Evaluation of the long-term durability of engineered dry covers for mining wastes, and consideration of associated design constraints

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Abstract. To reduce pollution of water resources it is often necessary to cover uranium mining waste heaps and tailings. In this paper the failure mechanisms which can be significant for a mineral sealing layer are set out and discussed. On the basis of this, the requirements for the construction of a cover are defined. The necessity for post-closure care is discussed and, finally, the question is addressed of when it is sensible to include a mineral sealing layer in a cover system.

Introduction

An important issue at many mining sites is the reduction of detrimental effects caused by the discharge of contaminated seepage from mine wastes. A frequently used method for the mitigation of environmental impacts from mining wastes is the construction of engineered soil covers on waste dumps or tailings. The purpose of such rehabilitation measures is to reduce the environmental impacts to acceptable levels as well as to facilitate future use of the former mining sites, e.g. for recreational purposes and/or to create wildlife habitats.

Although construction of a suitable cover does not reduce the contamination potential of the mine waste, it can delay the contaminant release and thus reduce the contaminant loads in the seepage per unit of time, i.e. reduce the rate of contaminant release, so that lower contaminant loadings are discharged over a longer time span. Ideally, the cover should reduce the contaminant concentration in the seepage to levels which are so low that even without seepage treatment the contamination of the receiving water bodies does not exceed acceptable levels. However, even if some water treatment is still necessary, the long-term costs will be lower than for a collect-and-treat option due to the financial discounting of future expenditures and the potential for improvement in water treatment technologies (e.g. passive or microbiological treatment).

The design and the construction of a cover system has to integrate carefully all site-specific aspects of the ecosystem, land-use and climate, with the characteristics of the waste and the cover materials, in order to minimise the short and long-term rehabilitation costs for the mine (i.e. costs for cover construction, water treatment (if necessary), cover maintenance and monitoring), as well as the future environmental risks. This paper discusses essential design and construction requirements to ensure the long-term durability of dry cover systems for mining wastes, focussing on cover systems that include a compacted and water-saturated clay sealing layer, to reduce the fluxes of oxygen and water into the waste materials.

Cover design

Dry cover systems for acid-generating or potentially acid-generating sulphide–bearing mine wastes often require a particular constructive component to minimise the fluxes of oxygen and water into the waste. The objective is to reduce contaminant mobilisation resulting from sulphide oxidation processes and to minimise the amount of contaminated seepage. This can be achieved by covers containing compacted soil/clay layers at high water saturation or industrially modified mineral materials or by synthetic liners (e.g. polyethylene geomebranes). Capillary barriers can reduce the water flux into a waste dump, but will not present a restriction for oxygen ingress.

For cost reasons, only the first mentioned type of cover was generally considered for the remediation of the waste dumps at the uranium mining sites in the eastern part of Germany. An example of a synthetic liner combined with a bentonite-gravel layer is that used in the cover system for uranium tailings at Ellweiler (in Rhineland-Palatinate, in the western part of Germany).

Experience from landfill sites indicates that a drainage layer on top of a clay layer increases the risks of desiccation and cracking of the clay barrier. A drainage layer improves the geomechanical stability of the system and acts as a capillary barrier to reduce the moisture flow from the clay into the upper layers of the cover system in dry periods. The disadvantage of a drainage layer is that water is removed in wet periods and the conditions in a subsequent dry period become more extreme. There is an ongoing discussion concerning the benefits and risks of a drainage layer in a cover system.

In the following discussions of design and construction requirements for engineered covers on mining wastes, only soil covers are considered, focussing on cover systems which include a compacted, water-saturated soil/clay layer (oxygen barrier) overlain by a substrate layer as required for the sustainable development of vegetation.

Potential failure mechanisms

Mechanisms which may threaten the long-term integrity of a compacted clay/soil barrier in a dry cover system on mine wastes include:

- cracking due to differential settlement of the mine waste,
- erosion,
- human intrusion,
- cryoturbation, i.e. disturbance due to frost,
- bioturbation, i.e. disturbance by animals
- root penetration,
- desiccation and cracking,
- slope failure.

