Call: RFCS-2023

Project: 101157379

MiDSafe

Advancing Post-Mining Waste Dump Safety and Sustainability

Deliverable 1.3

Comprehensive overview of the project

Public

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EXECUTIVE SUMMARY

The MiDSafe project, funded under the Research Fund for Coal and Steel (RFCS) is aimed at post-mining waste dumps, which represent a highly intricate category of earth structures. These structures exhibit complex geotechnical attributes exhibiting substantial variations in their physical, mechanical, and strength properties, occasionally leading to critical failures. The MiDSafe project focuses on enhancing safety and promoting sustainability in managing coal and lignite mine waste dumps. It involves a multifaceted investigation of geotechnical and environmental hazards associated with mine dumps, analysing them and proposing innovative mitigation measures. A core mission of MiDSafe includes establishing a comprehensive European Coal & Lignite Mine Waste Dumps Database, i.e. an extensive geotechnical database with added value, encompassing dumps from lignite and hard coal mines. This database will support risk assessment and the development of a practical monitoring system. Additionally, MiDSafe seeks to pioneer innovative materials to mitigate specific risks, evaluate options for repurposing waste dumps and design an advanced monitoring system for continuous data collection. This system will utilize and assist innovative methodologies such as fuzzy inference systems and 3D numerical modeling for assessing slope stability. As part of its scope, MiDSafe will develop a rigorous risk assessment methodology to identify potential risks impacting mine dumps. A comprehensive dump management strategy will also be formulated, along with the exploration of geotechnical aspects related to common revitalization methods. Notably, the MiDSafe project aims to minimize risks in post-mining waste dump management by introducing innovative materials like geopolymers and zeolites, advancing safety, and enhancing sustainability.

To ensure the delivery of high-quality results, 11 partners from 5 European countries will collaborate and contribute their expertise:

1. POLTEGOR-INSTYTUT" INSTYTUT GÓRNICTWA ODKRYWKOWEGO (Poland) – Coordinator
2. NATIONAL TECHNICAL UNIVERSITY OF ATHENS (Greece)
3. CENTRAL MINING INSTITUTE - NATIONAL RESEARCH INSTITUTE (Poland)
4. LIGNITE MINES ACHLADAS S.A (Greece)
5. WROCŁAW UNIVERSITY OF SCIENCE AND TECHNOLOGY (Poland)
6. TECHNICAL UNIVERSITY OF CRETE (Greece)
7. SOCIETATEA COMPLEXUL ENERGETIC OLTENIA SA (Romania)
8. SYSTRA SUBTERRA INGENIERIA S.L.U. (Spain)
9. UNIVERSITATEA 1 DECEMBRIE 1918 (Romania)
10. UNIVERSITATEA DIN PETROSANI (Romania)
11. VUHU A.S. (Czech Republic)

The research and development actions will be complemented by communication and dissemination activities aimed at building awareness, enhancing knowledge, and shaping attitudes among target audiences. These efforts are expected to foster acceptance of the project's results and facilitate their subsequent implementation and adoption.

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INTRODUCTION

The MiDSafe project addresses the major future challenges for the European coal and steel industry. The proposal is consistent with the political, scientific, and technological objectives of the Union.

The MiDSafe project addresses directly one research objective of the RFCS Research Programme for the Coal sector: "Improving health and safety" by focusing on safety issues related to post-mining waste dumps. The remaining two objectives, i.e., "Supporting the just transition of the coal sector and regions" and "Minimising the environmental impacts of coal mines in transition", are addressed indirectly since post-mining waste dumps are associated with every coal and lignite production region. The environmental impacts minimisation is addressed because certain investigated risks associated with dumps (like dump instability, for instance) may have substantial environmental impacts.

The MiDSafe project objective of supporting coal regions directly in transition from several European countries, thus contributing to the objective of the European Green Deal to focus on the regions and sectors that are most affected by the transition because they depend on fossil fuels or carbon-intensive processes. The project addresses the repurposing of end-of-life coal-related assets and infrastructure at coal (and lignite) mines by applying emerging and innovative technologies, especially in areas such as monitoring, risk assessment and development of innovative materials.

The MiDSafe project complies with the recommendations of the European Commission on complementarity, synergies and sequencing among research programmes and information exchange between projects financed under different instruments.

The MiDSafe project focuses on the long-term safety of coal and lignite waste dumps, proposing an innovative and improved methodologies using a dedicated advanced monitoring, 3-dimensional modelling of a landslide investigation process, supported by a continuous updated geotechnical database of existing dumps from lignite and hard coal mines. The overall of the project is to assess the associated risks and, on this basis, to create a feasible and practical monitoring system and to develop innovative materials to minimize certain risks.

PROJECT GOALS

Mining activities create waste, which in most of the cases is stored on dumps; the dumps, at the end of the mining activity, after preparation for conservation, must be equipped with effective means of monitoring those conditions and their evolution over time. In the context of the current project, gathering data, developing advanced stability models and improved monitoring techniques will help to better understand waste dumps behaviour and will ensure enhanced safety. At the same, time the impact on the environment will be minimized supporting a successful post-mining transition. In the initial phase of the project partners will use existing inner and outer waste dumps to gather information about the most influencing and vital factors. The objectives and added values to be obtained by this are the following.

- Organising and expanding knowledge on existing coal and lignite mine waste dumps

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Excavated materials, when dumped, obtain a different structure than their initial one, resulting in extreme consolidation displacements, especially in the initial stages of a dump. Furthermore, moisture (water content) crucially affects dumps regarding consolidation and stability. Thus, the most typical technical problem concerns the appropriate preparation of an area of subsoil foreseen for a future dump. Construction of soil structures causes significant loads in the subsoil and leads to an increase of load on water trapped in ground pores.

