SUSTAINABLE USE OF MINING WASTE DUMPS

A handbook for post-mining land developers and managers

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The work published here received funding from the EU's Research Fund for Coal and Steel under the project "SUMAD - Sustainable Use of Mining Waste Dumps" Grant No. 847227. The presented results reflect only the authors' view and the European Commission is not responsible for any use that may be made of the information they contain.

The research is published in the frame of the international project co-financed by the programme of the Minister of Education and Science entitled "PMW" in 2019–2022; grant number 5029/FBWiS/2019/2.

PUBLISHED BY
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ISBN 978-83-60905-07-4

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1. Foreword

This handbook, for developers and authorities, aims at addressing challenges of post-mining lands formed by the dumping of spoil material and details the novel observations, insights and conclusions of the SUMAD project in a way which is of use to those considering, or currently managing, the use of post-mining spoil sites. The project aimed to develop a better understanding of the heterogenity and the time-dependent mechanical behaviour of spoil material and promotes novel modelling techniques and their implementation in order to support the redevelopment and reuse of mining waste dumps.

The handbook provides a comprehensive overview of different sustainable rehabilitation schemes with a particular focus on the technical viability for the development of renewable energy infrastructure. It may act as a source of ideas and inspiration for the revitalization of sites with similar compositions.

2. About SUMAD

Sustainable Use of Mining Waste Dumps (SUMAD) is a European Commission's Research Fund for Coal and Steel (RFCS) funded project (no. 847227). The aim of the SUMAD project is to determine ways to optimise the use and long-term management of mining spoil dumps. The project unites European experts to investigate the future use of made-ground consisting of coal-mining spoil with a focus on geotechnical, sustainability, environmental and socio-economic challenges. This handbook is a joint initiative of the partnership working in the frame of the SUMAD project.

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3. About mining waste dumps

3.1. What is a mining waste dump?

Coal and lignite mining and processing generates considerable amounts of waste material which, depending on the origin of the material, can be divided into two main categories: overburden and processing residues called tailings (Figure 3.1). Overburden is waste rock and soil which is excavated in order to gain access to a coal or lignite seam. Especially in open cast mines, large amounts of the overburden need to be removed from the surface. Tailings are the non-coal minerals separated from the raw coal during coal processing in a coal preparation plant.

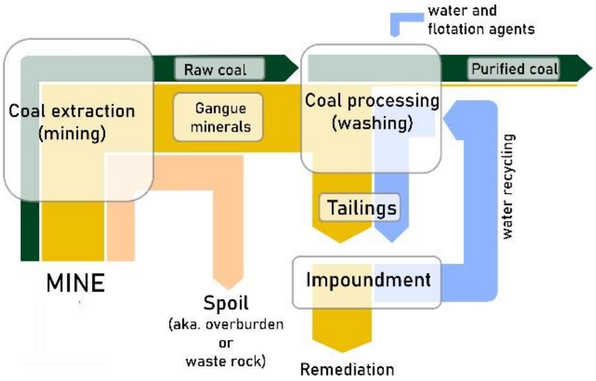

Figure 3.1. Schematic of the origins of spoil and tailings waste in coal mining (after Doka 2009)

The excavated overburden and/or tailings are usually transported by trucks or conveyer belts to an external dumping area and placed in piles also called spoils, dumps, gob piles, or pit heaps. They are characterised by different shapes and heights (Figure 3.2-3.4). The mining and processing waste may be also used as backfill material within the mining pit (in-pit heap). At the cessation of mining, such spoils are usually flattened out and the final pits are reshaped in order to be filled with water and form pit lakes.

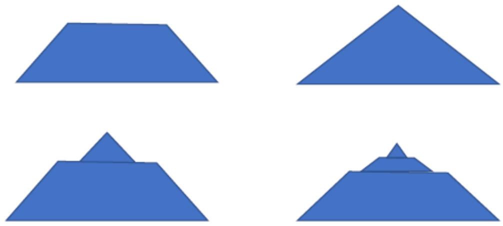

Figure 3.2. Different geometries of spoils

The spoils can contain a wide range of rock fragments and fines. The parent rock materials include conglomerates, sandstones (well or poorly sorted; fine, medium or coarse; lithic, siliceous, etc.), siltstones, mudstones, shales, laminites, claystones, cherts, ironstones and of course, coals. The spoils are shown to have significant quantities of leachable salts.

Figure 3.3. The "Panewniki" spoil located in Mikołów, S Poland - covers an area of approx. 100 ha (Image courtesy of GIG).

Randomness in the dumping process, various methods for the excavation and transportation and local site effects can influence the spoil behaviour in a dump site. The structure of a spoil material significantly differs from its original state (i.e. pre-excavation) and is usually considered as heterogeneous. Hence, the spoil materials exhibit a time-dependent mechanical behaviour.

3. About mining waste dumps

Figure 3.4. The "Skalny" spoil located next to the hard coal mine in Łaziska Górne, S Poland - one of the largest spoils in Europe with a volume of 15.5 million m³and a height of 92 m (Image courtesy of GIG).

3.2. Why is revitalization important?

In 2006 the Directive 2006/21/EC on the management of waste from the extractive industries (known as the Extractive Waste Directive) came into force in the European Union. The Directive's aim was to reduce, as far as possible, negative effects of mining and to regulate the waste produced by those industries. The negative effects of mining can be reduced through sustainable revitalization of mining-affected lands and spoils in particular.

The negative effects are associated to hazards which affect long-term stability of the spoils. The main potential hazards are: slope instability, erosion, landslides and subsidence, changes in hydrogeological conditions, internal drainage and acid rock drainage causing surface and groundwater pollution, dust emission from the exposed parts of the spoils and coal waste fires.

POST-MINING REVITALIZATION CAN BE DEFINED AS A RECOVERY OF DEGRADED POST-MINING LANDS AND THEIR ADAPTATION TO NEW NON-MINING FUNCTIONS WITH SOCIALLY, ECONOMICALLY AND ENVIRONMENTALLY VALUABLE OUTCOMES. FOR REVITALIZATION TO BE SUCCESSFUL AND SUSTAINABLE IN THE LONG RUN, EFFORTS OF MINE OPERATORS, LOCAL AND NATIONAL GOVERNMENT, PRIVATE INVESTORS AND LOCAL COMMUNITIES MUST BE COORDINATED.

3. About mining waste dumps

Slope instability of the spoils remains the main long-term hazard. Its intensity depends on the spoil location, construction method, geometry, type of dumped material and weather conditions (e.g. heavy rainfalls). Risk assessment and land stability monitoring procedures should be integrated in these spoil revitalization projects to prevent any sign of degradation and any potential damage to the environment and surrounding infrastructure.

Figure 3.5. Landslide of the Mieg spoil - Pechelbronn mine, France (Image courtesy of Ineris)

A mine operator is obliged to consider post-mining land reclamation prior to the beginning of any mining operations. Further development of the land to fully adapt it to new functions and complete revitalization with its social and economic effects is usually the responsibility of a future user of the reclaimed area, e.g. a local commune or an investor. Therefore, all reclamation and revitalization activities must take into consideration long term geotechnical and environmental issues because the spoils are structures which will most likely last much longer than the mining operations and affect the local communities for many years after the mining cessation.

The revitalization of the spoils should aim at supporting fragile areas impacted by the coal mining industry through actions designed to

Geotechnical instability

To accommodate increasingly high volumes of spoil within a mine, spoil pile heights and slope angles are increased. The typical height of spoil piles ranges from 30 m to 100 m and the slope of the spoil pile varies between 20° and 40°. As spoil pile heights are increased, the foundation material is subjected to higher stresses that may increase the rate of disintegration of base spoil material due to mechanical breakdown. Generally, the foundation spoil materials are subjected to mechanical breakdown over time due to a high overburden pressure, degree of saturation, cyclic drying and wetting caused by de-watering of the mining pit and recharge of water due to internal drainage or infiltration of rain water, and cyclic heating and thawing. The degradation of material properties of the spoil base materials is a primary cause for failures in the spoil piles during dumping, and flooding/dewatering events (Figure 3.5).

Soil and water pollution

Mining waste rocks containing sulphide minerals can cause soil and water contamination with an acidic discharge called acid rock drainage. Its release requires the sulphides in the dump to be oxidised and the oxidation products to be transported out of the dump by water flow. Once sites are contaminated with acid rock drainage, they can continue to pollute water for many years. The tailings pose similar environmental problems as the dumped overburden material, as the milling and flotation of the excavated coal rock renders the formerly secluded minerals more reactive. Due to the even smaller grain size of tailings, these problems are further amplified. Because of this, harmful heavy metal elements may be capable of contaminating the environment located around the spoil site.

Fires and internal combustion

The spoil produced from coal and lignite mining can contain burnable organic carbon. This carbon can spontaneously ignite and lead to fires on heaps or smoldering within heaps (Figure 3.6). Tailings from the milling of raw coal also contain significant coal fractions. When sufficiently dry, this can also pose a fire or smolder risk. Such fires are hard or impossible to control or terminate and can reach temperatures of 500°C which have been known to continue for months.

promote the emergence of new types of activities and the creation of new jobs. Revitalization should therefore be considered as both reclamation activities that prevent and minimize hazards by ensuring that the spoils and the spoil-affected areas are environmentally and geotechnically safe, as well as socio-economic renewal which makes these areas valuable to residents, visitors and tourists.

Figure 3.6. Endogenous fire of the spoil in Libiąż town, S Poland (Image courtesy of GIG).

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Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC (OJ L 102, 11.4.2006, p.15)

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4. Identifying revitalization potentials

4.1. Opportunities and limitations

As different spoils have their own characteristics in mine closure areas, their restoration or reuse directions can vary (Table 4.1). The potential future uses of spoils should be analysed with a focus on the long-term economic, environmental, and social impacts that reuse can have on the areas surrounding the mine.

The reuse direction determines the scope of works to be performed, which may include land smoothing and reshaping, pollution elimination, securing technical infrastructure, construction of drainage systems to discharge water safely, construction of hydrotechnical devices, soil restoration and revegetation. Typically, combined engineering and vegetational measures are taken. For agricultural or forest reclamation hydrological stability, potential pollution control and soil reconstruction are the key elements. If construction of any kind is planned on the spoil, a long term land stability analysis supported by ground movement and erosion control must be secured. Sufficient geotechnical information should confirm the viability of the proposed constructions.

Table 4.1. Post-mining land uses (after Ostręga and Uberman 2010, modified)

General type of use	Examples of new land functions after mine closure
Forestry	Forests of different functions: ecological, protective, productive, aesthetic, recreational etc.
Agriculture	Crops, animal breeding
Water storage	Recreational: swimming, water sports Commercial: retention reservoirs, drinking water reservoirs, industrial water reservoirs Fishing Wildlife habitat
Recreation	Leisure and tourism: sports and recreation facilities, accommodation facilities (campsites, summer houses, hotels, guesthouses), catering facilities Sports: e.g. ski slopes, bicycle routes, infrastructure for traditional and extreme sports
Culture	Theatre and open-air stages, exhibitions, exhibition and concert halls, galleries Memorial parks, memorial sites, places of religious worship
Education	Thematic (educational) paths, museums, including industry museums, open-air museums, eco-museums, archives of documentation related to industry history, training centres, historical monuments, cultural parks
Wildlife habitat	Nature reserves, ecological areas, habitat/species protection areas, natural monuments, protected landscape areas, greeneries
Residential use	Housing, holiday cottages
Commercial use	Industrial: e.g. industrial parks Service: e.g. business incubators, warehouses, shops, parking lots Municipal utilities: e.g. landfills Recycling: re-use of spoil materials for construction industry Renewable energy generation - photovoltaics, wind farms

4. Identifying revitalization potentials

Photovoltaics on spoils

For installing PV farms on dumps, different environmental, technical and economic criteria should be respected for ensuring stability and production of the energy for years. The slope of the dumps appears as the main constraint and limitation for the installation of PV farms. The slope angle should be less than 15°. In addition, a bespoke foundation system should be considered to ensure the site's long-term geotechnical safety. Installation of a PV farm on unconsolidated spoil material can produce deferential settlement causing the instability of the installation. Furthermore, like any electrical system, the PV system can locally release large amounts of heat in the case of a malfunction, and when installed on a spoil containing combustible materials, the fire risk increases and needs to be carefully assessed. Another issue is dust released from the spoil surface uncovered with vegetation and deposited on the PV panels which can decrease the efficiency of the energy production and increase the maintenance cost.

Furthermore, there are some recycling options for the spoil materials. Coarse mining waste and especially barren rock can be considered as materials for roads, building foundations or cement factories, depending on its geotechnical and geochemical characteristics. For many years, the mining industry has used waste materials in various small engineering structures closely situated to the coal mines. Nowadays, Europe encourages the sustainable recycling of these materials.

If the post-mining lands are identified as areas not suitable for agriculture or areas which do not have high economic value, their use as sites for the installation of renewable energy sources (RES), such as wind turbines, photovoltaic (PV) farms and ground source heat pumps, may be considered. These sites are generally highly suitable for such facilities given that they are highly exposed to wind and experience little to no shading from sunlight. Especially since the PV installations require relatively large areas for deployment and spoils can offer the necessary land (Figure 4.1). Many dumps are located near existing infrastructure, including roads and power transmission lines, due to prior mining activities. The availability of the existing infrastructure can reduce the renewable energy project costs.

Figure 4.1. Photovoltaic farm in coal post-mining area in Greece (Image courtesy of Public Power Corporation)

Wind farms on spoils

The installation of wind farms is another reuse option for spoils. If significantly elevated, they offer higher wind speeds than surrounding areas. However, steep spoil slopes may cause unfavorable wind turbulence. The best conditions for wind flow over the spoil are obtained for dumps with gentle slopes (up to 30°). As ground movements and settlements may occur within the spoils, wind farms require a high-quality foundation design and/or soil improvements in order to ensure stability under the normal operating and extreme load conditions imposed by the turbines. Furthermore, heavy construction equipment is used during the installation of the wind turbines and large-size components are transported. It is thus necessary to use a sufficiently large flattened area on the spoil top and appropriate technical road infrastructure. It is estimated that the costs associated with the construction of road infrastructure and foundations of wind farms located on the mine spoils may increase by up to 100% relative to the costs of their construction on natural soils.

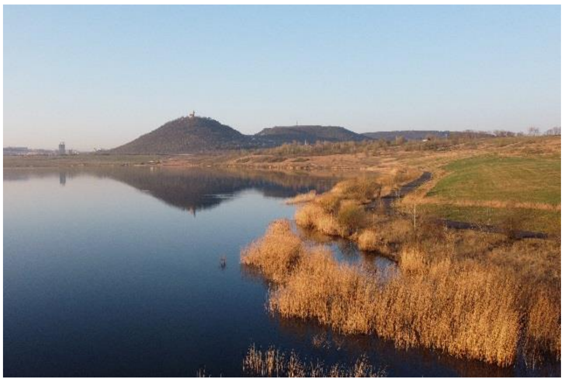

Figure 4.2. Post-coal mining Lake Most, Czech Republic (Image courtesy of DIAMO, státní podnik)

As spoils are rather complicated geotechnical structures and can present many hazards, their reuse and revitalization must be designed and carried out by competent professionals, who consider the specificities of the spoil structures and their surroundings (Figure 4.2-4.3). Special attention should be paid to geotechnical characteristics of waste materials and slope stability conditions. It should be noted that not all spoils can be revitalized, as some of them might present a high risk. To evaluate feasibility of a revitalization project, a risk assessment study should be carried out. More generally, the revitalization of the dumps should be analysed by a team of specialists providing an array of competencies: economists, sociologists, biologists, engineers, urbanists, etc.