A suitable, sufficiently thick substrate layer is required in these cover systems in order to ensure the long-term integrity of the clay layer and to facilitate the development of a sustainable cover of vegetation. Disturbance of the substrate layer, which can subsequently result in failure of the clay barrier, may result from:

- erosion,
- intrusion by humans (e.g. mountain biking, motocross) or animals (rodents, wild boars, etc.),
- uprooting of trees,
- slope failure.

In the following, some of the processes which may impair the performance of a cover system are discussed in more detail.

Differential settlement

Cracking due to differential settlement of the mine waste can be avoided by

- compaction of the waste material - possibly during the construction of the waste heap, and/or
- choosing an appropriate combination of clay material and moisture content to ensure deformation occurs without cracking under the anticipated range of movements.

Erosion and human intrusion

For the remediation of former uranium mines a minimum primary period of 200 years is considered when selecting and designing the protective measures. (During the selection of the measures a secondary 1000 year period is considered qualitatively.) For such periods protection against erosion becomes of central importance.

As there is generally no building on the remediated areas suitable vegetation can provide erosion protection. For this, the greatest risk is in the early stages, when the vegetation has not yet developed a sufficient protective effect. In this phase erosion protection must be provided through an appropriately intensive after-care.

Longer term, and especially under extreme weather conditions, the surface water drainage system becomes an erosion weak point, as the energy of the water becomes concentrated within it.

In the densely populated parts of Germany damage to vegetation and the cover resulting from inappropriate human activities (e.g. motocross) is a significant factor.

Frost / Animals / Roots

In the regions of Thuringia and Saxony affected by uranium mining the maximum frost depth is about 1 m, although locally greater depths cannot be excluded. In order to protect the sealing layer from burrowing animals (mice, rabbits, foxes, badgers) a minimum 0.3 m frost-free zone must be available in the vegetation substrate layer. This reduces the incentive for the animals to burrow into the less accessible, compacted sealing layer. From this a minimum thickness of 1.3 m can be derived (locally however more) for the vegetation substrate.

The rooting depth of plants depends essentially on the soil and the water conditions. According to the literature the rooting depth of native trees in Germany is up to 3 m, and 4 m under conditions of water shortage. Some meadow plants root deeper than trees. Saturated and dense (>1.8 g/cm^3) soil conditions restrict the depth of roots. When there is sufficient water and nutrients plants do not root deeper than 1.5 m in such conditions.

Plants require a certain degree of mechanical support, in order to resist loadings from storms and to a lesser degree from snow and from growing inclined due to uneven light availability. In natural conditions the soil is often denser at depth and there may be a rock weathering zone. A cover system is, in contrast, looser and has potential slip surfaces at layer boundaries (in the case considered here, between the sealing layer and the vegetation substrate). Trees growing on such a cover system are in considerably more danger of being uprooted than trees in natural locations. According to assessments obtained from forestry experts, with a vegetation substrate depth of 1.5 m the risk of uprooting becomes acceptable.

Desiccation / Cracking

The most significant failure mechanism for a sealing layer is the development of cracks. This occurs when a critical suction level, exceeding the tensile strength, is reached in the sealing layer. With further drying or in subsequent dry periods cracks can grow until finally the complete depth of the sealing layer is penetrated.

Laboratory and field experiments made during the BMBF research programme on the further development of waste deposit sealing systems show that on re-wetting the cracks in the sealing layer close again, but that they remain as water pathways. This means that a long-term increase in the permeability to gases can also not be excluded.

For a typical clay material we calculated the critical suction value for different construction methods. The results ranged between 100 and 200 kPa for compaction with a machine of medium weight at a moisture content higher than the Proctor optimum, and from 500 to 800 kPa for compaction with a heavy machine at a low moisture content. At a low moisture content means here at the optimum for the specific compaction equipment, but because the compaction energy is higher than in the standard Proctor test the moisture content would be below the standard Proctor optimum. The results show that the critical suction value can be significantly increased by compacting thoroughly at the lowest practical moisture content. The attainable critical suction value is however still far below that which can be generated by plants (the permanent wilting point is pF=4.2, which corresponds to 1500 kPa).