- Organising and expanding the knowledge regarding the past failures, focusing on failure mechanisms, on consequences in the mining areas and on the environment

There are many cases that the behaviour of a dump was different than designed. In most of such cases, a critical failure of a dump occurred, e.g. in Turów coal mine in Poland; Nagpur, Basundhara and other mines in India Arcturus mine in Zimbabwe; South Field mine in Greece and Merkur, Slatinice and Jiří mines in the Czech Republic. Based on the identified failure cases, it can be stated that there are cases of stability loss of the dumps with greater or lesser impact in many opencast mines around Europe and the rest of the world.

- Analysing geomechanical properties of dumps, specifically spatial variability, water effects and long-term stability

Dumps were often not designed with future valorisation in mind; thus, they consist of mixed soils, and evaluating their long-term stability is demanding. Researchers have presented few works towards evaluating the mechanisms related to instability associated with dry dumps. Partners of the present project have conducted extensive analysis on the behaviour of such dumps while particular case studies have been investigated. In every characterisation of spoils, their heterogeneity is a critical aspect. Spatial variability of spoil properties is critical for evaluating spoil dumps, their stability and potential exploitation; nevertheless, no work has yet been done on the spatial characterisation of spoil materials. The effect of the significant spatial variability of spoil properties is an issue that will be dealt with in-depth in this project, especially since the literature on this subject is limited. Moreover, partners will build on previous experience on dry dumps and focus on the effect of water in the current context of situation of climate phenomena. Due to global warming and climate change, heavier and more prolonged rainfalls are becoming more frequent, dramatically affecting the long-term stability of dumps. In this context, they will create premises for improved analysis within the framework of unsaturated soil mechanics.

- Creating a geotechnical database of dumps in Europe (European Coal & Lignite Mine Waste Dumps Database)

The MiDSafe Project aims to create a geotechnical database of existing dumps from lignite and hard coal mines to assess the associated risks and, on this basis, to create a feasible and practical online monitoring system and to develop innovative materials to minimize geotechnical and environmental risks.

It is planned to develop and implement a monitoring technology with innovative measurement solutions dedicated to existing dumps and future ones. The objectives and added values during this phase will include:

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- Proposing and presenting a new monitoring system for continuous measurements

Many different approaches are implemented for landslide monitoring, but no single instrument or technique can provide complete information about this process. Therefore, various combinations of surface and deep-seated monitoring are commonly used to define and assess landslide risk. The most advanced techniques and instruments are generally employed in order to understand and predict movements in active landslides located at unstable natural slopes. The nature of these movements is different for natural slopes and dumps. For these reasons, the results of the application of advanced methods of investigating landslides in natural soils indicate/require the adoption of similar or adaptive solutions in the case of landfills. A real-time monitoring system can help survey and identify signs before failure or accumulation of factors that could cause damage to the soil structure. It can also provide information for potential repairs, maintenances, and necessary inspection of dumps. Therefore, the Technology Readiness Level for the scope at the start of this Project is assumed to be TRL 3 or, since technology is implemented in relevant environment (operating mines and embankments), but during the course of this project will be extended among others to post-operation mines reaching TRL 6.

- Developing UAV data processing algorithms, as an innovative way of identifying changes in vegetation vitality

A change in vegetation vitality can be an indicator for in-situ geomechanical processes. UAV campaign will generate high resolution data via various sensors. During the project criteria catalogue will be developed to access vegetation changes, which correlate to surface degradation processes and geomechanical failures.

- establishing an operational relation between surface degradation processes and changes in the point cloud definition

The MiDSafe Project will bring added value to the stability calculation and analysis of dumps formed from overburden soil material. In terms of innovative content, the MiDSafe project aims to provide stability calculation using a hybrid method (measurement-based), as a handle and practical tool concerning spoil dumps. The added value will include:

- Proposing a new methodology for slope stability assessment in real time

In the MiDSafe Project, an innovative method based on Fuzzy Inference System (FIS) for assessing slope stability of coal mine dumps and calculate the risk of failure in real time will be developed. FIS will use mine dump terrain data from UAV and measurements (acceleration, moisture, etc.) from sensors installed in the dump and by employing a set of inference rules will predict the risk of failure in real time. This is expected to be a major innovative contribution with a significant added value.

- Creating an innovative concept with a 3D model that continuously assesses slope stability

Within MiDSafe Project, a 3D model that continuously assesses slope stability will be created. A 3D model (Digital Elevation Model – DEM) can be represented as a raster (a grid of squares, also known as a height map when representing an elevation) or as a vector-based triangular irregular network (TIN). The TIN DEM

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dataset is also referred to as a primary (measured) DEM, whereas the Raster DEM is referred to as a secondary (computed) DEM. The DEM is supplied with data through well-known and performant techniques such as photogrammetry, LIDAR, IfSAR or InSAR, land surveying. While proposed DEMs are built using data collected by remote sensing techniques, and/ or completed based on land surveying methods.

- Introducing computational algorithms into the generated 3D model of a dump, validating the 3D model

Quality assessment of DEM can be performed by comparing DEMs from different sources. Several factors play an important role in the quality of DEM-derived products: terrain roughness; sampling density (elevation data collection method); grid resolution or pixel size; interpolation algorithm; vertical resolution; terrain analysis algorithm.