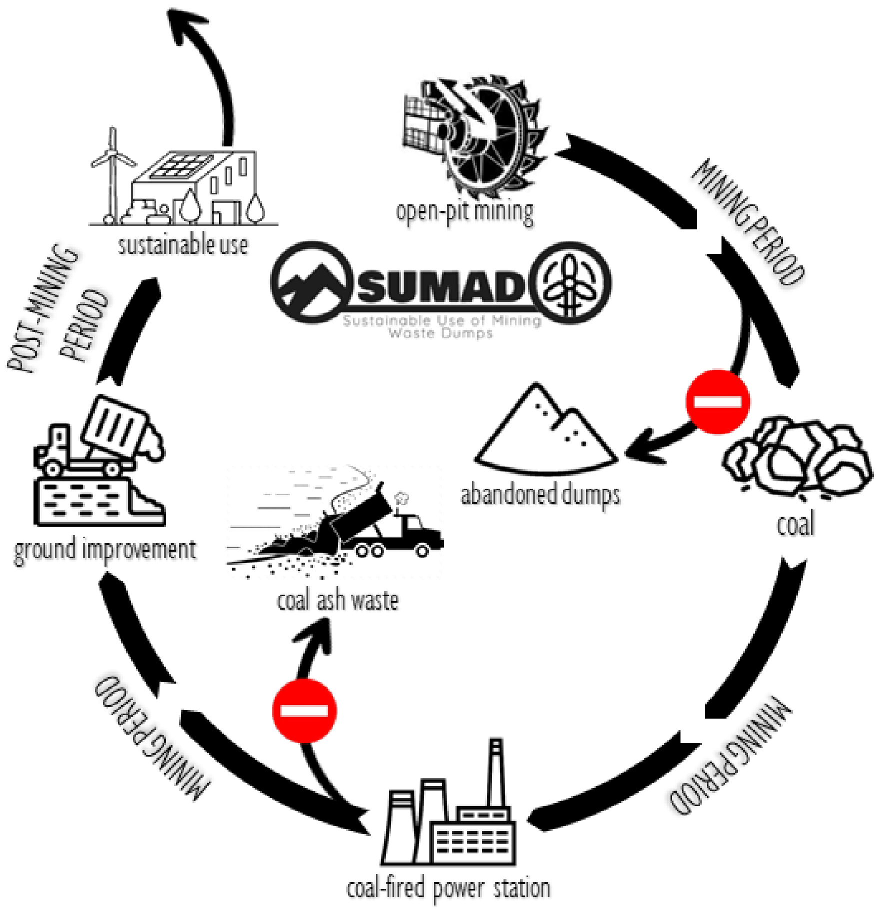

Figure 4.3. The idea of sustainable open-pit mining of coal

4.2. Key criteria

For a given mine spoil, there are typically many revitalization possibilities, and the revitalization budget is usually limited. Moreover, spoil revitalization is an investment which influences many, sometimes contradictory interests of different stakeholders. It may evoke a lot of positive or negative emotions and various expectations. Therefore, each spoil revitalization process should be carefully implemented, starting from:

- specification of the spoil properties on a very detailed level;
- identification of the current spoil revitalization status;
- development of a number of revitalization alternatives for consideration;
- assessment of the alternatives with respect to risk reduction using financial, and non-financial criteria (Figure 4.4);

The criteria listed above constitute a three-pillar risk management tool (Białas 2022) used within the SUMAD project to develop an assessment methodology designed to support decision-makers in planning revitalization processes of post-mining sites, particularly mine spoils. The Tool is presented in Section 7.

Since spoils may pose many kinds of risks to the environment, especially to people living in the surrounding areas, a comprehensive risk assessment related to the spoil condition before and after revitalization actions should be performed. These risks and their intended mitigation should be properly evaluated by implementing specific revitalization activities.

Another issue is to assess the financial aspects of the revitalization process. The mine spoils generate different costs but sometimes, especially after their revitalization, they can also generate certain benefits. Specification of several financial parameters related to the spoil before and after revitalization actions and calculation of basic economic indicators to assess profitability of the revitalization investment are an inseparable part of the cost-benefit assessment.

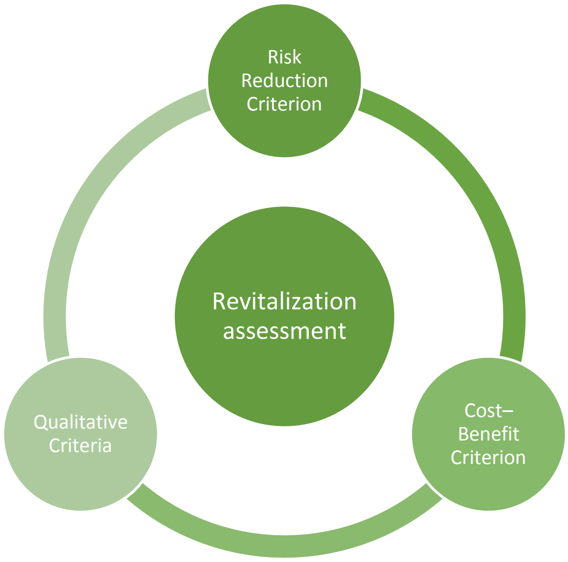

Figure 4.4. The key assessment criteria for intended spoil revitalization activities

Many diversified aspects of the spoil revitalization are hard to categorise as risks or financial implications. These issues tend to have social, political, cultural or psychological implications. To capture these issues and predict their negative or positive impacts, they must be subjected to a qualitative assessment.

For each revitalization option considered, it is very important to identify issues which may undermine or strengthen the planned revitalization efforts. With the risk, cost–benefit, and qualitative criteria applied, it is possible to determine the most viable among the available revitalization options.

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5. Overcoming geotechnical barriers

5.1 Geotechnical classification of spoil material

In addition to the political, social and economic considerations when examining post-mining revitalization of spoil dumps, one of the key challenges is associated with the civil engineering design. This relates to the design of any structural system (for example, a wind turbine tower and generating unit) and how that system interacts with, and is supported by, the ground (foundation system).

The design of the above-ground structural system is well established with design codes and standard practices available in literature. Locating such systems on a spoil-dump area will have no impact on these design procedures and hence this aspect is comparatively straight forward.

The more significant challenge is related to the ground and foundation system. Again, standard procedures do exist for the design of such foundation systems, however these are generally applicable to well characterised and homogenous ground conditions. Spoil materials provide two main challenges to the design engineers.

First, the spoil material is not homogeneous and zones of relatively competent (strong) material can exist directly adjacent to weak material. This makes it challenging to determine a single set of design parameters for the spoil strength and stiffness to be used in the design. Overlooking this variability could result in uneven settlement of the foundation systems and damage to the overlying structural systems.

The second challenge design engineers face is related to the characteristics of the spoil material. Although spoil material is variable, it is often the case that the material properties are dominated by what is referred to as 'high plasticity' materials. High plasticity means that the materials will deform significantly when loaded but over a long period of time. As such, any issues with the design may not become apparent for several years or even decades. The other challenge with high plasticity materials is their response to cyclic loading (as would be the case for a system such as a wind turbine) is not well characterised or understood. Indeed, should a spoil dump be dominated by low-plasticity materials, standard design procedures can be adopted and used. In the following sections, the geotechnical challenges and solutions associated with dealing with high-plasticity materials will be the focus.

Within this section the characterisation process for high-plasticity spoils will be discussed. This will be followed by an introduction to the design procedures adopted and finally, the scope to use small-scale laboratory testing to better understand the full-scale problem will be presented.

5.2 Characterisation of spoil material

In the same way that high-plasticity spoil materials pose a challenge for design, they also pose a challenge when being characterised using standard geotechnical testing methodologies. Where a triaxial test, which is a standard element test in a laboratory used to ascertain key parameters related to strength and stiffness, would normally take a couple of days, experience has shown that for some of the challenging high-plasticity materials found on spoil dumps, the tests can take months. Careful consideration and prioritisation of the testing plan is therefore required.

Although obtaining samples and testing in the laboratory does provide insights that cannot be obtained through other methods, in-situ testing has been shown to provide a large quantity of useful and insightful data which can be used to limit the number of laboratory tests required. In-situ refers to testing done on-site without the need to obtain laboratory spoil samples. While it can be relatively expensive to get the testing equipment mobilised to site, once in place, a large amount of data can be collected over a relatively short period of time. The best on-site testing method is the 'Cone Penetration Test' (CPT), shown schematically in Figure 5.1, which involves driving a rod (with a cone on the end) down into the ground. The cone measures the load required to drive the rod into the ground and can also measure the pore (water) pressure within the ground. This data combined, once appropriately processed, allows for most major design parameters to be ascertained. When specifying the on-site testing, consideration must be given to the deadload of the testing machines. Given the weak nature of some spoil material, it could well be the case that the on-site material does not have sufficient strength to support the testing machines, as shown in Figure 5.2. Smaller machines are available, and it is possible to use load distributing mats, however consideration for this must be given before allowing machines on-site.

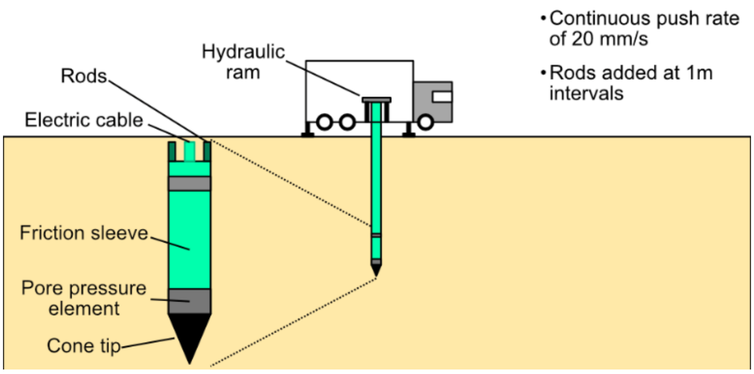

Figure 5.1. Schematic showing the operations of a CPT truck.

Figure 5.2. View of a testing machine becomes stuck in the soft spoil material.

An added complication comes from the type of loading many sustainable energy applications (such as wind turbines and geothermal pile systems) are now subjected to. Namely the increase in cyclic (time varying) load application, particularly in the horizontal direction. The loading on a wind turbine is shown schematically in Figure 5.3. This cyclic loading is transmitted down into the ground and, in the case of spoil dumps, will be resisted by the spoil material. It is therefore important to understand how the properties of the spoil material will vary over time when subjected to cyclic loading. This, even in competent and well characterised homogeneous soil, is challenging, and hence provides one of the most significant risks to the geotechnical engineering design. There is limited equipment capable of conducting in-situ cyclic testing. So to understand how the behaviour of the spoil material will vary with loading cycles, it is preferable to obtain samples which can be tested in the laboratory. Depending on the type of loading expected, a 'cyclic simple shear' or 'cyclic triaxial test' would be required to determine the design parameters necessary.

As part of the SUMAD project, extensive laboratory characterisation testing was undertaken along with in-situ field testing. How these tests were specified, the apparatus used, analysis undertaken, and the results obtained are detailed in Deliverables D2.1 and D2.2.

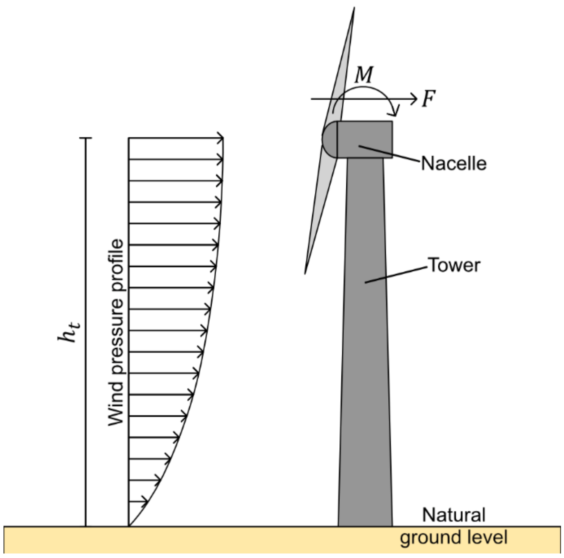

Figure 5.3. Typical types of loading on a wind turbine.

5.3 Design considerations

There are a wide range of potential structural systems which could be utilised at spoil-dumps. However, the most challenging of these would be a structure such as a wind turbine tower due to the high lateral loads, the cyclic nature of these loads, and the low tolerance to movement of the nacelle (uppermost part which holds the blades and generator). As such, some discussion will be provided here, using the wind turbine as an example, regarding these design considerations.

There has been much work performed by the geotechnical research community on the design and response of foundations for these types of structures (Bhattacharya et. al 2014; McMahon & Bolton 2014). Traditionally, foundations have been designed based on an 'ultimate limit state approach'. The ultimate limit state (ULS) is the maximum load that the foundation can carry without the catastrophic failure of the soil supporting it. The issue with a ULS design approach is that there is no consideration of the deformation (settlement and/or rotation) of the foundation that occurs before it reaches the ultimate limit load. If excessive deformation of a foundation occurs during construction of the above-ground structural system such that the above-ground system is rendered useless, it could still be considered that the foundation has 'failed' despite not reaching an ultimate limit loading condition. Failure due to deformation limitations as opposed to catastrophic load failure is referred to as the 'serviceability limit state'. The concept of a serviceability limit state (SLS) is of critical importance when it comes to designing the foundation systems for sensitive structures (i.e. structures which cannot tolerate significant deformations) such as wind turbines. Unfortunately, the cost of a design meeting a serviceability limit state instead of ultimate limit state will be higher due to the larger foundation systems required to meet this more stringent restriction. However, failure to do so will render the final structural system useless and potentially unsafe.

Design of foundation systems for sensitive structures, such as wind turbines, must follow a serviceability limit state design (based on acceptable deformation).

The need for SLS based design is of particular importance when it comes to locating these foundation systems on spoil material. This is because spoil material tends to accumulate deformations over time, meaning that the short-term performance of a structure post-construction may be deceivingly acceptable. However, to ensure the full lifetime design performance, accumulation of deformations over time must be considered at the design stage. It is particularly important to consider the impact of the cyclic loading on the accumulated deformations during the serviceability limit state design.

A thorough investigation on various possible foundation systems has been carried out as part of the SUMAD project and, as a result, gravity foundations and pile-groups have been selected to be feasible foundation systems for spoil dump sites – these foundation types are shown schematically in Figure 5.4. Both foundation types have their advantages and disadvantages.