The vegetation substrate layer must be such that the critical suction is not exceeded at the top of the clay seal. It must be thick enough for the plants to find sufficient water and nutrients without generating high suctions at the boundary to the sealing layer. Cracks resulting from such suctions become accessible to roots, and can then be widened as further water is extracted. From this is derived the requirement that the vegetation substrate layer should have the highest possible storage capacity for water which is available to plants. In the literature, a minimum of 20 cm of water is given.

The necessary thickness of the vegetation substrate can be calculated as a coarse approximation with computer programs such as HELP. Calculations which we made with Version 3.05 for a specific uranium mining waste heap in Thuringia showed that for drying to the permanent wilting point not to occur the following layer thicknesses had to be assumed:

- plateau and north facing slope 1.5 m;
- east and west facing slopes 2 m;
- south facing slope 3 m.
- Use of the program for this purpose was however found to be problematic, as:
- it required daily weather data;
- the capillary rise of water was not considered;

- the behaviour of plants in dry periods was not described correctly, in that the amount extracted by them was independent of the soil water content.

We consider that the calculated thicknesses are too great.

For a vegetation substrate above a sealing layer the minimum thickness given in the literature is 1.5 m. For trees, a thickness of 2 m or more is typically given. It is recommended that the minimum thickness required is determined for the specific site.

Slope stability

For the system analysed here the sealing layer is directly overlain by the vegetation substrate. In the context of the stability of the cover system doing without a drainage layer has a number of weaknesses;

- there is a critical slip plane between the sealing layer and the vegetation substrate;
- in wet periods a significant amount of water can build up on top of the sealing layer, reducing the available shear resistance.

In demonstrating that the system is sufficiently stable the wind loads from trees should be considered. As the roots should not penetrate into the sealing layer they cannot be considered to have a stabilizing effect.

Cover requirements

Sealing layer

The sealing layer should have the lowest possible field conductivity. In our opinion it is more appropriate to define the required field conductivity than the hydraulic permeability of the material. This, along with other requirements, can be derived from the desired field conductivity. The pore air volume should also be as low as possible, in order to minimize the passage of oxygen (and radon).

To obtain the desired properties in the sealing layer the following requirements must be met during its construction:

- The material should contain a wide range of particle sizes (for low residual permeability and low tendency to cracking);
- compaction should be with the heaviest possible equipment with the objective of reaching a high density (e.g. ≥100% of the Proctor maximum density);

- compaction should be at a water content which is optimized for the equipment in use and is therefore lower than the standard Proctor optimum water content;
- at a minimum in the joint zones between adjacent construction panels, compaction should be in two layers in order to avoid local water pathways there.

The necessary logistic and technical measures must be taken to avoid material being delivered and compacted in too moist a condition.

Vegetation substrate (water storage layer)

From the discussion of failure mechanisms it can be seen that to protect the sealing layer the thickness of the vegetation substrate should ideally be 3 to 4 m, but at least 1.5 m. This thickness does not provide absolute security against a long-term degradation of the functioning of the sealing layer, but, on the other hand, there are no reported observations indicating that a loss of effectiveness is to be expected.

If a thin vegetation substrate layer is aimed for, in order to minimize remediation costs, this must be considered in planning the after-care, as the expenditure required for the long-term monitoring and maintenance rises as the thickness of the vegetation substrate layer is decreased.

In order to obtain the desired properties the following requirements should be met during the construction of the vegetation substrate layer:

- the thickness should be at least 1.5m
- the available field capacity, i.e. the water storage capacity between field capacity (pF=1.8) and permanent wilting point (pF=4.2), should be at least 15 vol.% or 22.5 cm of water;
- in its upper zone (to a depth of 1.5 m) the layer should be constructed with the minimum possible compaction to achieve a density of less than 85% of the Proctor maximum density;
- any part of the layer below a depth of 1.5 m should be heavily compacted (in order to increase the resistance to penetration by animals and roots).