Regarding the innovative content of the MiDSafe Project, a decision-supporting tool will be prepared and presented as guidelines for European coal and lignite mines for identifying and assessing risks that will potentially occur during or after dumping. The added value planned is a rigorous study of the stability of dry dumps, analysis of geotechnical issues on common revitalisation methods and elaboration of an assessment methodology of risks that may affect mine dumps.

Additionally, recipes for innovative geomaterials (zeolites for waste treatment and geopolymers for soils stabilization) will be introduced based mainly on mineral waste (from coal mines and power plants) deposited in dumps. The developed recipes will be easily modified to obtain products with specified functionality. The resulting products will meet the real, current needs of the environment and will have specific mechanical and physicochemical parameters. The innovative approach of the project is, therefore, the development of materials with different functionalities ensuring both effective stabilisation of dumps and effective minimisation of the pollution spreading, for the production of which mainly waste materials are used. The proposed solutions align with the principles of the circular economy in the context of the coal mining and energy sector. Moreover, these materials will significantly extend the life and safety of mining waste dumps, allowing the possibility of recycling ashes deposited in landfills and saving materials used in dump construction.

The dumps under construction and the future dumps are expected to be the main receptors of these technologies. Additional added value aligns with various of the specific objectives:

- development of technical solutions for the selection and optimisation of selected procedures/methods implemented on a laboratory scale
- assessment of the technical and economic feasibility of the proposed procedures/methods for the production of geopolymers and zeolites
- creation of guidelines for the application of innovative materials for existing dumps to minimise certain risks
- establishment of a database of innovative geo-materials used to mitigate geotechnical and environmental risks in mine dumps.

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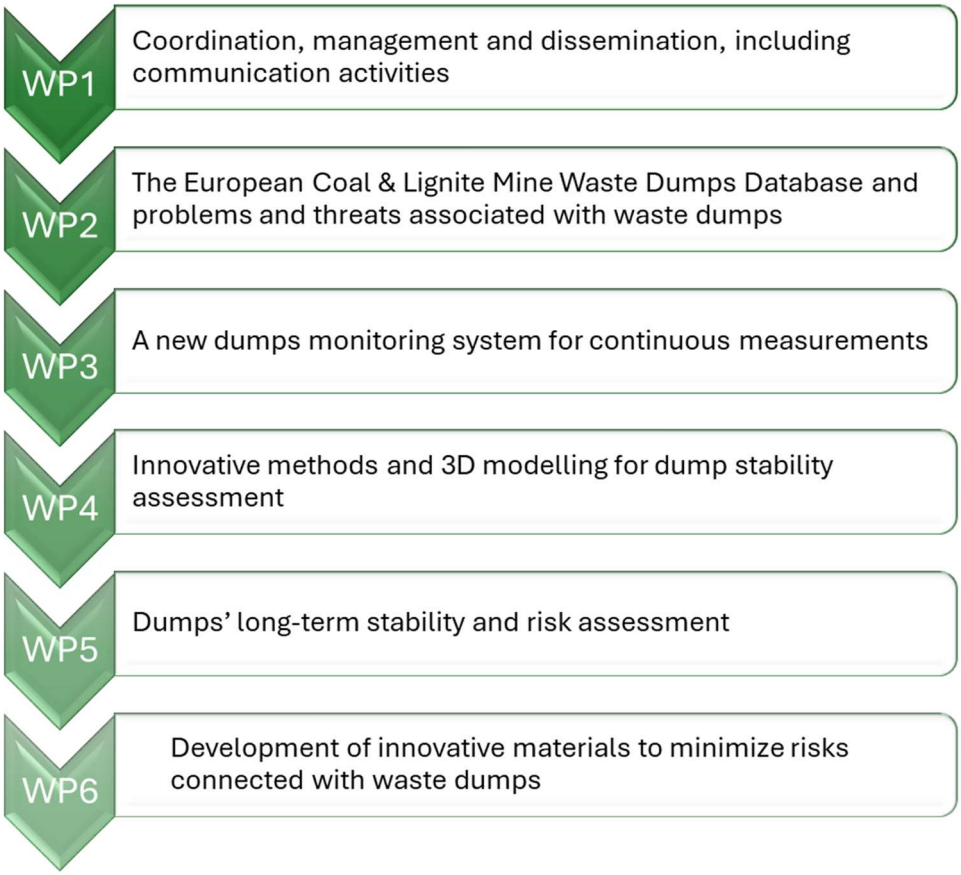
PROJECT STRUCTURE

The MiDSafe project consists of six work packages each targeting specific aspects of post-mining waste dumps. By ensuring that each component aligns with the broader objectives, the structured framework serves as a foundation for cohesive planning, efficient execution, and thorough assessment. This methodology minimizes ambiguity and enables all stakeholders to remain focused on the project's goals, ensuring accountability, consistency, and measurable outcomes at every stage.



Work Package 1: Coordination, management and dissemination.

Work Package 1 (WP1) serves as the cornerstone of the MiDSafe project, dedicated to coordinating and managing all activities to ensure seamless execution. This work package is tasked with monitoring task progress to ensure alignment with predefined timelines and objectives. A key function of WP1 is fostering effective communication among project partners by facilitating regular updates, reporting on individual contributions, and maintaining an open and transparent flow of information.

Beyond communication, WP1 oversees the technical and administrative elements of the project. This includes organizing meetings, managing budget distribution, and ensuring optimal resource utilization across all work packages. Additionally, WP1 is instrumental in integrating efforts across different work packages, fostering collaboration, and maintaining cohesion throughout the project.