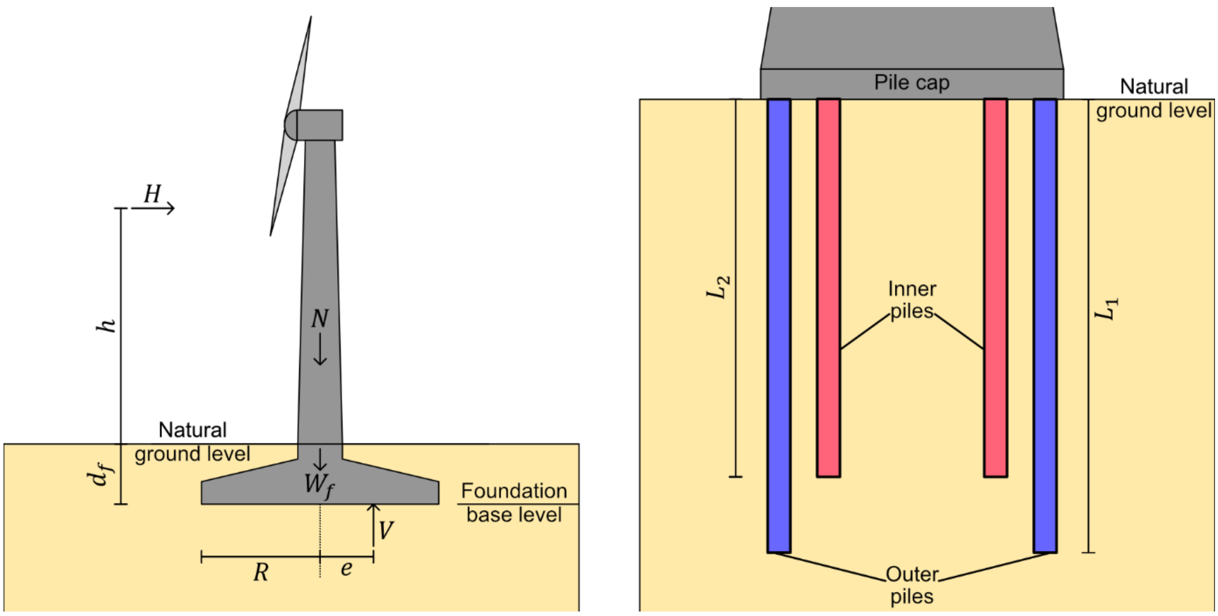

Figure 5.4. Schematic showing types of foundation systems for wind turbines.

Gravity foundations are relatively simple to construct without the need for specialist machinery. However, they tend to be much larger in scale than pile-groups, meaning a larger plan area on site is required and an increase in the concrete used (with corresponding embodied carbon costs). In addition, their ability to resist horizontal loads (something which is prevalent with wind turbines) is not as great as their ability to support vertical loads so the horizontal resistance of the foundation needs to be carefully considered during the design phase.

Pile-groups are a somewhat more flexible solution as the number, size and depth of the piles can be adjusted based on the strength of the spoil material and the expected applied loading. However, the installation of piles does require specialist machinery with more comprehensive quality control checks. Some temporary works may be required to support the machinery on-site, providing a stable platform on which to operate from. Piles, designed correctly, can be very effective at resisting horizontal loading making them a particularly suitable solution for wind turbine installations.

It was found during the SUMAD project that careful application of traditional serviceability limit state design principles was appropriate for the design of foundation systems for spoil dumps areas, if the input parameters (obtained from the characterisation of the spoil material) were cautiously selected. The heterogeneity of spoil material means that conservative values must be selected. Although there may be zones of strong spoil material within the ground around the foundation, the performance of the foundation will be mostly controlled by the weaker material present and hence the parameters relating to this material should be used as input to the design. Validation of the design should then be completed by use of numerical models with the implementation of random field methods (which captures the impact of the heterogeneity). Details on the design processes adopted can be found in Deliverables D2.3 and D2.4.

5.4 Small-scale laboratory testing

Small-scale laboratory testing involves scaling down the dimensions of the real structural system to a level at which it is practical to build and test several versions of the system within the laboratory setting. This might therefore result in a pile diameter which is 10mm instead of 1m, for example. The advantage of such laboratory testing is the ability to control and measure ground and structural properties more precisely than in the full-scale site situation, the ability to test numerous different scenarios for a comparatively low cost, and the ability to test to destruction without any associated health and safety risks of doing such a test at full scale. Naturally, there are counter arguments against small-scale laboratory testing, such as how well does the model match reality, and how is the heterogeneity (variability) of the spoil material captured within such a small-scale model. However, with carefully set objectives for small-scale testing, it can prove an incredibly powerful tool when validating and/or testing design concepts.

Design work is based on standard codes (equations) and, on occasion, the results from numerical computer simulations. It is important to highlight therefore that the design process itself is not undertaken by completing small-scale laboratory testing, instead the small-scale testing is merely a means to test and validate proposed designs and to better understand the potential performance (for example, the magnitude of deformation) of the systems.

Small-scale testing formed a major part of the geotechnical investigations of the SUMAD project and were used to validate the developed numerical models (see Section 5.5). Due to the heterogeneity of spoil material, and the requirement to have control and consistency over small-scale testing parameters, a replica spoil material was used instead of utilising real site samples. However, the replica was carefully chosen to ensure it replicated the most challenging aspects of the real spoil material (primarily the high plasticity, as discussed in Section 5.1). As the properties of the replica spoil could be ascertained, this facilitated accurate calibration of the numerical models. It would be recommended that a similar approach be adopted for any future small-scale testing. Details of the developed replica spoil can be found in Deliverable D2.3.

The small-scale testing being discussed here is focused on the spoil material and the mechanical performance of the spoil material when subjected to different loading scenarios. This is because the design for the above-ground components of a wind turbine will not need to be different when cited on a spoil waste dump compared to when cited on standard ground conditions if the foundation is appropriately designed.

Getting the foundation design right means there are no additional design challenges for the above ground system due to its location on a spoil waste dump.

Spoil, as with all geotechnical materials, is challenging to test in the laboratory due to its 'non-linear stress-strain behaviour'. What this means is that the behaviour (mechanical response) of the spoil depends on the stress level it is subjected to. Clearly the stress level in a small-scale model will be significantly less than the stress experienced in the full-scale situation. As such, the observed behaviour of the small-scale model will not accurately reflect the expected behaviour of the full-scale. However, geotechnical engineers have a method to deal with this challenge by using a 'geotechnical centrifuge'. By placing the small-scale model in a geotechnical centrifuge the gravity can, in effect, be increased such that the stress within the small-scale model matches that of the full-scale and hence the observed behaviour will be reflective of the full-scale problem. In the SUMAD project, testing was undertaken at an elevated gravity of about sixty-five times earth's gravity. To give this some context, the maximum 'g-level' experienced by a fighter pilot is nine times earth's gravity, and roller coasters may subject passengers to a g-level of around five times earth's gravity. Operating a small-scale model within these very high gravity environments is therefore challenging and specialist centres exist across Europe with the facilities to undertake such laboratory testing. A view of a geotechnical centrifuge is given in Figure 5.5. These machines vary in size from about four meters in diameter up to about ten meters in diameter.

Figure 5.5. A picture of the Nottingham Centre for Geomechanics Beam Centrifuge.

The cost and timescale associated with undertaking a small-scale test on a centrifuge precludes a large number of tests from being undertaken. However, it must be remembered that typically what is being sought from such tests is sufficient data to validate a numerical model, which can then be used to explore a larger variety of different design parameters. As such, one or two high quality tests is sufficient, as long as they are well specified. Details of how the tests undertaken as part of the SUMAD project were specified can be found in Deliverable D2.4 and the data obtained can be found in Deliverable D2.5.

5.5 Numerical analysis of spoil materials

The spoil nature and its challenging interaction with construction systems make numerical analysis an appropriate way to approach the problem. Advanced geotechnical numerical analysis should be used in the case of foundation design or other reclamation options that might include noticeable loads, complex load paths, and significant changes in water conditions. With numerical modelling, the overall response of the spoil-foundation-structural system can be analysed systematically. Notice, however, that the advanced knowledge that can be offered with numerical modelling demands more information in terms of in-situ and laboratory tests. More details can be found in Sections 5.1 and 5.2 in the sequel (see also case study).

Numerical modelling is an advanced way to quantify infrastructure response when complex conditions render simpler solutions inappropriate.

Masoudian et al. (2019) presented an overview of the geotechnical characteristics of several European lignite mine spoil heaps and compared these with available data collected from the literature. They concluded that the spoil heaps' classification and index (physical) and engineering properties indicate a remarkable variability (larger than typical in situ soils). It is noteworthy that the heterogeneity of these mixed spoil materials is affected not only by natural processes but also by other factors related to mining procedures, such as the spoil's transportation method (belt conveyor vs. haul trucks), the dumping method (spreaders vs. trucks, and top-down with an angle of repose vs. bottom-up in layers), the different origin of the soils (e.g., if they come from one or more mines with the same or different geology) and the duration and time planning of different construction stages (based on different mine development phases). The difficulties in quantifying the properties of spoil materials are reflected in several slope failure incidents, which often lead to environmental hazards and cause attention and concern from society.

For environmentally compatible management of spoil dumps and their efficient exploitation, it is crucial to understand and properly quantify the material's geotechnical (physical and engineering) properties and define its constitutive behaviour to allow for the development of an appropriate geotechnical design. This task is not trivial given the variable (sometimes chaotic) nature of spoil material; it is a heterogeneous material not subjected to standard soil norms, as was also verified in this work. Hence, common geotechnical evaluations should be applied with particular caution. Although several studies exist relating to the slope stability of spoil heaps (see references above), very few include detailed geotechnical characterisation of the spoil material (Okagbue 1984; Ulusay et al. 1995; Masoudian et al. 2019). A more in-depth analysis of this complex spoil material is expected to lead to better insights, improved analysis and safer, cost-effective, and sustainable design.

As a result, spoil material has to be classified and appropriately characterised to identify the critical parameters for its response. Indicatively, these parameters include the elasticity and strength of the material and their uncertainty, the non-linear response of the representative spoil material, and the heterogeneous nature of the spoil heap. A balance between the sophistication of the constitutive model and its simplicity and applicability through numerical software was key for this project.

In parallel with the constitutive model, an appropriate numerical tool was searched for, to effectively simulate these experiments. A wide range of approaches from the current state-of-the-art research and everyday engineering practice were considered and the proficiency and competency of three different state-of-the-art numerical software were examined on the spoil materials' mechanical response (Plaxis 2D of Bentley, RS2 of Rocscience, and FLAC2D of Itasca).

The following case study presents the specific methodology to be followed from geotechnical testing of spoil materials to an initial numerical analysis. A characteristic spoil behaviour was characterised and quantified, analysing typical geotechnical tests. Then, the crucial parameters defining the response of waste material were identified and then replicated by a constitutive model; such parameters indicatively are the non-linear response, stiffness, and strength of the spoil materials. Different constitutive models and laboratory element tests (e.g., triaxial, oedometer) were employed to capture the spoil's constitutive behaviour. The emerging differences between the numerical and physical results were also investigated.

CASE STUDY: FROM SPOIL CHARACTERISATION TO NUMERICAL MODELING (Greece)

SPOIL CHARACTERISATION

A massive Greek spoil heap was employed for the baseline response, measuring 5 km in length and reaching more than 150 m in height. The spoil heap is composed of overburden material from two surface lignite (brown coal) mines. According to approved development plans for the area, two infrastructure systems (an old national road and a railway line) will be relocated upon the spoil heap. These relocations will allow mining operations to continue in the adjacent surface lignite mines. Nonetheless, several engineering challenges related to these plans are yet to be solved, as the spoil material's complexity (composed primarily of high plasticity silts with an intermediate engineering behaviour) presents difficulties for analysis and design. In particular, although no stability problems have been reported over the years, all efforts to predict the magnitude and completion time of ongoing consolidation settlements have failed. An extensive database has been established based on extended investigations on the physical and engineering properties of the spoil heap, and a statistical analysis has been employed to evaluate the results. Furthermore, cross-correlations and dependencies between physical and engineering parameters of the spoil have been quantified to gain a more in-depth understanding and provide input for reliability analyses. Moreover, available data was plotted and compared against well-known correlations from the literature, contrasting results for the spoil material against typical soils.

A preliminary approach towards the characterisation of the Soulou spoil material was made by Zevgolis et al. (2018); a variety of additional information and more in-depth analysis was made during the SUMAD project. The classification of spoil materials according to the Unified Soil Classification System (USCS), over depth and along the longitudinal axis of the dump, is presented in Figure 1. Many different soil types appear in a spatially random arrangement, ranging from coarse-grained gravels and sands to fine-grained silts and clays. In principle, such a classification could provide a first approach to identifying different layers or even more a stratigraphy along the axis of the spoil heap; however, in the present case, no distinction of separate layers can be established. Furthermore, not even one particular structure can be easily identified, as different materials are intertwined, creating formations that cannot lead to organised patterns. Compared to more common geotechnical cases, this extreme complexity needs additional evaluation of the different materials in search of a way to organise the spoil materials.

Figure 1. Classification of spoil material (according to USCS) along the longitudinal axis of the spoil heap (Zevgolis et al. 2021).

In a further attempt to distinguish possible soil layer trends or structures, the two main soil strength parameters considered were: effective friction angle ϕ' and effective cohesion c'. These two parameters were determined through undrained triaxial tests. The variation of these two mechanical parameters with depth is presented in Figure 2; the data shows that a clear trend with depth cannot be inferred. Other geotechnical properties and parameters, such as uniaxial compression strength, constrained modulus, and coefficient of permeability, were also assessed similarly; however, discernible patterns were identified.

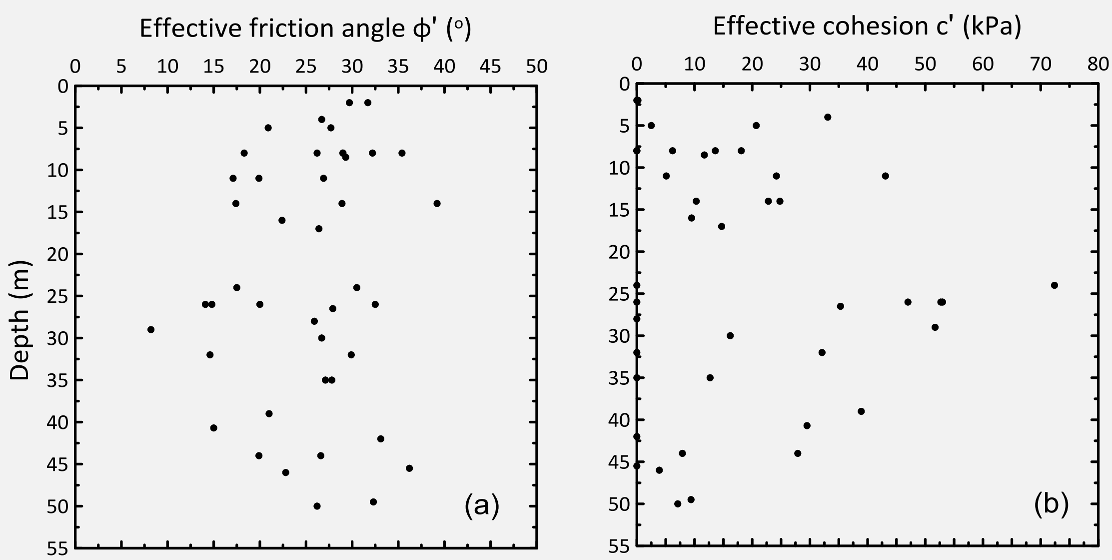

Figure 2. Variation of (a) effective friction angle ϕ' and (b) effective cohesion c' with depth (Zevgolis et al. 2021).

5. Overcoming geotechnical barriers

In addition to the above considerations, the construction methods of the spoil heap suggest a priori a soil mix with a nearly chaotic nature. Waste ground materials were transported to the dump site using continuous methods (i.e., conveyor belts with spreaders) and discontinuous means (i.e., haul trucks). These two methods result in differing states of the ground material at the location of the deposition. Additionally, the dumping method was not always consistent; bottom-up and top-down directions of dumping were employed at different times, while the original topography was initially flat but, in some cases, also inclined. In general, bottom-up constructed dumps are expected to demonstrate better engineering properties than those made using top-down methods (Zevgolis 2018).