Plants and animals

The following points suggest that woodland vegetation should be aimed for on waste piles with this type of cover:

- sowing grass, and establishing a woodland in parallel to this, hinders the spread of plants with particularly aggressive roots (e.g. dock, thistle);
- woodland restricts unwanted human activity on the cover (e.g. motocross);
- a mixed woodland provides the best long-term erosion protection;
- in temperate climatic zones the natural long-term vegetation is woodland, and by planting desired species those with aggressive roots can be restricted.

To protect the sealing layer against mice and rabbits the presence of their natural predators can be encouraged, e.g. by providing perches for birds of prey. To the extent that the intended use of the area permits this, the populations of wild boar and of badgers should be kept as low as possible by hunting.

Slope stability

In order to ensure the necessary long-term stability of the slopes we recommend the following:

- in the determination of the allowable slope angle and of the necessary shear strength parameters of the sealing layer material it must be taken into account that under extreme weather conditions full saturation of the vegetation substrate layer can occur (for thickness up to about 2 m) in longer slopes (some 10's of metres long);
- if a cohesion value is to be included in the calculations of slope stability this should be determined in careful triaxial tests carried out under drained conditions at the appropriate low stress level;
- for a vegetation substrate layer thickness of 1.5 m the slope gradient should not exceed 1:3, but flatter would be better.

Construction quality

To minimize the risk that the cover system will fail as a result of material deficiencies or construction errors, reliable quality assurance must achieved during construction. Appropriate recommendations (e.g. in Germany the "GDA-Empfehlungen") should be applied.

After-care

The institutional controls and after-care must be so arranged that the cover functions as intended for the time period which the specialists consider to be necessary. For residues from uranium mining the 200 year primary time period which was mentioned above provides some indication of the timescale. After-care generally includes:

- maintenance of the cover itself (repair of erosion damage);
- maintenance of the surface water drainage system to ensure undiminished effectiveness;
- maintenance of the vegetation to protect against erosion and against the spread of species with aggressive roots.
- If this is necessary, collecting and treating contaminated water is also part of the after-care, but this is not the subject of this Paper.
- Repairs to the cover should not first be made when the sealing layer is already damaged, but rather when damage is to be expected if an observed process is allowed to continue. The reasons for this are:
- damage to the environment should be avoided if possible;
- a repaired sealing layer is unlikely to have as high a quality of the original, as smaller equipment will be used and there will be more joint zones;
- erosion damage can extend very quickly, so early repair can be the cheapest option.

Concluding remarks

As a conclusion we would like to address the question of whether it is sensible to construct a cover with a mineral sealing layer when taking into consideration the expenditure in construction and after-care and the risks of failure.

In our opinion the answer must depend on the individual circumstances, but the following principles can be established:

- If the degradation of all the affected environmental media by substances from the source <u>remains and will remain</u> at a tolerable level, even without sealing, then a sealing layer (with the objective of reducing the outflow of contaminants) should not be constructed.

- If all significant seepage from the source is collected (i.e. the remaining outflows can be tolerated) and long-term disposal of this without causing any damage is possible and this is economically viable, then a sealing layer need not be constructed.
- In our opinion the pre-requisite for this is that those responsible for the rehabilitation commit themselves to long-term water treatment or that a fund for this purpose (or an equivalent arrangement) is set up. (For operating facilities it is therefore advisable to reach a binding agreement on the time, the extent and the responsibility for after-care before establishing a new potential source of contamination.)
- In cases when the contaminant inventory makes it imperative that the long-term sealing effect of the cover is ensured, and the consequences of degradation cannot be accepted as a residual risk, then it is our view that an appropriate geomembrane should be included in the cover system.