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A critical aspect of WP1 is the creation of a detailed Communication and Dissemination Plan. This plan will define the objectives and scope of the project's outreach activities, identifying the key audiences and stakeholders, establishing core messages, and specifying the tools and timeline for message delivery. Its implementation will be closely tracked to ensure it achieves the desired impact and reach.

To enhance the dissemination of project outcomes, WP1 includes the development and regular updating of a dedicated project website, complemented by active engagement on social media platforms such as Facebook, LinkedIn, and Twitter/X. Additionally, all project partners will actively contribute to publishing research findings in both national and international journals.

Work Package 2: The European Coal & Lignite Mine Waste Dumps Database and problems and threats associated with waste dumps

The objectives of this work package involve several key tasks. First, it aims to gather and analyse previous designs and data concerning existing coal mine waste dumps, to understand past design methodologies and operational practices. A second objective is to establish a comprehensive database that documents mine waste dumps across Europe, including information on their location, size, history, and current condition.

The work package also seeks to collect and analyse data on past failures of coal mine waste dumps, focusing on the failure mechanisms, the consequences these failures had on the mining areas, and their environmental impacts. Another objective is to critically investigate existing regulations and guidelines related to the design and stability of waste dumps, ensuring that current practices are aligned with the best standards and legal requirements.

Additionally, the package involves examining long-standing mine waste dumps and comparing their current conditions with the original designs, to identify any deviations or issues that have emerged over time. Finally, the work package will focus on identifying critical factors that cause problems for the mine waste dumps and their surrounding areas, in order to address stability and environmental concerns more effectively.

Together, these objectives aim to improve the understanding and management of coal mine waste dumps, ultimately contributing to better design, safety, and environmental protection practices.

Task 2.1. An analysis on coal and lignite mining dumps: archival data, original designs, past failures, guidelines, and regulations

The first stage of this task involves the collection of relevant geological, geotechnical, and hydrogeological data from the chosen dumps. These data will be analyzed in detail to understand the properties of the dumps and their potential for stability or failure. Archival designs that describe historical dumping processes will be reviewed and compared with real-time, in-situ measurements in later stages of the project. The purpose of this comparison is to validate historical assumptions and improve the accuracy of future monitoring efforts.

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A major focus of the task is the detailed characterization of the dumps. This includes assessing the dimensions of the dump, its construction date, the angles of its slopes, and the types of base-terrain soils. Additionally, the construction timelines of the individual dump benches will be reviewed, along with the types of soils that have been dumped. Key factors, such as the critical properties of the dumped soil in relation to the stability of the dump, will also be considered. This includes assessing compaction, moisture content, cohesion, and other physical properties of the soil. The hydraulic history of the dump will be analyzed, considering the water content and drainage patterns, as well as the methods used for dewatering the dump and the consolidation of the materials over time. These factors play an important role in determining the stability of the dump and assessing potential risks, such as erosion or liquefaction.

Global regulations and guidelines focusing on dump stability and environmental concerns will be collected and analyzed. This analysis, in conjunction with past failures, will provide valuable insights for the subsequent work packages. The lessons learned from these failures, along with established engineering practices and international standards, will guide the numerical, environmental, and risk analyses in future project phases.

An investigation into the characteristics of standard inner dumps in coal mines will be. Both geometrical and geotechnical aspects of these dumps will be studied, using existing data to understand their behavior. The findings from this study will form the baseline for further numerical modeling and back analysis, providing essential input for predictive models of dump behavior.

Task 2.2 Survey of chosen dumps

The aim of this task is to conduct a comprehensive analysis of dump stability by selecting appropriate test sites and evaluating various critical factors influencing their integrity. The project partners will focus on examining the key soil properties that impact dump stability for at least five selected test sites. This comparison will involve assessing the current condition of the dumps against the original designs, as determined through prior research and a database developed in Task 2.1.

A significant component of the task involves Unmanned Aerial Vehicles (UAVs) to capture high-resolution data. Through UAV flights, the relationship between soil-rock properties, structural joints, and multispectral sensor data will be explored. The UAV campaign aims to create accurate 3D models of the dumps, essential for assessing their stability in later stages of the project.

Additionally, how various parameters affect dump deformation will be investigated. The parameters to be considered include soil moisture content, propagation velocity of longitudinal and transversal seismic waves, as well as both surface and subsurface displacements. A deeper understanding of the factors influencing dump stability will be contributed to by the results of these investigations, which will enable a comparison of the actual state of the dumps with their original designs. The groundwork for further stability assessments and potential interventions in subsequent phases of the project will be laid by this analysis.

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Task 2.3. Development of the potential indicators of dump deformation

Within this task the development of potential indicators for dump deformation involving identifying key parameters that can signal instability or structural changes in waste dumps will be developed. These indicators are critical for monitoring the safety and environmental impact of such sites.

Task 2.4. Analysis of re-utilisation options

Project partners will analyze various re-utilization options for the inner and outer waste dumps of hard coal and lignite open-pit mines. Additionally, both the current and past planning and design processes, along with the level of public involvement in these processes will be examined. Soil properties and its influence in possibility of re-utilisation of dumps will also be taken into consideration.

Work Package 3: A new dumps monitoring system for continuous measurements

This WP is focused on monitoring aspects. It aims at presentation of cost-effective monitoring system for post mining dumps.

Task 3.1. Definition of capacities and capabilities of monitoring equipment

This task involves the development of a new measuring equipment system that will consider several critical factors, including measuring accuracy and reading error, the planned installation method, equipment security, data collection and transmission, and the measuring interval. The project partners will present the capabilities of available measurement equipment on the market.