Furthermore, the dump was created from the waste material of two different mines, indicating, to some extent, different origins of the soil materials (given that even adjacent mines might have experienced different geologic phenomena, tectonics, etc.). Finally, quite often, disposal of certain layers might have ceased for reasons related to the mine's production and then started again after some time (which might be months or even years). In this case, some parts of the dump might have consolidated, while other parts might still be experiencing consolidation.

These factors add to previous conclusions and further support that a general stratigraphy or even characterisation of layers with depth cannot be identified. Given the disordered structure of the spoil material, it is reasonable to employ a statistical treatment of the heap as a single material with significant inherent variability, expressed in terms of common statistical moments (mean values, standard deviations, etc.); this approach has also been followed during the SUMAD project. Thus, the geotechnical characterisation of the spoil heap and the statistical processing of the data, for both physical and engineering soil properties, were implemented only considering one soil layer.

SPOIL CHARACTERISTIC BEHAVIOR AND CRITICAL PARAMETERS FOR NUMERICAL ANALYSIS

Moreover, three representative samples from different depths (2m-2.5m Sample 1, 16m-16.5m Sample 2, and 30m-30.5m Sample 3) have been identified. They were classified as high plasticity silts with PI≈13% and LL≈57%; the stress-strain curves from consolidated undrained triaxial tests were used to quantify the constitutive response for three different mean effective stresses p=100kPa, p=200kPa, and p=400kPa (dashed lines in Figure 3).

Table 1. Constitutive model parameters (Theocharis et al. 2020)

Parameters	Mohr-Coulomb	Hardening Soil	Soft Soil
E or E_{50} (kPa)	10,000	5,000	-
ϕ (°)	25	25	25
c (kPa)	5	5	5
ψ (°)	0	0	0
v	0.3	-	-
m	-	0.5	-
E_{oed} (kPa)	-	5,000	-
c_c	-	-	0.2
c_r	-	-	0.037

It is not assumed that the response of this material is the accurate one of the spoil heap's, but rather that the "average" behaviour of the spoil heap would follow this response. Overall, triaxial test results suggest an apparent behaviour similar to a normally consolidated clay, identifying hardening behaviour and a tendency for volumetric decrease with the increase of deviatoric stress, pressure dependency, and a vanishingly small elastic region. Various constitutive models that could be implemented for this type of response are available in the literature. However, the heterogeneity of spoil material and the fundamental differences from natural soils (described in the SUMAD reports in detail) prohibit the use of very sophisticated models, usually based on physical aspects of geomaterials which are absent in this case.

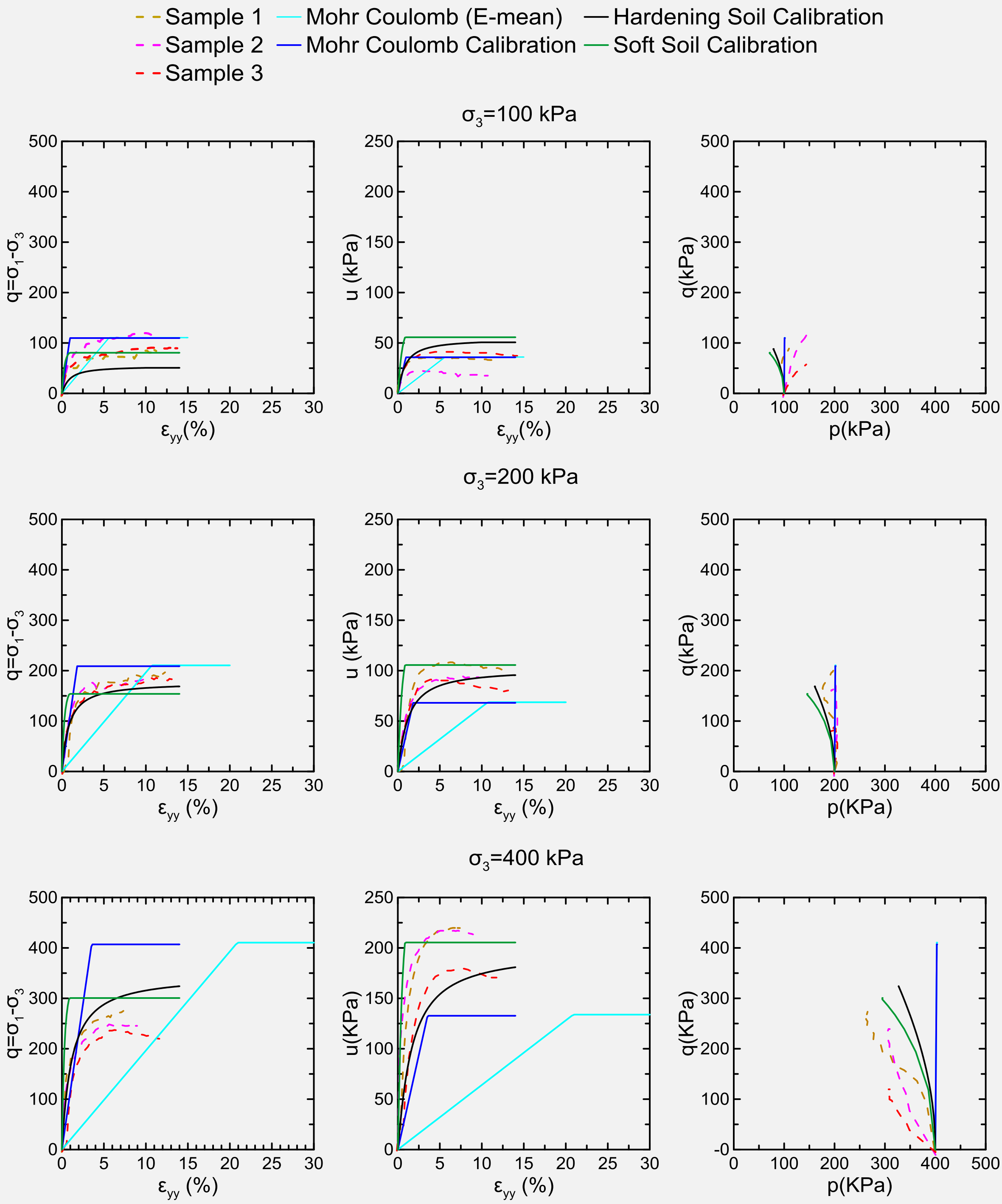

Figure 3. Consolidated undrained triaxial tests for three characteristic samples, three different initial mean effective stress (p) of spoil materials, and three fits with different constitutive models Mohr-Coulomb (MC), Hardening Soil (HS), and Soft Soil (SS) (Theocharis et al. 2020)

5. Overcoming geotechnical barriers

Simple and advanced models are employed in this work for the monotonic response of the spoil material; the Mohr-Coulomb elastic-perfectly plastic model (MC), the Hardening Soil model (HS), and the Soft Soil model (SS) as implemented in Plaxis software have been validated towards the spoil's characteristic response. The calibrated parameters of the three models are denoted in Table 1: E is the Young modulus for the MC model, E_{50} is the secant stiffness for the HS model, φ is the effective friction angle and c the cohesion, ψ is the dilation angle, v is the Poisson ratio, m is a HS model parameter relating stiffness to the stress level, E_{oed} is the oedometric modulus, cc is the compression index, and cr the re-compression index. The three models represent different degrees of sophistication in constitutive modelling and are all presented versus the laboratory results in Figure 3.

Mohr-Coulomb is a simple choice based on the heterogeneity of the spoils, the uncertainties of its properties, and the lack of physical mechanisms. It adequately fits the monotonic behaviour in deviatoric stress but cannot accurately follow the pore pressure changes. The Hardening Soil model follows the pore pressure build-up more closely during the undrained triaxial shear and accurately represents the non-linear nature of response; however, the spoil material builds up pore pressures more rapidly than the model. Finally, the Soft Soil model represents the pore pressure build-up most accurately but proposes a more rapid deviatoric stress increase than the experiments. Overall, it is observed that the Hardening Soil and Soft Soil models are more accurate than the Mohr-Coulomb model.

RECLAMATION SCENARIOS ANALYSIS BASED ON SPOIL CHARACTERISATION AND NUMERICAL MODELING

Finally, different reclamation scenarios were evaluated based on the characterisation and calibrated constitutive behaviour. This investigation aimed to answer whether heaps of lignite mines, such as the Greek spoil heap under investigation, can be used for civil infrastructure or renewable energy projects. Specifically, four different construction scenarios are tested: a highway, a railroad, a small building on shallow footings, and a wind turbine. Criteria based on international design standards are set for each of the different scenarios. Literature, design standards, regulations, and 3D finite element analysis were employed to determine the spoil's suitability for each scenario.

Initially, highway or railroad constructions on the spoil heap were examined. Design standards govern road and railroad construction, with soil stiffness being the essential parameter for deciding the subgrade's suitability. Highways and railroads generally require stiff soils to ensure that large and differential settlements do not jeopardise the construction's serviceability. The stiffness is quantified through the CBR value (indirectly), Young's modulus (E), and the resilient modulus M_R. Since no experimental results exist regarding the CBR or the M_R, they were calculated preliminarily for the purposes of this work using well-established empirical relationships. Based on the results, the spoil material does not meet the minimum requirements of any used standard, and thus it cannot serve as a subgrade without proper treatment for either situation.

Another reclamation scenario looking at buildings with shallow footings was investigated using 3D finite element analysis. The spoil material's capabilities were determined by investigating the vertical load and bending moment within the constraints that ensure the construction's safety and serviceability. Three serviceability limit envelopes were constructed - for three constitutive soil models - defining the acceptable loading combinations. The three constitutive models provided different results in terms of acceptable loading combinations. Typical loading combinations of two-storey buildings were included in the Mohr-Coulomb envelope. The Hardening Soil envelope barely included such loads, while the Soft Soil envelope included combinations corresponding to much smaller buildings. The major problem was the enormous settlements that emerged for relatively small loads, which would damage the superstructure long before the footing reached its maximum bearing capacity.

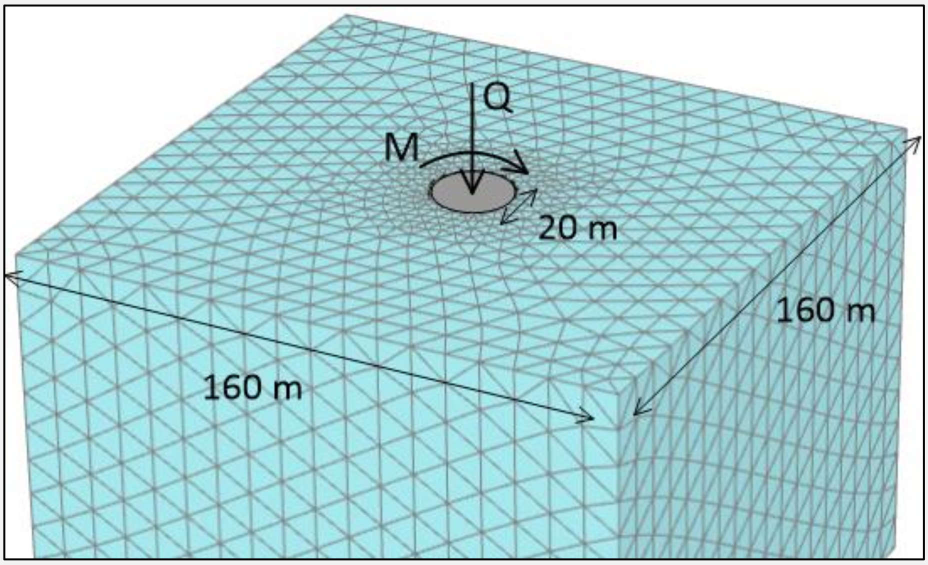

Figure 4. Finite element discretisation and a schematic view of an embedded shallow cylindrical raft foundation (Theocharis et al. 2022)

Finally, a reclamation scenario regarding the foundation of wind turbines with shallow cylindrical raft foundations was tested through a 3D numerical analysis (Figure 4). Again, three serviceability envelopes were created, providing the acceptable loading combinations; they were compared to typical loads from medium-sized wind turbines. The comparison shows that this scenario is not possible. Wind turbines are subjected to large vertical loads and vast overturning moments, much higher than the spoil's limits. The spoil provides very little settlement and rotation resistance, making it impossible to use as founding ground for such megastructures.

Overall, the spoil material under consideration cannot be considered adequate as foundation soil for the examined scenarios. Since the spoil has low stiffness and strength, ground improvement techniques must be implemented. For instance, ground cementing or gravel piles can prove vital in highway, railroad, and shallow footing construction. An alternative foundation type, a cylindrical raft with piles, appears to be the only possible wind turbine construction scenario. Finally, further studies and on-site tests could be conducted to gain more information about the nature and behaviour of the spoil material and to quantify its response to different loading conditions.

5.6 Ground improvement techniques

As discussed in the previous sections, spoil material poses a significant geotechnical challenge, particularly in terms of minimising settlement of sensitive structures. Settlements can be classified into two main categories: instantaneous and long-term. If the settlement from either or both of these categories proves to be too excessive for any feasible foundation design, then ground improvement works need to be undertaken. Different soil improvement

GROUND IMPROVEMENT IS THE APPLICATION OF VARIOUS GEOTECHNICAL METHODS THAT ARE USED TO IMPROVE SOIL ENGINEERING CHARACTERISTICS SUCH AS DENSITY AND BEARING CAPACITY AND TO PREVENT SETTLEMENTS, SLOPE INSTABILITY AND SOIL LIQUEFACTION techniques (mechanical consolidation, adding lime, etc.) can be used to increase strength of the soils. Methods include, but are not limited to, compaction (repeatedly loading the soil to cause the settlement to occur prior to construction of the final structure), grouting (adding a man-made product to the ground to cement the particles together and hence provide additional stiffness and strength), and reinforcement (where, for example, mesh or small piles are added to the ground to increase its strength and stiffness). There are also methods available to speed up the long-term settlements, or alter the position of the groundwater table, so they occur during the commissioning of the structure and hence can be compensated for. Below, a case study will be reported and the utilisation of several ground improvement methods will be discussed.

CASE STUDY: A LARGE-SCALE GROUND IMPROVEMENT EXPERIMENT (Czech Republic)

INTRODUCTION

Mining is always associated with the creation of dumps and heaps–large embankments from overburden materials. Despite the engineering construction being very difficult in these areas because of their geotechnical complexity, dumps and heaps cover usually up to tens of square kilometres and thus offer interesting potential for future use.

In frame of the experiment, ground improvement techniques for dumps were tested and sustainability credentials of the different methods were assessed. Based on principles of circular economy, an attempt was made to verify a cost-effective solution based on the use of by-products typical for mining regions in order to find an optimal technique for minimising the environmental affects connected with mining. Therefore, three field experiments were undertaken that focused on the stabilisation of the dump's soils with compaction, lime and fluidised bed combustion ashes.

