed, e.g. Sepro), but this is likely to be dependent upon throughputs required and the material being processed. The key aspect in the development of these projects will be characterising their geology and mineralogy so that progress could be made in the development of processing flowsheets, economic evaluations and in the creation of pilot plant. The strong technical resource and numerous equipment suppliers available in Europe will surely be sufficient to develop a flexible, modular and mobile processing plants.

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# APPENDICES

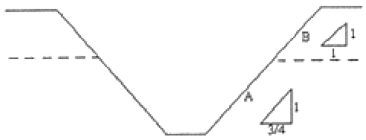
## APPENDIX A: DENSITY IN T/M$^3$ OF SOME SOIL TEXTURES

| Osha classes | Texture | Density in t/m$^3$ Yu et al, 1993 |
|---|---|---|
| Type A | Clay | 2 |
| | Sandy clay | 1,8 |
| | Silty clay | 1,4 |
| | Clay loam | 1,5 |
| Type B | Silt | 1,5 |
| | Silty loam | 1,5 |
| | Angular gravel | 2,5 |
| | Sandy loam | 1,4 |
| | Some sandy clay loam | 1,6 |
| | Some silty clay loam | 1,4 |
| Type C | Gravel | 1,8 |
| | Sand | 1,6 |
| | Loamy sand | 1,6 |

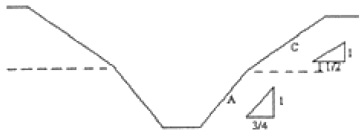
## APPENDIX B: MAXIMUM ALLOWABLE SLOPES IN LAYERED SOILS

In layered soil, the slopes required change according to two sloping criteria provided by OSHA:

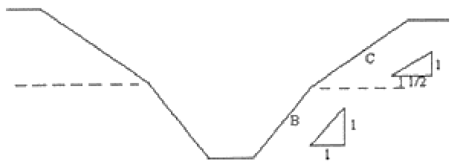
- If the more stable soil is below the less stable soil, the sloping for each layer is the same as the simple slope for that soil type.
- If the more stable soil is above the less stable soil, the entire system is sloped according to the less stable soils simple slope



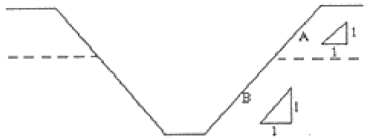
B OVER A



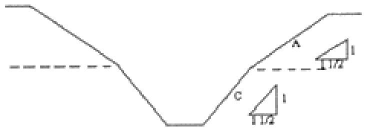
C OVER A



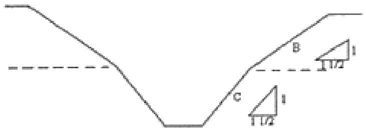
C OVER B



A OVER B



A OVER C



B OVER C

## APPENDIX C : SHAPE OF TRENCHES

Shape of a trench depends upon the following factors:

- Type of the soil;
- Prevailing environment of the site (buildings, utilities);
- Size of pipe for drainage purposes;
- Location (roadway, open field);
- Shielding or shoring availability.

Specific trench types are described below:

A: Straight trench: When the walls of a trench are parallel to each other and at right angle to the base, this type of trench is called straight trench. Straight trench is preferred to use in the areas where there is limited surface area to disturb such as near to the buildings or roadways. Trench boxes or shoring would be required as protection system (**Figure A**).

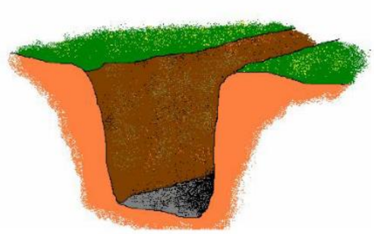


Figure A: Straight trench (HMTRI, 2000).

*B:* Sloped trench: In sloped trench, the walls of the trench are angled to prevent collapse. These angles of trench walls are called slope angles, which are determined by the trench depth or soil type. This type of trench is usually use on areas where disturbance of a large area is not a big problem such as on construction sites or when the protection systems are not available. Sloped trench is also used to place large pipes or culverts (**Figure B**).

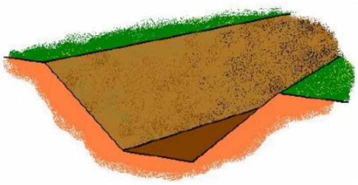


Figure B: Sloped trench (HMTRI, 2000).

*C:* Benched trench*:* When the sides of a trench are cut down to form steps is called benched trench. The distance between these steps and their height is totally depends upon the type of soil (**Figure C**).

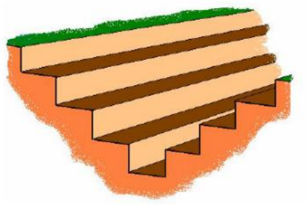


Figure C: Benched trench (HMTRI, 2000).

*D:* Bellbottom pier hole: A trench which top is usually narrow then its bottom and in cross-section it gives a bell shape appearance is called bellbottom pier hole trench (**Figure D**). This trench presents higher risk of collapse than the other types that is why additional protection system is needed. Bellbottom pier hole trench is mostly used in footing placement.

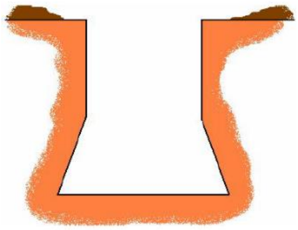


Figure D: Bellbottom pier whole trench (HMTRI, 2000).