Task 3.2. Presentation and use of the new monitoring system

The unmanned aerial vehicle (UAV) measurements will play a critical role in the ongoing monitoring and data collection efforts for the project. These UAV campaigns are expected to be conducted concurrently with soil material dumping activities, as outlined in Work Package 2. The UAV measurements will help capture detailed aerial data, providing valuable insights into the processes and changes occurring within the environment being studied.

The project partners will facilitate UAV-based photogrammetry across three different locations: Romanian, Polish, and Czech mines. The data collected through these UAV campaigns will be systematically gathered on a centralized server. Subsequent project partners will be responsible for updating and refining the data in a 3D model, contributing to the dynamic nature of the data visualization and analysis process.

Additionally these flights will be monitor and assess changes in the vitality of vegetation, particularly the health of plant species in these areas. The data from these UAV-based surveys will be used to develop a comprehensive criteria catalog aimed at evaluating the risks associated with vegetation vitality changes. This catalog will also serve as a monitoring tool to track shifts in vegetation health over time, contributing to more informed environmental management practices and risk assessment strategies.

Work Package 4: Innovative methods and 3D modelling for dump stability assessment

The objectives of this work package are to develop a new methodology for slope stability assessment, which will include rules and key parameters for lifelong emergency monitoring of dump sites. It also aims to explore the possibilities of using 3D modeling techniques for dump sites, emphasizing how these

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technologies can improve stability assessment and monitoring. The work package includes the creation of a continuous 3D model that will assess slope stability in real time, integrating data for ongoing monitoring. Additionally, computational algorithms will be developed and incorporated into the 3D model to enhance its analytical capabilities, allowing for precise and efficient stability evaluations. Finally, the work package aims to validate the 3D model by testing it with an optimized number of measurement points to ensure its reliability and effectiveness in practical applications.

Task 4.1. Development of a new methodology/rules for quick slope stability assessment

Data and results obtained in WP2 will serve as the foundation for developing rules to assess slope stability. The new methodologies for stability assessment are expected to be significantly more effective than traditional methods, which primarily focus on soil identification.

A Fuzzy Inference System (FIS) will be developed to assess slope stability and calculate the risk of failure in real-time. The FIS is well-suited for integration into real-time monitoring systems due to its ability to process uncertain or imprecise data. It will utilize terrain data from UAVs and installed sensors to estimate slope stability. The system will apply a set of inference rules, which will be derived from both factual knowledge and experiential insights gained from prior work packages and expert contributions. These rules will enable the FIS to make accurate and dynamic stability assessments based on real-time data, offering a more advanced and adaptive approach to risk evaluation compared to classical methods.

Task 4.2. Research on dump and base-terrain 3D models and 3D model preparation

The task involves developing a 3D model for assessing the stability of waste dumps. The model will evaluate the structural integrity using geotechnical data and incorporate real-time monitoring of parameters like soil moisture and pressure. Algorithms will be used to assess the stability of earthen structures, considering factors such as shear strength and slope stability. The model will also be connected to a centralized database for real-time data access and management, enabling stakeholders to make informed decisions. By combining terrain data with in-situ parameters, the model will offer accurate and dynamic stability predictions, improving safety and risk management.

Task 4.3. Development of computational algorithms into the generated 3D model of dump

A computer application for the 3D model and an in-situ parameter visualization database will be developed as part of this task. The application is designed to enable direct assessments based on the established criteria and assumptions, ensuring an accurate representation of the waste dump's stability. It will incorporate algorithms that make use of the measured parameters gathered throughout the project, allowing for dynamic updates and refined predictions. The results from surface modelling and monitoring will also be integrated into a geo-neuronal network concept, which will enhance the analysis and prediction capabilities of the system, providing a comprehensive and data-driven approach to waste dump stability evaluation.

Task 4.4. Validation of the created 3D model

This task is crucial for ensuring the quality and accuracy of the new 3D model for slope stability. The calibration process will rely on the proper verification of the model's performance through the integration

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of incoming data, followed by checking and validating the results in real-world conditions. The objective is to fine-tune the model, ensuring that it accurately reflects the actual behaviour of the slope and performs reliably under varying circumstances. Calibration will involve implementing adjustments based on observed data, enabling the model to make more precise predictions and assessments of slope stability.

Work Package 5: Dumps' long-term stability and risk assessment

This work package aims to develop appropriate numerical models for assessing the stability and potential revitalization of waste dumps, with a particular focus on the influence of water and the effects of inhomogeneity in the spoil material. It will identify critical parameters for dump stability, including the impact of water and the spatial variability of critical properties through numerical analysis. Reference case scenarios will be characterized to evaluate the long-term stability of dumps. Additionally, a reliability methodology will be developed to assess the long-term stability of dumps, alongside a comprehensive risk assessment methodology for dump management. The work will also include the creation of guidelines for risk assessment during the construction of dumps and their subsequent management, ensuring the safety and sustainability of dump operations over time.

Task 5.1. Numerical analysis for the stability and revitalisation of dumps

During this task, slope stability issues that may lead to collapse will be identified, analyzed, and thoroughly characterized. These issues will be simulated using geotechnical software (e.g., PLAXIS, RS, or similar), focusing on the spatial nature of spoil properties, which has often been overlooked in spoil analysis and design. Stability analyses will be also conducted using software based on Limit Equilibrium theory for the relevant dumps.

Water flow modeling will be applied to integrate the effects of water flow and water table variations after rainfall into the geotechnical models. The focus will be on the impact of increased pore pressure in the foundation, which can trigger circular failures and lead to environmental disasters.