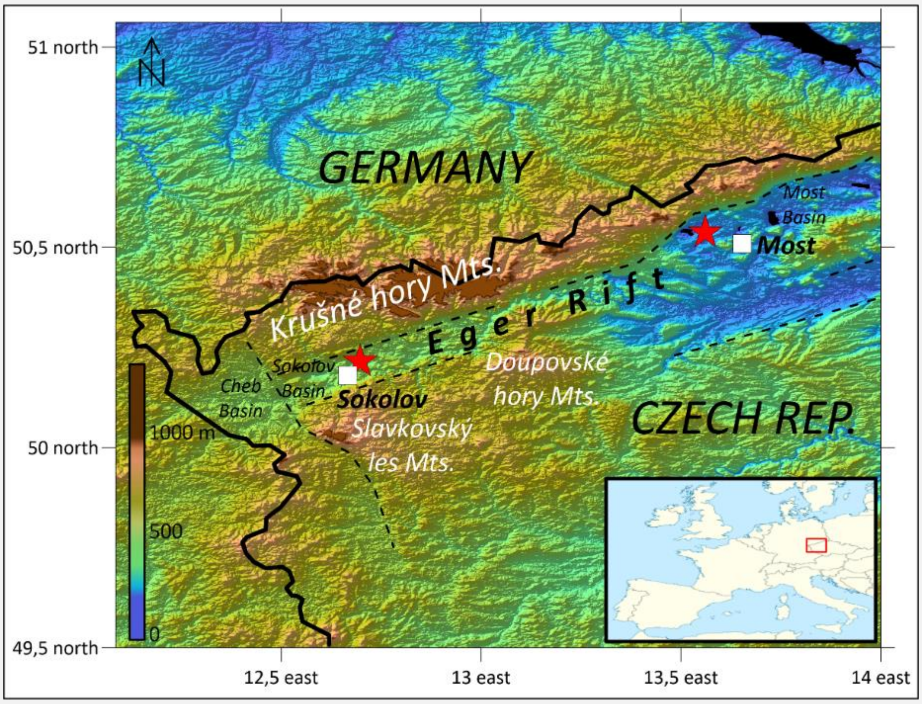

Figure.1. Location of the study sites.

STUDY SITE

The field experiments were undertaken at two study sites (Figure 1). For the first field experiment, the inner dump Obránci míru (OM) was chosen. With an area of 857 ha and a volume of 593,7 mil. m3, this dump is one of the largest within the Most district (Northwest Bohemia). The current owner and local stakeholders recently introduced a transition project called the Green Mine, which focuses on the effective hydric revitalization and reutilization of the entire mining area (including OM dump) resulting in the installation of alternative energy solutions. The OM dump is comprised of grey soft clays and illitic claystones, usually with high or very high plasticity. The dump is over 160 m high with an average thickness over 100 m and backfilling has been undertaken there since 1922.

The second study site was the Družba dump within the Sokolov district (Northwest Bohemia). The average dump thickness is 16–20 m where the soils contain a high ratio of clay mineral montmorillonite, which permanently binds water to its mineralogical structure. Due to time and weather, these clays degrade and quickly turn into plastic soil, which can show extremely low bearing capacity values.

Because of the poor geotechnical properties, both dumps have never been considered for future reutilization. Therefore, they were chosen as ideal sites for this SUMAD field-experiment.

MATHERIALS AND METHODS

The field experiments comprised of three steps:

1) The experimental area was levelled by dozers and then compacted by a heavy-duty single drum roller compactor, which delivers vibration forces equivalent to 75tonnes. On this improved ground, 5 plate load tests (using a 300 mm diameter loading plate) were carried out in accordance with the method detailed in Eurocode 7, in order to describe the compaction rate of dump soils.
2) The second step comprised of performing a ground stabilisation technique where lime (CaO) was injected into the soil to depths of 0,5 to 0,6 m. The mixing ratio was 3% of CaO/1t of improved dump soils. Because of physio-chemical processes between CaO and wet clay minerals, the internal structure of the clay soil changes: soil moisture decreases (by 1-2% to 1% of CaO), improving compaction conditions and significantly increasing their loading capacity. Finally, the ground was compacted by a heavy-duty single drum roller compactor. 13 plate load tests were then carried out within the experimental area after ground stabilisation.
3) The third step consisted of covering the improved dump ground with a spreading layer of fluidised bed combustion ashes. A Heavy-duty roller compactor spread the mixture in two layers, both 300 mm thick and continuously compacted. Finally, the embankment was covered by a 100 mm thick gravel layer (0 – 63 mm fraction) to aid with weather-protection. 12 plate load tests were then carried out on the ground-improved embankment.

Fluidised bed combustion ashes

Because of their properties, these products of combustion have a wide use potential in soil stabilisation. Water additive fluidised bed combustion ashes were chosen for this experiment because the water additive aids in the chemical initiation of the solidification process. The solidification process usually takes up to 28 days depending on the physical properties of ashes used and the water mixing ratio (tab. 1). The processes results in an increase in the compressive strength of the soil (Figure 2).

Figure. 2. An example of a solidification sample of fluidised bed combustion ash–the sample showed a semi-rock character during the compressive strength test (50kN).

Table 1. Physical properties of used fluidised bed combustion ashes.

Lab. sample			Value
Soil moisture	w	[%]	44,2
Bulk density	ρ_{ss}	[kg.m^{-3}]	680
Apparent density	ρ_s	[kg.m^{-3}]	2550
Porosity	n	[%]	73,3
Degree of saturation	S_r	[%]	41,1
Bulk density after compaction 100 %	ρ_{PS100}	[kg.m^{-3}]	1615
Filtration coefficient density after compact.100 %	k_i	[m.s^{-1}]	5,96 – 6,24.10^{-7}

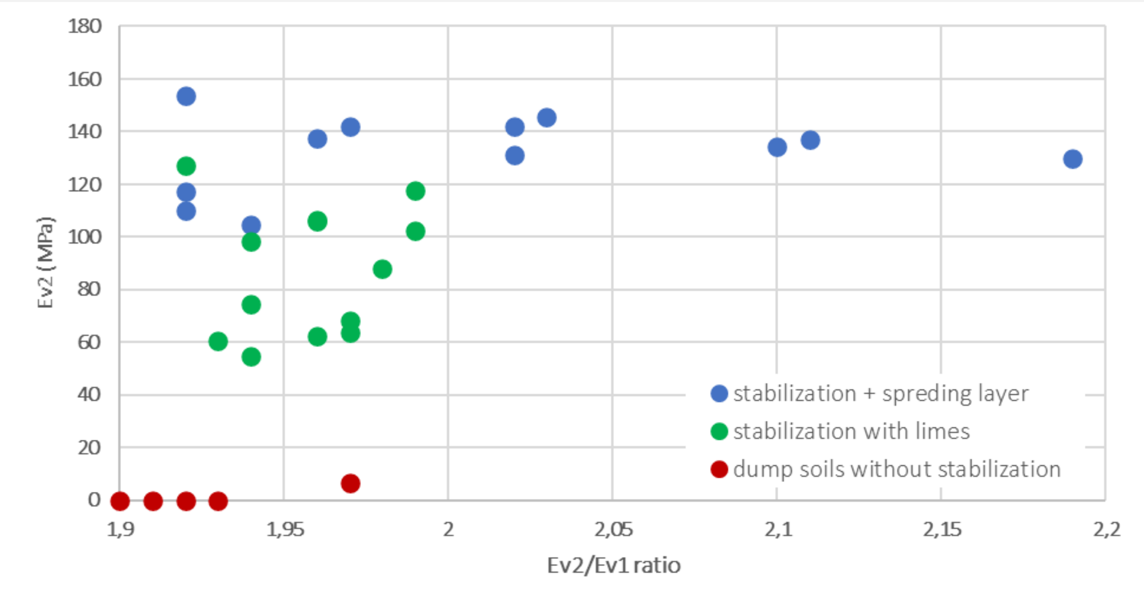

Figure. 3. Comparison of plate load testing results within the experimental area.

RESULTS

Compaction of dump soils by heavy-duty roller compactor

Four of the five plate load tests failed and the maximum bearing capacity (characterised by Ev2) could not be determined because the testing plates sank into the ground (fig. 3). The fifth test showed extremely low values of Bearing Capacity (Ev2 = only 6,5 MPa). These initial tests prove that the dump soils remain unsuitable for foundation installation, and the method is completely insufficient without other significant ground improvement works.

Stabilisation of dump soils with lime

13 plate load tests were performed within the experimental area after the additional ground stabilisation. It is shown that the ground Bearing Capacity of the soil increased by a factor of 12 from the previous method (Ev2 values span from 55 to 127 MPa, with an average 87 MPa). This method proved to be very effective and achieved a significant geotechnical improvement of the dump soils.

Stabilisation of dump soils with power plant ashes

This method was used in combination with the lime injection stabilisation technique discussed above. The combination of these two methods proved to be very effective as the bearing capacity of the dump soil improved by a further factor of 2 from the level observed for the lime stabilised soil (from average Ev2 = 87 MPa to Evf2 = 132 MPa; see Figure. 3). These bearing capacity values not only allow for the movement of heavy machinery but also allow for the construction of solar parks, smaller geotechnical constructions or light prefabricated buildings.

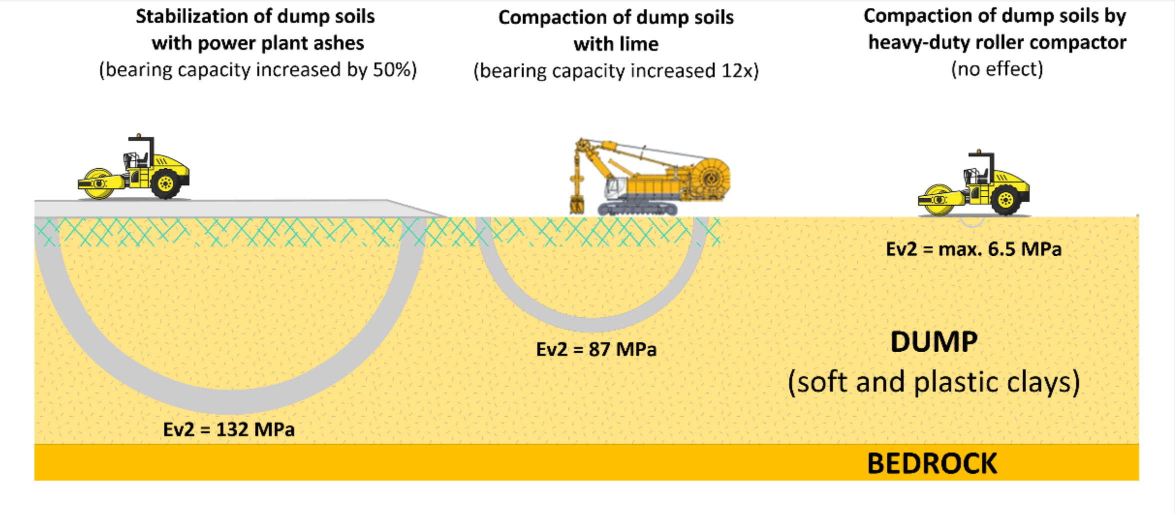

Figure. 4. Effect of all three techniques used for ground improvement.

KEY POINTS

- Most Mining Dumps (mainly those consisting of clays and sandy clays) cannot be used for future construction without improvement of the ground conditions.
- Ground improvement techniques usually used in construction practice are not suitable due to the dump thickness typically being tens of meters.
- Large-scale field experiments proved that dump ground can be significantly improved by ground stabilisation techniques like the injection of lime or the spreading of power plant ashes. A combination

of these methods can increase the bearing capacity by up to 20x that achieved by simple ground compaction. Our plate load tests showed an average value of Ev2 = 132 MPa after the utilisation of lime and power plant ash stabilisation.

- This method is in line with circular principles because it allows coal combustion by-products to be used in the sustainable revitalization of abandoned mine dumps and eliminates the origin of coal ash wastes.

Summary

This chapter has provided a high-level review of the challenges associated with spoil material from a mechanical performance perspective. Methods to characterise the spoil material and then the use of this characterisation in the design of foundation systems has been presented. Significantly more detail can be obtained from the referenced deliverable reports. Section 5.4 highlighted an option which is currently underutilised by industry in general – small-scale laboratory testing to collect high quality data capable of being used to validate numerical models. This validation increases confidence in the performance of a numerical model and hence permits for more challenging designs to be completed and more efficient designs to be produced. Section 5.5. described how such a numerical analysis should be approached. Finally, methods to improve the ground conditions to better carry the loads applied were considered in Section 5.6.

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6. Estimating renewable energy potentials

Investing in renewable energy sources is one of the most advantageous ways of developing unattractive post-mining areas into the ones which bring direct profits. The idea of using photovoltaics and wind turbines as well as heat pumps (a mine spoil as a lower heat source) at coal mining spoils seems like a natural direction to sustain energy production after mine closure. Methods for revitalizing dumps by installing renewable energy systems have some limitations, such as: periodicity (time of day, season), weather conditions (solar irradiance, wind, temperature), costly energy storage, etc. For this reason, real-time monitoring of climatic conditions is required. The following data types are monitored: the average available solar energy (important for the assessment of the efficiency of photovoltaic cells), speed and direction of wind (affects the efficiency of wind turbines), changes in groundwater level (risk of flooding and periodic soil softening), soil and air temperature, dustiness, which affects the degree of contamination of the photovoltaic modules and thus the efficiency of the photovoltaic power plant. The monitoring data is used in the decision-making process on the optimal use of the revitalization method.

Monitoring can be carried out using data from a monitoring station which can record the following parameters (Figures 6.1-6.2):

- solar irradiance, important for assessment of the efficiency of photovoltaic cells,
- wind intensity and direction which affect the performance of wind turbines,
- precipitation,
- soil temperature, influencing the soil behaviour,
- dust concentration which affects contamination of photovoltaic modules,
- air temperature and humidity which is important in selecting the revitalization method,
- groundwater level (risk of flooding and periodic soil softening).

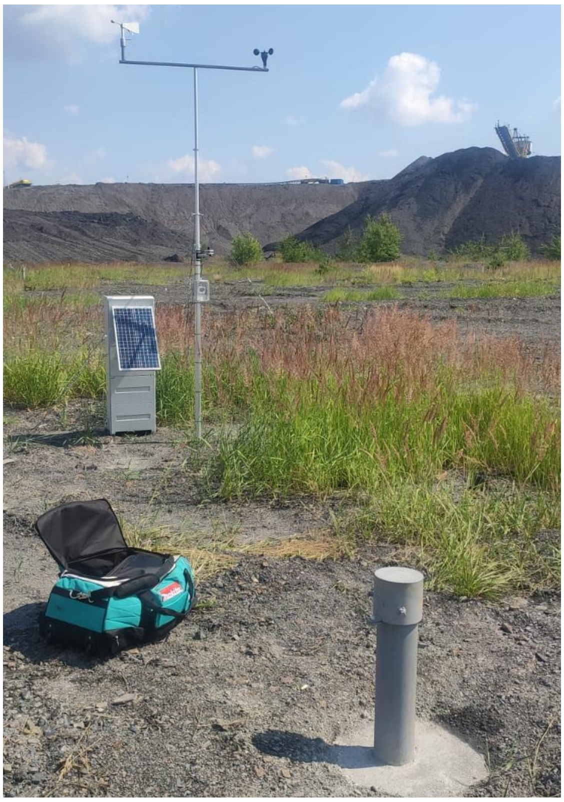

Figure 6.1. Monitoring station at the heap of LW Bogdanka mine, E Poland (Image courtesy of KOMAG

It is also beneficial to undertake measures to inventory the dump area in 3D using laser scanning and low level photogrammetry, carried out with the use of drones. These activities serve to assess displacement and subsidence of the ground and the impact of erosion on the dump area.

The influence of individual parameters on the feasibility of constructing photovoltaic and wind power plants is presented below.

Figure 6.2. Monitoring station at the Albrechtice dump, NW Czech Republic (Image courtesy of VUHU)

Solar radiation intensity (direct module output)

Investment in photovoltaic installations should start with an analysis of the potential of solar energy resources in the area of interest. For the analysis and exploration of problems related to solar energy, the following basic parameters describing solar radiation should be used (Figure 6.3):

- intensity of solar radiation, that is the power density of solar radiation reaching the Earth per m^2 of surface in one second. This parameter is generally expressed in [W/m^2]. The average intensity of solar radiation reaching the atmosphere border is 1.39 kW/m^2 and is called the solar constant. Due to absorption and scattering in the atmosphere, only a part of this radiation reaches the surface of our planet where the radiation intensity is about 1000 W/m^2.
- Insolation, i.e. the sum of the intensity of solar radiation per unit area over a given period of time. This parameter determines the energy resources at a given place and time, usually expressed in kWh/m^2 per year .

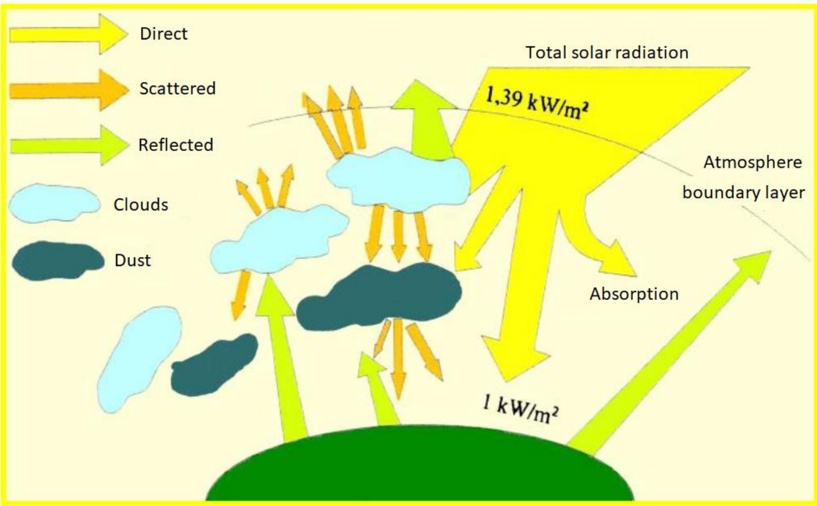

Figure 6.3. Distribution of solar radiation on the Earth

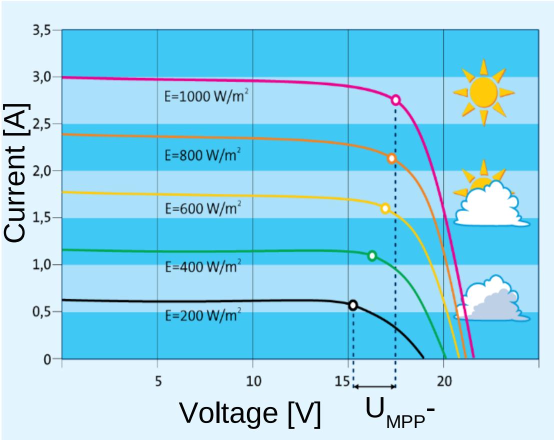

Figure 6.4. Effect of change in solar radiation intensity on photovoltaic module efficiency

Solar energy is strictly dependent on the season and cloudiness. Figure 6.4 shows an example of a reduction in solar radiation, assuming the insolation in a clear sky equal to 1000 W/m^2.

Insolation varies from region to region. Within Europe its range is quite wide (Figure 6.5). Despite the fact that in the southern countries there is a very high intensity of solar radiation and insolation, the associated high temperature is not conducive to the efficiency of photovoltaic installations.

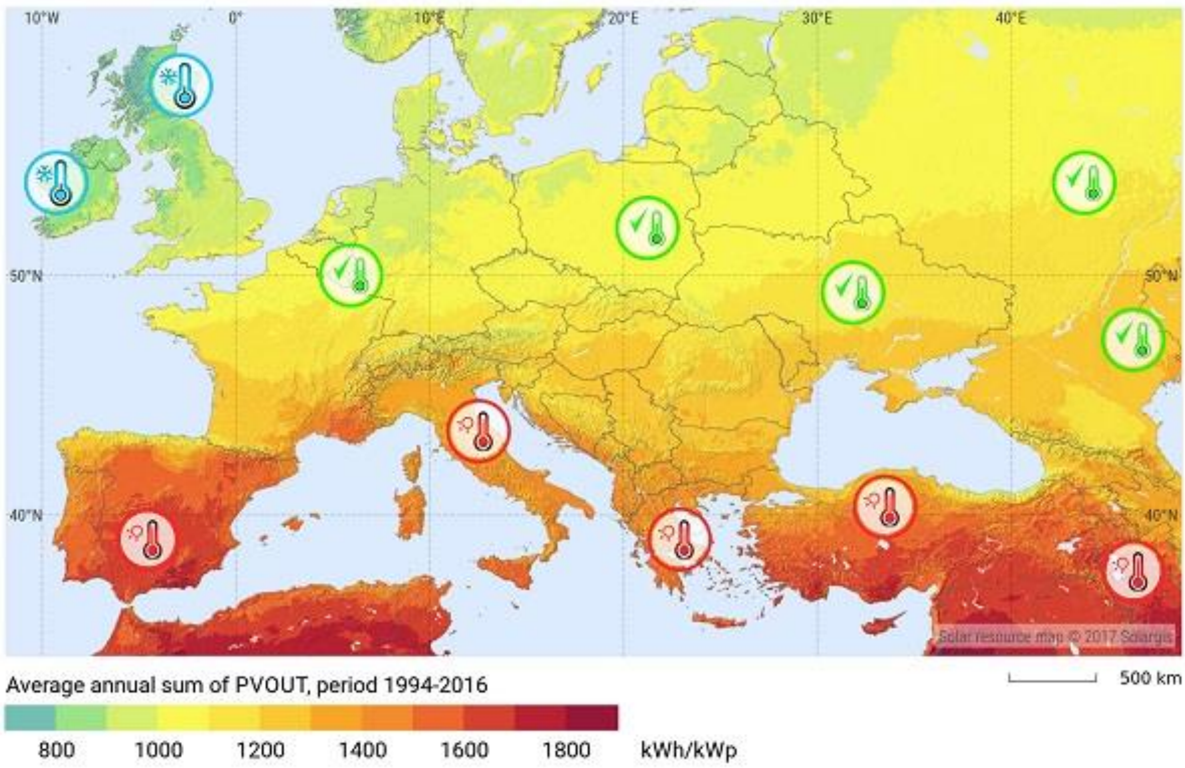

Figure 6.5. Insolation in Europe

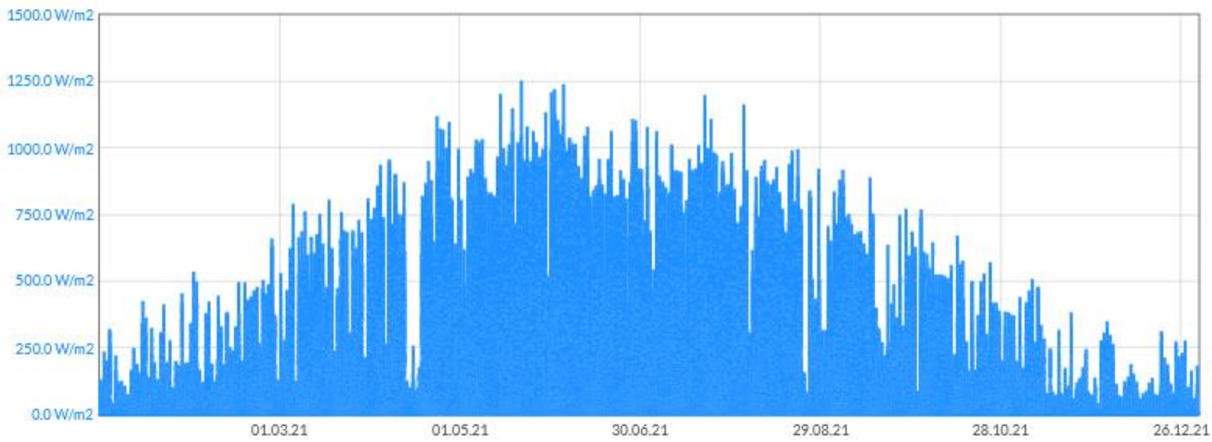

Figure 6.6. Solar irradiance recorded in 2021 at the heap of LW Bogdanka mine, E Poland - four winter months account for only 12.0% of the annual energy production, which corresponds to roughly one summer month.

Dust concentration

Manufacturers of photovoltaic modules ensure that if the modules operate in normal weather conditions, cleaning them is not necessary due to the fact that the surface is covered with self-cleaning layers. It is also argued that cleaning the modules would cause them to fail mechanically. In practice, however, contamination of the PV modules such as dust, pollen, soot, leaves, moss, bird droppings, coal combustion products, etc. greatly reduces the efficiency of the PV system. Dirt is often difficult to see with the naked eye as it first settles on edges and frames and then overlaps the entire surface of the module. Unfortunately, rain only partially removes dirt, and more and more manufacturers recommend the need for professional cleaning of photovoltaic modules, especially to remove persistent contaminants such as bird droppings. While dirt caused by animals is difficult to predict, thus by measuring dust concentration, it is possible to estimate the amount of pollution that can affect the efficiency of photovoltaic installations. This is also important in mining areas where dust is associated with operations using heavy machinery. This type of dirt will not be removed by rain, on the contrary, it will become larger and more difficult to remove with time, and this, in a short time, will lead to a loss of 10% or more in the modules efficiency.

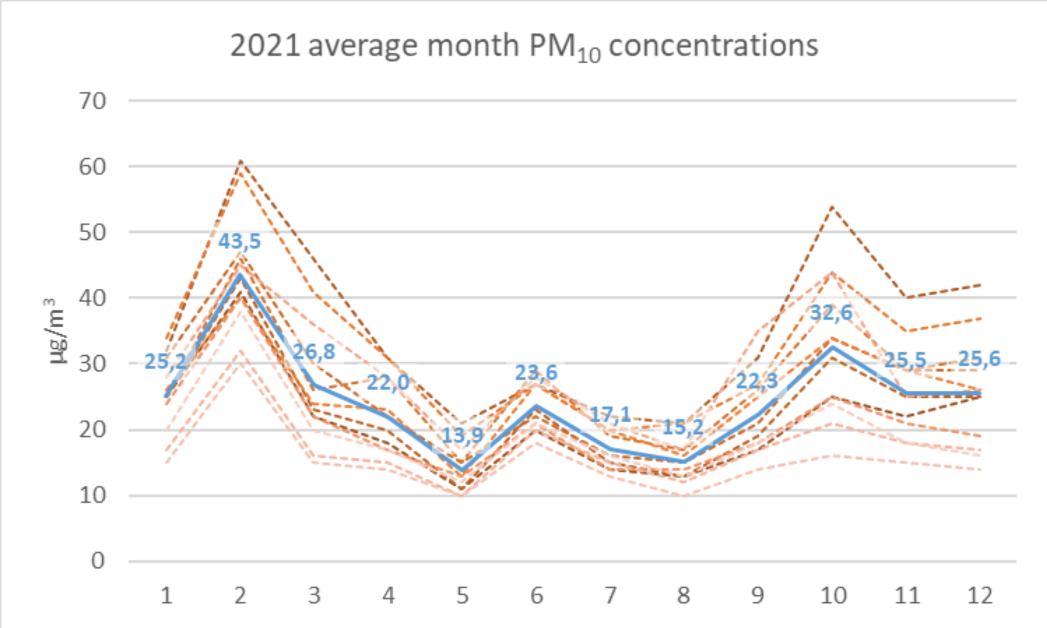

Figure 6.7. Characteristics of soiling by dust particles (PM10) in the Most basin, NW Czech Republic in 2021. Representative curve (blue) was determined by the Laboratory of air pollutants measurements (operated by The Brown Coal Research Institute - VUHU) based on long-term experiences and measurements from 11 meteostations.

Air temperature

Temperature of the modules has a direct impact on the amount of electricity generated. It is assumed that for each degree above 25°C (STC conditions, for which the manufacturer specifies the parameters of the PV modules), the power drops by up to 0.45%, depending on the PV technology used (Table 6.1).

Table 6.1. Temperature coefficients for different PV technologies

Technology	Temperature coefficient of power [%/°C]
Mono-c-Si	-0,40
Multi-c-Si	-0,45
a-Si	-0,20
a-Si/μc-Si	-0,26
CIGS	-0,36
CdTe	-0,25

Operating temperature of the photovoltaic module depends on ambient temperature, intensity of solar radiation, structure of the module itself and speed of the wind, which is the module's natural coolant. At air temperature of around 40 ° C, the modules can warm up to 70 ° C, which results in a loss of efficiency of up to 15% of the module's power.

Due to the design of photovoltaic modules, it is not possible to continuously measure the temperature on the active surface. In monitoring systems, the temperature of the bottom surface of the PV module is measured. It is assumed that the temperature of the active surface is about 3°C higher than the temperature of the bottom surface.

Temperature measurements allow to assess if the monitored power drops are caused by high temperatures, or a system malfunction or failure is the reason.

Wind speed and direction

It is possible to estimate the potential of a site for recovery of wind energy on the basis of the "wind atlas". Due to the fact that the data contained in such atlases are averaged in a given area, they may not take into account local terrain conditions such as artificial hills (dumps). Such elevations change wind pressure and allow access to higher atmosphere layers. In this case, it is advisable to estimate the local windiness through in-situ surveys. The vertical wind speed profile (Fig.5) or the speed gradient in the boundary layer defines the wind speed as a function of height above the ground. It is the key parameter of wind energy potential, and allows to determine the energy efficiency of a turbine. In practice, it is determined using the interpolation function on the basis of wind measurements or, less precisely, on the basis of the roughness class of the terrain.

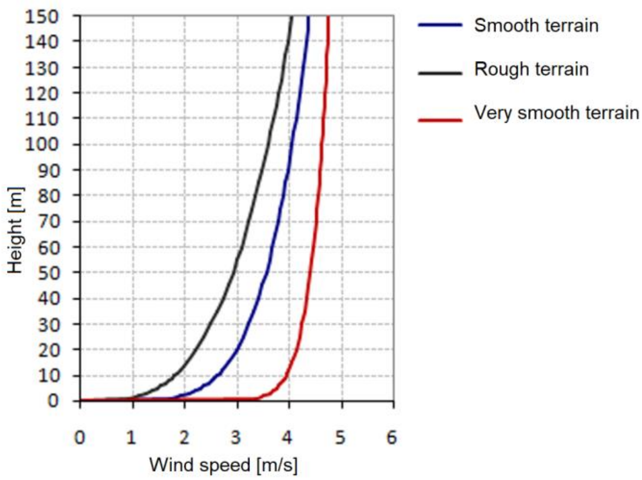

Figure 6.8. Vertical wind speed profile

Based on the measured data, it is possible to develop a distribution of speeds over a period of a year and, as a result, to predict the energy production of a wind turbine. Additional information obtained from wind measurements is the direction of the dominant wind. This is important when planning the location of wind turbines at a future wind farm. Before investing in the wind turbines it is recommended to perform wind measurements at a height not lower than 75% of the turbine rotor axis height.