Based on the analysis of critical parameters from previous tasks and the numerical analysis performed here, reference scenarios related to dump stability will be organized and developed. One of these scenarios will be further evaluated with the incorporation of innovative materials, as discussed and developed in the next work package.

Task 5.2. Development of a reliability and a risk assessment methodology for assessing the long-term stability of dumps

Reliability concepts will be implemented to account for the uncertainty of the main variables in safety and performance issues. Probabilistic approaches, such as the Point Estimate Method, will be combined with deterministic numerical modeling to provide a more comprehensive analysis. These methods will highlight additional safety aspects, such as the probability of slope failure or the likelihood of inadequate performance. The outcomes from these reliability analyses will contribute to a more robust risk assessment regarding the stability of dumps.

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Data from the case studies analyzed in WP2 and results from the monitoring system in WP3 will be used to verify the reliability methodology by comparing the outcomes and consequences of the analysis with actual data. This task will interact and provide feedback with WP2, WP3, and WP4.

Based on these analyses, a multi-criteria risk assessment and prioritization tool will be developed within the framework of WP2 and WP3 to support more informed decision-making.

Task 5.3. Elaboration of guidelines for risks assessment during and after dumping

In this task, a decision-supporting tool will be developed to identify and assess risks that may occur during or after dumping, and these will be presented as guidelines for European coal mines. The goal is for these guidelines and algorithms to enable the evaluation of most mine dumps. The tool will also assess the probability of incidents that, while not resulting in immediate failure, could still indicate significant risks, such as increased deformations, which are important for overall risk assessment.

The structure of the guidelines will be suggested based on existing methodologies, ensuring they are robust and applicable. These guidelines may also inform the work of the expert group on risk management in the extractive sector, established by DG Environment. Furthermore, the guidelines will incorporate an index for revitalization to support sustainable management practices.

The guidelines will be verified using data obtained from the monitoring system developed in WP3 to ensure their accuracy and relevance in real-world applications.

Work Package 6: Development of innovative materials to minimise risks connected with waste dumps

This work package focuses on developing methods for recycling ashes deposited in landfills by transforming them into geomaterials suitable for use in mining dumps. The WP will include the development of technical solutions for selecting and optimizing procedures and methods on a laboratory scale to ensure the effective reuse of these ashes. Additionally, the technical and economic feasibility of the proposed procedures for producing geopolymers and zeolites will be assessed, considering their potential for large-scale implementation.

Innovative materials will be developed to minimize risks during or after the operation of mining waste dumps, contributing to safer and more sustainable management practices. Guidelines will also be created to facilitate the application of these innovative materials to existing dumps, aimed at reducing specific risks associated with their operation and long-term stability.

Task 6.1. Selection of precursors for the production of zeolites and geopolymers from industrial waste and natural raw materials

This task focuses on identifying the key factors that influence the choice of components for innovative materials, particularly their availability, unit cost, specific absorption and chemisorption properties, and overall efficiency. The primary analysis will concentrate on energy waste, such as fly ash, which presents both a quantitative and qualitative challenge. The task will also explore the use of supplementary waste materials, including bottom ashes from fluidized bed boilers, carbonization products from low-temperature

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pyrolysis of car tires, sulphur pulp from natural gas purification, granulated slag from metallurgical plants, and construction and demolition waste, which is the most voluminous waste stream in Europe.

The optimal materials and their mixtures for producing zeolites and geopolymers will be assessed and selected through structural tests (e.g., BET and SEM) and geochemical tests (e.g., XRD, XRF, and EDS). These tests will help determine the most suitable combinations for the production of these innovative materials. Additionally, a sample bank of materials and their properties will be created to support future research and development.

Task 6.2. Design and development of geopolymers for use as soil stabilisers

The developed geopolymeric materials will be evaluated to minimize the environmental impact of mine dumps by enhancing slope stability through geopolymer-based stabilized soils. Initially, recipes for geopolymer binders will be created using fly ash from lignite combustion and other waste materials, based on the properties identified in Task 6.1. These recipes will be selected through verification of chemical, mineralogical, and mechanical properties. Once selected, the geopolymer binders will be used to produce "geopolymer-stabilized soil" specimens in the laboratory, focusing on effective dump stabilization.

The synthesis conditions, including raw material proportions, activating solutions, curing temperatures, and aging periods, will be studied using fly ashes from Polish and Greek coal mines, as well as other industrial waste materials. Mechanical properties of the stabilized soils, such as shearing resistance and shear modulus, will be assessed, with a focus on their geotechnical characteristics and structural integrity under varying environmental conditions.

Task 6.3. Design and development of zeolites for use as heavy metals and pollutants absorbents

The developed zeolites will focus on minimizing the spread of pollution, such as reducing gas emissions from thermal processes and limiting metal leaching from waste dumps.

The optimal synthesis recipe will be determined to ensure effective pollution reduction, which will be verified by assessing the sorption potential of the synthesized materials. The application of these materials will be tailored to the specific requirements of the site, including geotechnical conditions and pollutant emission levels. In the final phase, the zeolites will be applied to a real waste dump, selected based on WP2.

Project partners will collect soil samples from the selected dump to evaluate the impact of the zeolites on the chemical properties, conducting leaching tests and phytotoxicity tests on selected plants.

Task 6.4. Technical, economic and environmental assessment of the application of the developed innovative materials

In this task, the economic efficiency of geosynthetic materials production will be evaluated using a Cost Benefit Analysis (CBA) to assess the economic viability and benefits of the production processes.

Additionally, a Life Cycle Assessment (LCA) will be performed in accordance with ISO 14040, covering four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation to evaluate the environmental impact of the geosynthetic materials throughout their life cycle.