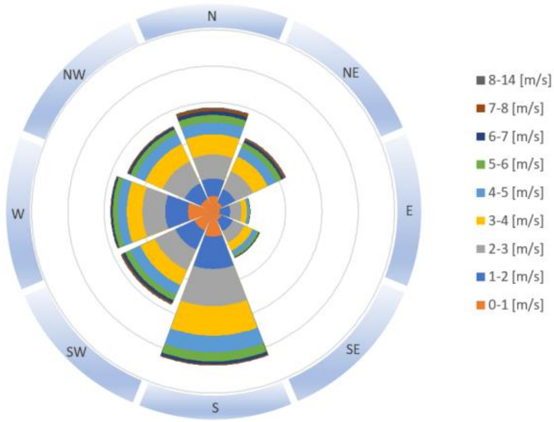

Figure 6.9. Wind speeds and directions recorded in 2021 at the heap of LW Bogdanka mine, E Poland

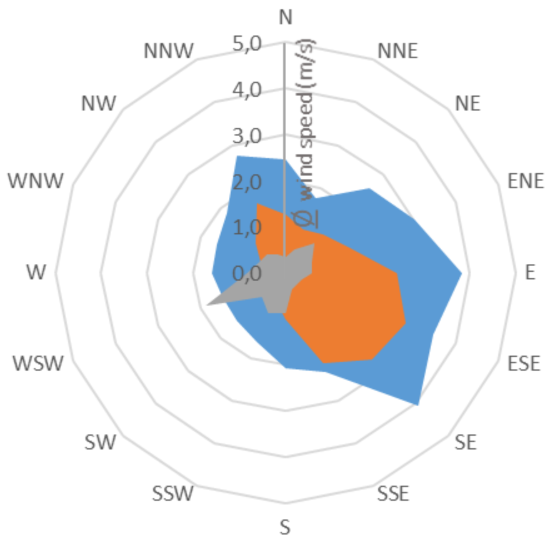

Figure 6.10. Average values of wind speeds from respected directions measured at Marcela (blue), Slatinice (orange) and Albrechtice (grey) dumps, NW Czech Republic.

Ground temperature and ground conditions

In below zero temperatures, the water in the ground freezes causing the so-called frost heaves. These can damage foundations, drain pipes, geothermal heat exchanger pipes, etc. The depth of ground freezing is the distance from the surface to the bottom of the below zero temperature zone. The ground is usually moist, which means that it contains water particles, and these also freeze. The depth at which the constructed object will be located depends on the depth of freezing of the ground, its type and the groundwater level.

Figure 6.11. Ground temperature plot (-50cm) recorded in 2021 at the heap of LW Bogdanka mine, E Poland

The final level of the foundation is determined by an engineer, who adapts the design to a specific object and location. If there are any doubts related to the quality of the soil, it is worth performing a geotechnical survey of the soil. After taking and analysing the soil samples, a geo-technician can give detailed recommendations. Designing the foundation of wind turbines is one of the most difficult engineering tasks. The biggest problem is the complexity of the impacts transmitted by the foundation onto the subsoil. In addition to static effects, there are also cyclical and dynamic effects related to the operation of a wind farm. During preliminary works, prior to the construction of a wind turbine, field tests to a depth equal to about 1.5 of the foundation diameter, with the most common drilling depths of about 25 m, are recommended. It is important that at the stage of planning the ground tests, the people who decide about their scope and foundation method should be aware of the complexity of the issues of cooperation between the structure and the soil. Based on field and laboratory tests, the following geotechnical parameters, necessary for the correct design of the foundation of the structure, should be determined:

- type of soil divided into lithological layers,
- maximum level of the groundwater table,
- parameters describing physical soil properties,
- effective strength parameters of the soil,
- shear strength of the soil in conditions without drainage,
- static and dynamic soil deformation modules,
- Poisson's ratio with drainage and without drainage.

Groundwater level

An extremely important parameter affecting the design of foundations is the presence or absence of pressurized groundwater.

Foundations subjected to these pressures may differ in cubature even by about 30%. Taking into account the significant impact of this fact on the investment costs, it is always advisable to carefully check the water conditions, e.g. with use of piezometers. One can additionally refer to archival test results from a given area. The variability of the water parameters over a 20-year period may turn out to be quite large. In this context, the situational and height analysis of the given investment area and the identification of possible watercourses or the risk of water accumulation are also helpful.

Ground displacement and subsidence and the impact of erosion

Ground displacement or the influence of erosion on the slope of heaps can be monitored using modern drone measurement techniques. The most accurate measurement methods are laser scanning and photogrammetry.

Laser scanning is based on very fast determination of coordinates of a large number of points by laser measurement. The resulting set - the so-called "point cloud" allows, after appropriate processing, to generate a three-dimensional model of the scanned object. Laser scanning technology is used in cartography, architectural inventory, deformation measurements of engineering structures, environmental studies, archaeology, etc. The laser scanner determines the position of points in any spatial coordinate system XYZ. Coordinates of individual points are determined in relation to the centre of the scanner (polar coordinates). These are determined by the horizontal and vertical angles and the distance to the object measured by the laser beam. Knowing the position of the scanner you can determine the coordinates of points in any coordinate system. Processing of laser scanning data consists of the following steps:

- mutual registration of point clouds and their combination into a single model,
- data filtration,
- data interpolation,
- numerical terrain surface model.

Figure 6.12. View of the scanned area of the LW Bogdanka mine, E Poland - a fragment of the dump was inventoried in 3D using laser scanning and low-level photogrammetry, carried out with the use of drones.

Photogrammetry is a scientific and technical discipline which, based on photogrammetric images (so-called photograms), allows the precise reproduction of shapes, sizes and the arrangement of objects on the ground. Photogrammetry in geodesy is most often used when creating maps and determining the height of various objects, and also significantly facilitates measuring large distances or areas. Photogrammetry most often uses perspective images obtained by means of cameras. The recorded image is subject to photogrammetric measurement, in which we use mathematical dependencies occurring between the type of projection represented by the image and the three-dimensional positioning of points of measured objects.

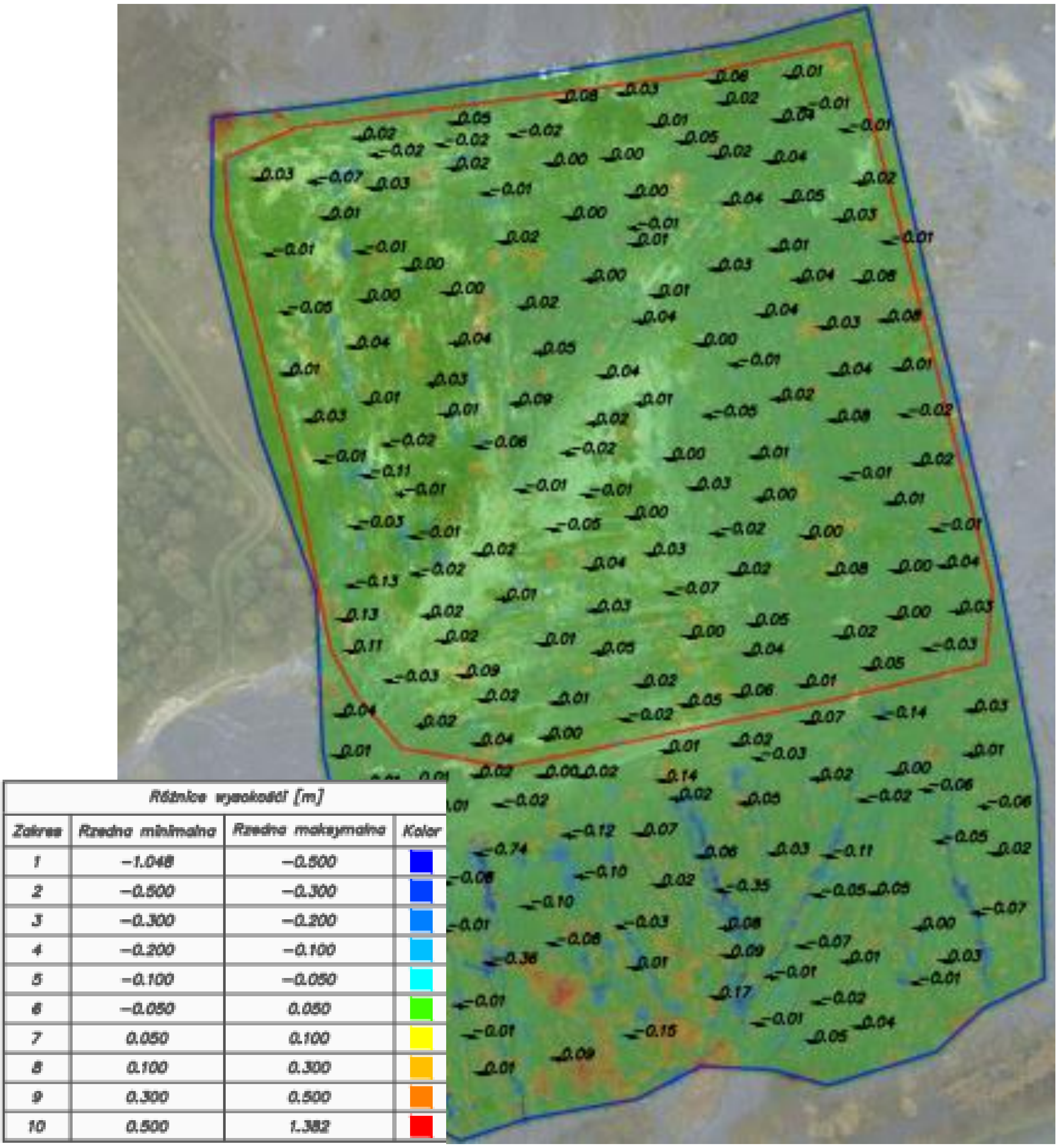

Figure 6.13. Pit and embankment values in the scanned area of the LW Bogdanka mine dump, E Poland - from September 2020 to October 2021 no significant ground displacements or settlements were observed in the surveyed area.

7. Assessing risks

Industrial activities, especially mining, can be responsible for ecological degradation of areas and objects or create risks to human health, the natural environment and the economy. It is difficult to revitalize such areas because revitalization operations, which take time and money, must be coordinated due to their multidirectional nature as well as having to account for human factors.

To mitigate the risks imposed by the post-mining objects and areas, it is necessary to apply different revitalization techniques which should benefit the area ecologically while also being acceptable from an economic and social point of view. To implement a suitable revitalization strategy, one needs to have a deep knowledge of the revitalized area based on previous experiments and analyses. The analyses must be multidirectional and should involve risk factors, financial issues, and social perception. What is more, the decision process is usually complicated and might need to be supported by novel tools. An example of such a tool is a software named SUMAD Risk Management Tool (SUMAD RMT), which intends to support decision-makers in planning revitalization processes of the post-mining sites, particularly spoil heaps.

The aim of SUMAD RMT is to provide feasible revitalization plans with realistic revitalization techniques that should be able to properly reduce risks induced by the degraded objects. In addition, these plans must be economically effective, accepted by society and free from different non-financial constraints. This requires the risk management methodology to include a cost–benefit analysis and a qualitative analysis focused on soft factors and decision support.

SUMAD RMT is capable of supporting decision-makers in selecting the most advantageous revitalization activities for the heaps, based on the results of the comprehensive and multidirectional analyses. Different heap properties (geotechnical and environmental), heap-related risk factors, and economic and non-economic constraints are considered by this tool.

SUMAD RMT was developed by considering the three-pillar assessment criteria (mentioned in Section 4.2) and is broken down into three main software modules (Figure 7.1):

1. **RRA – Risk Reduction Assessment**

Heaps may generate different risks to the environment, especially to people who live in the vicinity. These risks have to be properly analysed and mitigated by customized revitalization activities. The RRA module can develop a comprehensive risk picture depicting the heap before (called inherent risk) and after (called residual risk) the revitalization actions. Additionally, the risks introduced by the implemented revitalization activities are managed.

2. **CBA – Cost–Benefit Assessment**

Different heaps impose different costs but sometimes, especially after their revitalization, similar benefits. The CBA module allows the tool users to specify several financial parameters related to the heap before and after revitalization actions and calculate basic indicators which will help to assess the revitalization investment efficiency, such as NPV (Net Present Value), DPBT (Dynamic Payback Time).

3. **QCA – Qualitative Criteria Assessment**

Generally, heaps might create problems for the environment and for people living in the surrounding area. Many diversified issues of social, political, and psychological, character are hard to express as risks or financial categories. Therefore, the QCA module allows non-financial factors related to the heap before and after revitalization actions to be considered.

These software modules are supported by additional features (Figure 7.1).

In order to carry out the above-mentioned, complex, multidirectional analyses (RRA, CBA, QCA), the tool has to be able to identify detailed characteristics of different kinds of heaps. The Heap Properties (HP) module includes an extensive and diversified set of parameters which describe the revitalized object and its environment (localization, owners, morphology, geology, pollutants, etc.) and provides input parameters for other modules.

The revitalization process assumes the application of a package of diversified Elementary Revitalization Techniques (ERTs). The main issue is for many projects is deciding on how to identify the most advantageous package for the analysed heap and how to meet the requirements for a range of different stakeholders. The package includes activities that must be undertaken to achieve the assumed revitalization effects with respect to the planned land use, risks, costs, benefits, and various other constraints. It is possible for decision-makers to define several packages of ERTs called Revitalization Alternatives (RVAs). These RVAs are subjects of the RRA, CBA, and QCA analyses. To properly manage the RVAs, a Revitalization Alternative Composer (RAC) is designed. It allows for the specification of an initial set of revitalization techniques, usually applied ad hoc before the officially planned revitalization process begins (called “zero” alternative RVA [0]), and for the identification of several Revitalization Alternatives RVA[1 … N−1], which are the subject of multi-directional analyses, in order to select the most advantageous one for implementation (as the target RVA).

There are numerous terms related to the analyses which lead to the selection of the target RVA (threats/hazards, vulnerabilities, impacts, Elementary Revitalization Techniques, cost–benefit categories, QCA categories). In order to avoid problems while defining these terms ad hoc, a knowledge base is developed. The base is comprised of a coherent and classified set of terms related to the heap revitalization. This knowledge base is managed by the Predefined Data Manager (PDM) which maintains a common set of predefined data for any revitalization project. In the process of developing the revitalization plan, this data is shared with other modules. The knowledge base is, in fact, the project domain knowledge base.

The results obtained from RRA/QCA/CBA analyses are relatively complicated. Therefore, one must aggregate the results in order to present them to decision-makers properly. This is the role of the Data Management, Aggregation, and Visualization (DMAV) software module. DMAV supports decision-makers by providing them with structured information. The information serves as the input necessary to select the target RVA for the implementation and generation of the revitalization plan.

The assessment of risk factors (likelihood, consequences) during the risk analysis (RRA) are burdened by uncertainty. This issue can be dealt with by using a historical database that includes past heap incidents. This operation is performed by the Heap-related Events and

Incidents Registration (HEIR) module. The HEIR module allows any historical data related to different heaps in the world, especially the revitalized ones, to be registered. When the given risk scenario, i.e. pairs <threat/hazard-vulnerability>, is considered with the use of the RRA, the related incidents can be presented. Thus, the person who conducts the analysis can modify the preliminary assessment taking into account past events.