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POTENTIAL IMPACT OF THE PROJECT

The MiDSafe Project has the potential to make a significant impact across various domains, particularly in improving the safety, sustainability, and environmental management of coal and lignite mine waste dumps in Europe. One of the primary objectives of the project is to prevent the geotechnical failure of mine waste dumps, which can have catastrophic consequences for surrounding environments and communities. Through the creation of a comprehensive geotechnical database, advanced monitoring systems, and innovative risk assessment techniques, the project aims to significantly reduce the risk of dump instability. This will help prevent landslides and subsidence, enhancing the safety of both mine sites and nearby regions. Furthermore, the real-time monitoring systems enabled by technologies like UAVs, fuzzy inference systems (FIS), and 3D modeling will provide early warnings of potential failures, allowing for timely interventions, maintenance, or remediation, thus improving overall safety.

In terms of environmental sustainability, the MiDSafe Project aims to minimize the environmental damage caused by mining waste dumps. These dumps often have significant environmental impacts, particularly related to water contamination, erosion, and air quality. By improving dump stability and introducing innovative materials such as zeolites and geopolymers, the project seeks to reduce the environmental footprint of these dumps. Stabilizing the dumps and reducing their tendency to release harmful substances will help protect surrounding ecosystems and minimize pollution. Additionally, the project's approach to developing geo-materials using waste products from coal mines and power plants (like ashes) aligns with circular economy principles, ensuring that waste products are repurposed instead of disposed of, thereby promoting more sustainable waste management practices.

The MiDSafe Project also supports the transition of coal regions away from fossil fuels, which is a major objective of the European Green Deal. As coal regions in Europe move toward more sustainable energy sources, MiDSafe provides an important solution for managing the legacy of coal mining. By repurposing end-of-life coal-related assets and infrastructure, the project supports the just transition of coal-dependent regions, ensuring that mining waste is handled safely and sustainably. This approach can help these regions transition to greener alternatives, while also addressing the social and economic challenges that often accompany such transitions. Additionally, the project's innovations could create new jobs in research, development, and monitoring, contributing to the economic revitalization of coal regions undergoing transformation.

Another significant impact of the MiDSafe Project lies in technological and methodological innovation. The development of new materials such as geopolymers and zeolites to stabilize mining waste and reduce environmental contamination could have wide-reaching applications. These materials can be used not only in coal and lignite mines but in other industries facing similar waste management challenges. The ability to adapt these materials for specific conditions makes them versatile and valuable in various environmental engineering projects. Moreover, MiDSafe's advanced monitoring technologies, including UAVs for vegetation health assessments and 3D modelling for real-time slope stability evaluation, will push the boundaries of traditional geotechnical monitoring, providing more accurate, comprehensive, and efficient methods for assessing and managing waste dumps.

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The project also aims to provide a data-driven approach to risk assessment and decision-making. The creation of a large-scale, integrated European Coal & Lignite Mine Waste Dumps Database will allow for a more systematic approach to managing mining waste. This database will be a valuable tool for assessing risks, developing monitoring systems, and designing better management strategies for coal mine waste dumps. By integrating real-time data, MiDSafe will facilitate more informed decision-making and more efficient resource allocation for managing mine sites. Additionally, the development of a fuzzy inference system (FIS) for real-time risk assessment based on various data inputs, such as moisture content, slope angle, and vegetation health, represents a breakthrough in predictive geotechnical modeling. This system will enable more accurate forecasting of dump failures and allow for more proactive interventions to reduce risks.

Finally, the MiDSafe Project will have a significant socioeconomic and community impact. Many communities near coal mines are vulnerable to the risks associated with unstable mining waste dumps, including displacement due to landslides and environmental degradation. By enhancing the stability of these dumps and minimizing the risk of catastrophic failures, MiDSafe will directly contribute to the protection and security of local populations. This will improve the quality of life and ensure the health and safety of those living in mining areas. Additionally, the project's communication and dissemination activities will foster a better understanding of waste management technologies and practices among local governments, mining operators, and affected communities. By promoting awareness, the project aims to ensure that its findings and innovations are effectively implemented and adopted in real-world scenarios.

In conclusion, the MiDSafe Project has the potential to revolutionize the management of coal and lignite mine waste dumps, enhancing geotechnical safety, reducing environmental impacts, and supporting the sustainable transition of coal regions in Europe. Through cutting-edge monitoring technologies, innovative materials, and data-driven risk assessments, the project will improve safety and sustainability in mining waste management. By addressing the critical challenges posed by post-mining waste dumps, MiDSafe will play a pivotal role in shaping the future of the coal sector, making it safer, more sustainable, and more aligned with the European Green Deal.

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ANNEX: STATE OF THE ART

Current and Completed Relevant Projects

RCFS 847299- RAFF (2019-2022)

Investigating safety and environmental concerns associated with the creation and use of pit lakes, RAFF has developed risk assessment methodologies for these unique landscapes. The research undertaken within the RAFF project illustrated the important role played by the presence of water in the creation of pit lakes, in the sense of the significant decrease of the stability reserve and the inherent increase in the risk of landslides. The MiDSafe project promises to continue this direction of research by identifying the possibilities of real-time monitoring of moisture, but more importantly of monitoring the hydrostatic pressure exerted by the presence of water (this having a significant influence, in the sense of reducing the stability reserve, by reducing the normal pressure exerted by the stored material). Overall, MiDSafe can leverage RAFF's findings to enhance its approaches to managing safety in post-mining rehabilitation scenarios.

RCFS 847250- TEXMIN (2019-2022)

The TEXMIN project emphasized the effects of extreme weather events on mining and post-mining. It identified and evaluated the environmental impacts on active and abandoned mines caused in the short term, and with the evolution of climate change in the long term. Climate scenarios were created from regional climate models and a review of baseline parameters were conducted. Impacts related to increased precipitation, temperature and atmospheric pressure shocks was identified and assessed for selected mines over various European areas. This allowed a focus on issues such as mine water, gas emissions and structural stability. Various risks were identified to be managed due to extreme events and climate change, an adapted monitoring strategy was suggested and a risk tool was developed to for an appropriate management of risks and the implementation of preventive measures. MiDSafe can build based on existing knowledge on climate effects and refine results and conclusions focusing only th epost-mining regions. Additionally, insights on climate effects on mine dumps from TEXMIN can be used as a baseline input for further and more detailed analysis of the MiDSafe project.

RFCS 847227 – SUMAD (2019-2022)

The SUMAD project aimed to optimize the use and long-term management of coal and lignite spoil dumps. These spoil dumps, consisting of heterogeneous materials from coal extraction, present significant geotechnical and environmental challenges. SUMAD addressed some of these challenges by investigating sustainable revitalization strategies, including renewable energy infrastructure deployment, advanced physical and numerical modeling, and risk assessment. A key outcome will be the development of the SUMAD Risk Management Tool (RMT) to guide the reuse of spoil dumps, enhancing efficiency and promoting new technologies for post-mining site rehabilitation. While SUMAD focused on revitalizing spoil dumps with sustainable practices, the MiDSafe project complements and enhances its results by improving the stability and safety of mine dumps through advanced methods, monitoring, and the creation of a comprehensive geotechnical database. Together, these projects address critical aspects of post-mining waste management, from structural stability to innovative reuse and revitalization.

RCFS 899518- MINRESCUE (2020-2023)

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MINRESCUE aimed to address one of the major challenges of coal mining industry in Europe: developing innovative concepts for managing, recycling, and upcycling waste geomaterials generated by coal mining activities across Europe. The problem of Coal Mining Waste Geomaterials (CMWGs) is particularly important as the volume of disposed waste is enormous. The core objective of the project is to develop and validate a strategy to upgrade CMWGs as constituents in sustainable construction materials and products. Hence, with significant money saving and environmental footprint reduction, MINRESCUE will significantly contribute to the establishment of a circular economy in coal mining areas.

RFCS 101057326 – **POMHAZ (2022-2025)**

The PoMHaZ project focuses on advancing methodological knowledge for multi-hazard analyses in mining basins, addressing physical interactions between hazards and improving risk management practices. A Decision Support System (DSS) and GIS tools will be developed to integrate these analyses and facilitate land-use planning and hazard mitigation. The project includes validating tools on abandoned coal mines in Europe and answering key questions about hazard interactions, intensity, and probability. Expected outcomes include a comprehensive DSS for stakeholders, combining databases, numerical models, and AI-driven insights to support strategic, tactical, and operational hazard management. The PoMHaZ project complements the MiDSafe project by focusing on multi-hazard risk assessment and management, particularly through the development of advanced tools like DSS and GIS. While MiDSafe emphasizes enhancing the stability and safety of mine dumps using geotechnical databases and innovative materials, PoMHaZ adds value with its systematic approach to analyzing hazard interactions for decision-making. Together, the projects contribute to a holistic understanding and management of risks associated with mining and post-mining activities.

RFCS - SLOPES (2015-2018)

The SLOPES project united European experts to advance technologies and methodologies for analyzing and monitoring slopes in open-pit lignite mines. The project focused on three main areas: integrating modern monitoring techniques (of the time) into real-time automated risk assessments; conducting stability and probabilistic analyses of open-pit slopes using advanced numerical modeling; and studying the long-term stability and ground movements of lignite mine spoil materials. The outcomes included developing reliability-based methods for risk evaluation, enhancing design optimization, and providing decision-support tools for open-pit mining operations. The MiDSafe project advances further some concepts built during the SLOPES project by addressing advanced issues on the stability and risk assessment of slopes and spoil heaps. While SLOPES emphasized monitoring of the time, modelling, and real-time risk evaluation of slope stability, MiDSafe expands these principles to the broader management of mine dumps. MiDSafe focuses on enhancing safety through geotechnical databases, innovative materials, and monitoring systems, creating an evolution line between the two projects in improving post-mining safety and sustainability.

RFCS- COALBYPRO

ERA-MIN2- DEASPHOR

WPN/4/67/CLEAR/2022 - CLEAR

National Centre for Research and Development Polish German Cooperation Call

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RFCS 101112386 — H2GEO

The H2GEO project focuses on a comprehensive technology for managing mining waste dumps. The main idea of the project is to use separated mineral fractions and fly ash for the production of geopolymer composites. It is planned to use CO2 as a carrier in the composite production process. Another important aspect of the project is determining the potential for hydrogen production through the gasification of energy fractions. High-quality raw materials for the production of geopolymers and hydrogen will be ensured by the use of an innovative mobile separator for processing mining waste. The project will enable the creation of environmentally friendly and economically viable installations utilizing materials from selected post-mining waste landfills. Achieving the project's main goal will be possible by accomplishing intermediate objectives, including the development of technologies dedicated to the production of geopolymers and hydrogen. The technology developed within the H2GEO project focuses on waste dumps from hard coal mining, while the MiDSafe project focuses on dumps from lignite mining. Moreover, as part of the MiDSafe project, a database will be developed which, unlike the database in the H2GEI project, will include geotechnical information relevant to the project.

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