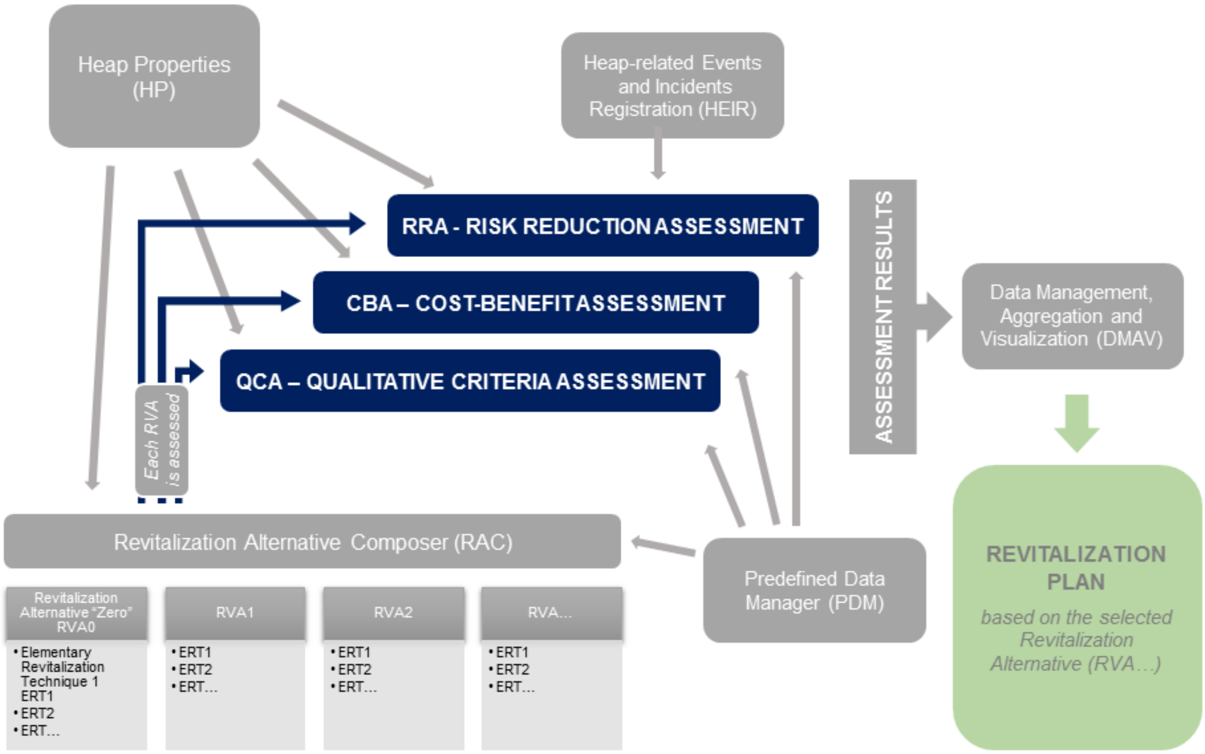

Figure 7.1. The structure of the SUMAD Risk Management Tool (modified after Białas 2022)

The revitalization planning process starts by launching a revitalization project in the tool for the selected heap. The process is iterative and its five main steps can be distinguished.

Step 1: Identification of the heap to be revitalized and preliminary revitalization activities

The heap specification is a concise, structured heap representation in SUMAD RMT, constructed by the revitalization project team based on site documentation, experiments and observations. It contains the following:

- Administrative records containing the heap owner, localization, etc.,
- Geometrical parameters, including the area height, volume, shape,
- Geological parameters, including age, critical water contents of fine-grained soil, consistency, particle size, compressibility, stiffness, cohesion, structure, kind of heap material, technical conditions, surface usability,
- Pollutants related to ignitability, corrosivity, radioactivity, reactivity, toxicity, littering, including bulky waste as well as biodegradable and non-degradable materials,

- Heap environment records, including landscape characterisation, climate parameters, air pollution status, vegetation and animals (especially protected ones), surrounding water, protected areas such as culture heritage or nature,
- Auxiliary information, like legal restrictions and available financial, technical, and operational resources.

Next, all revitalization actions, called here Elementary Revitalization Techniques (ERTs), implemented at the analysed heap until now, are identified and specified as a “zero” revitalization alternative RVA0. For example, the RVA0 may include basic techniques such as:

- ERT1: Decreasing the heap volume by ca. 10% and using this material for levelling the external degraded areas and for concrete production,
- ERT2: Partial afforestation,
- ERT3: Partial soil cleaning,
- ERT4: Hydrological improvement.

Step 2: Preliminary analyses

For the considered heap’s RVA0 (current state), the RRA, QCA and CBA analyses are applied in an attempt to identify further possible revitalization activities.

The RRA requires the identification of risk scenarios and for each of them the assessment of:

- the event Likelihood (L), using the predefined (configurable) scale, e.g.: Nearly impossible (value=1), Low (2), High (3), Almost certain (4),
- the event Consequences (C) using the predefined (configurable) scale, e.g.: Negligible (value=1), Low (2), High (3), Critical (4).
- The risk value (RV), defined as the product RV=L×C, is measured in the range from 1 to 16 where:
- RV from 1 to 3 is considered the “Acceptable” risk – marked green in SUMAD RMT,
- RV = 4 or 6 or 8 is “Tolerable” (usually monitored) – marked yellow,
- RV = 9 or 12 or 16 is “Unacceptable” (should be mitigated) – marked red.

L, C, RV and the acceptance levels are configurable in SUMAD RMT. Threats/hazards, vulnerabilities, and many other items for the CBA and the QCA, can be downloaded from the PDM or can be locally defined (in the project).

The CBA framework includes three separate matrices for:

- CAPEX (CAPital EXpenditure),
- OPEX (OPerating EXpenditure),
- BENEFITS.

Their rows include configurable groups of categories and subcategories. The columns represent particular years of the analysis time span, e.g. time span may be 20 years. The analysis requires a setup of analytic parameters (currency, discount rate, budget, constraints and time span) in the beginning.

For the given RVA, the related expenditures and benefits are planned for defined years within the assumed time span and financial parameters (indices), like NPV, DPBT are calculated. The CBA analysis for RVA0 is only considered as auxiliary information as it is impossible to implement cost-benefit planning for the past

7. Assessing risks

The considered revitalization alternative may be able to properly mitigate the risks and have promising financial parameters. However, it might not be implemented due to other social and political factors that may cause it to be less effective. These factors are evaluated with the use of the qualitative criteria (QCA) module.

Table 7.1. The example of the QCA framework.

QCA CRITERIA	WEIGHTS% 100	
ECONOMICS	25	100
Impact on market and trade relations		20
Impact on financial situation of residents		30
Impact on real estate market		10
General investment climate, economic stability		20
Public-private partnerships		20
SOCIETY	30	100
Acceptance for revitalization activities		40
Living conditions in the place of residence		40
Engagement in sport activities, tourism, social events		20
POLITICS	10	100
Complexity of decision process		60
Compliance with local policies		20
Influence of politicians		20
LAWS AND REGULATIONS	10	100
Lawfulness		20
Ownership structure complexity		20
Restrictions and additional formal regulations		60
ENVIRONMENT	25	100
Weather conditions, climate		60
Aesthetics		30
Waste management		10

During the preliminary analysis, the QCA provides non-financial information to decision-makers, allowing them to assess the current constraints and opportunities related to the heap affected by the RVA0 activities, facilitating the planning of the revitalization alternatives to improve the current state of the heap. It is very important to identify issues which may positively and negatively influence the planned revitalization efforts.

The QCA framework (see Table 7.1) is represented by a matrix which requires the right configuration of parameters at the beginning. The matrix rows define groups of criteria. The particular criteria are assessed by the analyst. The groups and the criteria within any group have weights assigned to them. The sum of the group weights should be 100. The criteria have weights too. Their sum should also be 100. The weights express the importance of a criterion or group in the analysed project.

Step 3: Composing and analysing the revitalization alternatives

After considering the current state of the heap, RVA0, the planned land use and results of the preliminary RRA, CBA, and QCA analyses, one gets a general picture of the inherent risk, current cost–benefit parameters, and non-tangible factors. It is then possible to propose a number of reasonable revitalization alternatives for further consideration. The proposed revitalization alternatives should:

- mitigate at least “unacceptable” risks;
- be in line with the assumed land use, business needs, citizens’ expectations, natural environment, etc.;
- be feasible (considering financial and non-financial constraints).

This allows several alternative revitalization schemes to be proposed which, in the next step, can undergo further RRA, CBA and QCA analyses, in order to finally select the target RVA for implementation.

Step 4: Alternative assessment with respect to risk (RRA), financial (CBA) and non-financial (QCA) factors

Each new revitalization alternative may include some ERTs, which may cause new risk cases and should be managed by adding extra ERTs to the RVA, until all risks scenarios are tolerable or acceptable. It is important to note that the entire risk management process is iterative and all pillars, RRA, CBA and QCA, interrelate with each other.

To assess more precisely the L and C values for a hypothetical event described by a risk scenario, the analyst can review similar events from the past registered by the HEIR component.

RRA is applied for all alternatives. For each RVA, the CAPEX, OPEX and BENEFITS analyses should be performed to obtain the basic financial indicators (NPV, DPBT) and different charts to compare financial parameters. QCA is also performed for each new RVA.

Step 5: Decision making

Decision makers are provided with current, detailed or aggregated information from the analytical pillars. The decision maker is able to review the detailed results or go back to the SUMAD RMT operations at any time, e.g. when there is a need to modify/continue the analyses, or when a new RVA should be defined because the previous one is unsatisfactory or unfeasible. A summarizing report, i.e. a revitalization plan, can also be generated by the tool at any time.

SUMAD RMT embraces all revitalization planning stages, from the heap properties specification to the assessed options proposed to the decision-maker. The planning process is based on very detailed and diversified input data and produces aggregated results.

The planning is based on the risk management, financial and non-financial assessments. This process allows for a wide range of factors related to the planned revitalization application to be considered. It is important because applied ERTs introduce a diverse range of new risks for the revitalized object. For example, new risks related to wind turbines, PV installation, even a huge number of heap visitors can be considered by the tool. QCA allows for the identification of different side effects that could be easily omitted causing surprising negative effects during the implementation and use. The PDM knowledge base representing the domain data raises the projects reusability. The RRA, CBA, QCA analytic modules provide a unified picture of all revitalization options which aids the decision-maker. Detailed information about the methodology implemented in SUMAD RMT is presented by Białas 2022.

In order to access SUMAD Risk Management Tool, please contact:

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References

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8. How to create a successful revitalization?

Historically post-coal mining revitalization strategies have not received much attention. However, in recent years, as we have moved into a period of phasing out coal mine use in Europe and begun a transition to a low carbon economy, post-mining revitalization has become increasingly a concern for local communities, operators, and local authorities. The issue of securing a more sustainable and economically secure future for coal regions in transition is an important social challenge.

Mine operators are obliged to have a post-mining reclamation plan in place before mining operations even begin. Usually, this plan involves ensuring the environmental safety of the former mining areas and restoring vegetation. However, currently it is uncommon to propose a revitalization use which goes beyond re-vegetation and which develops the economy or provides work for the local community.

Fulfilling more developed revitalization goals requires proper advanced planning and management. A revitalization strategy for a particular post-mining area must balance several factors: environmental and geotechnical safety, technical feasibility, costs of available technologies, local economic and human resources, needs of inhabitants, and public acceptability. Revitalization concepts should be fully assessed in terms of possible outcomes, potential for success and costs-benefit analysis. Moreover, the needs of all community members such as public bodies, private investors and local businesses, non-governmental organizations and most of all, inhabitants, should be addressed with careful consideration when planning post-coal mining revitalization. All these groups have a place in the post-mining picture and have their roles to play in the just transition of coal regions.

A significant player in dictating post revitalization choices is local governments, who oversee all activities taking place in areas of their administration and draw up strategic development plans aimed at achieving certain economic and social goals for their communities. They also have an intimate knowledge of the needs and capability of the local inhabitants - such as entrepreneurial activity, resident activism, non-governmental organizations, good infrastructure, and renewable energy resources. In addition, local authorities adopt detailed land use plans that contain zoning regulation and use other ordinances to regulate land use. Therefore, there is no new investment in green infrastructure, renewable energy installations, manufacturing facilities, etc. if it is not permitted under the local zoning regulation. Local governments can also help to strengthen the acceptance of certain revitalization activities among the local inhabitants. A well thought-out revitalization strategy achieves the economic goals of local communities however technical and logistical challenges provide a significant barrier to achieving this.

Implications of post-mining revitalization activities on the economy, the environment and society should have long-term vision. Particularly given the implemented revitalization will last for decades and financial resources dedicated to it should be well spent. Decisions taken today may radically influence the future, in addition to the naturally changing needs of society over time - therefore various options should be considered in relation to their long-term implications.

If construction of new facilities in post-mining areas, especially on mine spoils, is considered as part of revitalization actions, it should be preceded by gathering adequate information about the geotechnical characteristics of the site including its load capacity, stability and hydrogeological conditions. It should be remembered that a post-mining area is not a typical area for construction and may be exposed to various risks. As such standard design practices do not always provide sufficient consideration to produce a safe design. For such an unusual site to meet construction requirements, designers will have to consider geotechnical risks, ground improvement methods, non-standard types of foundations, etc. They should determine the most economical and efficient way to implement a construction project, given the soil conditions and the structural loads which can be carried. With the use of appropriate modelling methods, it is possible to improve quality of designs and overcome designing challenges.

Figure. 8.1. Key stages of the revitalization management process.

Key aspects of the revitalization management process:

- One must see the whole picture. There are always many issues to be considered, various sources of influence and different stakeholders – among others, two opposing groups, the mine operators who would like to reclaim the post-mining land at the lowest possible costs and the local administrators and residents who wish that as much as possible is done by the mine operators as they are the ones responsible for land degradation.
- Post-mining areas and the affected communities are characterised by various levels of dependency on the mining sector and different potential in terms of economic strength, entrepreneurship, social networks, technical infrastructure, natural resources, etc. All these factors must be carefully considered. A properly implemented risk management tool can

be useful in managing these different factors.

- Scientific approach and engineering expertise can help to properly assess technical feasibility of the planned revitalization actions and to avoid unexpected technical and logistical difficulties and underestimation of time and financial resources the revitalization will require.
- A key to success is cooperation and bringing together actors of all groups affected by the coal mining – coal sector workers, farmers, foresters, small and large entrepreneurs, land developers, banks, energy providers, etc. Post-mining area revitalization should be in line with the agenda of local government in terms of land management in order to provide long-term benefits for the local community.

The factors to consider and the process to follow are summarised schematically in Figure 8.1.

9. Conclusions

Traditionally the post-mining revitalization of spoil-dump sites has been limited to re-greening or provision of recreational space. The development of these sites beyond these relatively simple applications has been limited by technical obstacles and lack of societal motivation. However, as more and more sites are being decommissioned, the future use of these locations is being examined ever more closely. This handbook has presented the high-level considerations that are required to be made when looking to undertake more comprehensive revitalization of post-mining spoil dump areas. Aspects such as community influences, risk analysis, economic viability, and technical design have all been considered and the interplay between these factors discussed.

Underlying the high-level summary presented in this handbook, extensive detailed work has been undertaken by the RFCS SUMAD project partners. Ultimately the detailed work feeds into a risk management decision tool, such as the 'SUMAD RMT', to better inform those responsible for managing the revitalization work.

It must be highlighted that no generic 'one size fits all' solution can be provided for the revitalization uses of post-mining waste dumps. The site-specific geotechnical, governmental, economic, and societal pressures all influence the decision-making process. Ultimately the work of the SUMAD project should guide those decision makers towards the most effective and technically feasible solution for their site.

Readers are encouraged to explore the different influencing factors in greater detail by referring to the deliverables and reports produced as part of the SUMAD project.

The work published here received funding from the EU's Research Fund for Coal and Steel under the project "SUMAD - Sustainable Use of Mining Waste Dumps" Grant No. 847227.

The research is published in the frame of the international project co-financed by the programme of the Minister of Education and Science entitled "PMW" in 2019–2022; grant number 5029/FBWiS/2019/2.

ISBN 978-83-60905-07-4