

FINDINGS OF INTERNATIONAL REVIEW OF SOIL COVER DESIGN AND CONSTRUCTION PRACTICES FOR MINE WASTE CLOSURE¹

Maritz Rykaart, Daryl Hockley, Michel Noel, and Michael Paul²

Abstract. Selected results of an international review of soil cover design and construction practices and performance is presented in this paper. The review, which was carried out in 2003, initially included 177 case studies in 14 countries. This has subsequently been updated to include more than 200 individual case studies. The case studies include soil covers for tailings impoundments, waste rock piles, backfilled pits and heap leach pads. The mining operations included precious metals, uranium, coal and oil sands. This is the first international review to focus on the practical questions related to soil cover construction practices, and specifically how that relates to long-term cover performance. This paper provides some suggestions as to how operators, regulators and practitioners could improve soil cover design and construction practices, as learned from these actual case studies.

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² Maritz Rykaart is Senior Geotechnical Engineer, SRK Consulting (Canada) Inc., Vancouver, BC, V6E 3X2, Canada. Daryl Hockley is Principal, SRK Consulting (Canada) Inc. Michel Noel is Senior Geotechnical Engineer, SRK Consulting (Canada) Inc. Michael Paul is Director, WISMUT GmbH, Chemnitz, 09117, Germany.

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Introduction

Wismut GmbH (Wismut) is currently undertaking one of the largest mine closure projects in the world. This project, spanning almost two decades, costing approximately U.S. \$8 billion, entails rehabilitation of uranium (U) mines in East Germany. Part of this project entails the closure of 18 U waste rock piles. Wismut has been working with SRK (Consulting) Canada Inc. (SRK), since 1990 on various components of this project, including the establishment, monitoring and evaluation of large scale test soil covers. Throughout this process, Wismut has also been conducting a series of in-house surveys of cover design and construction practices. In 2003, Wismut contracted SRK to carry out a detailed international review of cover design and construction practices for mine waste rock piles, in climate zones similar to that experienced at the Wismut sites. This information was used by Wismut to compare their own practices with those adopted internationally, as a final reality check prior to proceeding with detailed cover design and construction.

The review highlighted some interesting and surprising issues, with respect to the use and application of soil covers for mine waste closure. Subsequent to completing this review SRK has continued to expand the database of case studies. This paper documents some of the pertinent issues highlighted during the review which should be of interest to cover design and construction practitioners.

Study Methodology

The international review of cover design and construction practices included a review of over 300 published and unpublished sources references as well as additional case studies and relevant information gleaned from SRK's in-house experience, consultation with leading cover design and construction professionals, and interviews with mining company professionals with significant soil cover experience.

In order to facilitate the data collection process, SRK developed an information template listing the pertinent information needs that would facilitate the most effective collection of relevant information. Preference was initially given to evaluating full scale natural soil covers constructed on waste rock piles in climate zones similar to that experienced at the Wismut sites. However, it soon became apparent that case studies in this category were limited, but, that valuable relevant information could still be gleaned from looking at a more comprehensive field of cover design and construction practices.

Therefore, the review was expanded to evaluate case studies in a broader variety of climate zones, natural and synthetic covers, over a variety of mine waste types (waste rock, backfilled pits, tailings and heap leach facilities). Some particularly useful information was also gleaned from experimental or research studies. In all, a total of 177 case studies were investigated, spanning 14 countries and five continents. Since completion of the review presented to Wismut in 2003, SRK has consistently been adding to this database, which has now grown to 200 case studies in 16 countries. Table 1 list a summary of case study locations.

Table 1. Origin of case studies researched as part of the international review of cover design and construction practices.

Continent	Country	Number of Case Studies
North America	Canada	40
	United States	85
South America	Brazil	4
	Chile	2
Africa	South Africa	13
Europe	Sweden	6
	United Kingdom	2
	Germany	18
	France	1
	Czechoslovakia	1
	Greece	1
	Norway	1
	Spain	2
	Australia	Australia
Asia	Indonesia	5
	China	1
Total		200

Soil Cover Function

One of the single most surprising findings of the review was that few of the case studies documented the reason for constructing the cover in the first place. Further questioning suggested an apparent disconnect between mine closure goals/objectives and selection of mitigation measures to address these goals/objectives. The reason for this disparity is not clear; however, there does seem to be a misconception that soil covers and mine closure are synonymous, and therefore soil cover performance is used to set mine closure objectives as opposed to setting objectives independent of what mitigation measure may be adopted.

For the purpose of this review a clear distinction was made between closure objectives and cover functions. Closure objectives are defined as the fundamental reasons/motivations for completing a closure project. Examples of possible mine closure objectives are listed in Table 2.

Table 2. Examples of possible mine closure objectives.

Remove human/animal health/safety risks
Prevent/remove/minimize environmental impacts
Reclaim social/economic land value
Regulatory compliance
Release bonds
Improve corporate image

Once closure objectives for a site or a mine waste facility have been set, appropriate mitigation measures must be selected to ensure that the closure objective can be met. Soil covers is one possible mitigation method that can be used to achieve a closure objective. Based on this understanding, it can be argued that a soil cover must have a distinct function that will ensure that the closure objective is met, i.e. the soil cover function is the “*work*” that the cover must perform in order to achieve part/all of the closure objective. Based on this definition, examples of possible soil cover functions are listed in Table 3.

Table 3. Examples of possible soil cover functions.

Radiation control
Waste stabilization (i.e. dust, erosion, frost)
Seepage/leachate management (oxygen/infiltration control)
Physical stabilization (slope stability)
Thermal control (i.e. promote permafrost)
Promote vegetation
Access control (i.e. prevent direct contact with waste)

Regulatory Framework

With the exception of coal mining in the United States (1977 SMCRA Legislation; Nawrot *et al* 1988), the review did not find reference to prescriptive regulations for the design and construction of soil covers associated with the mining industry. In Australia, the Australian Best Practice Guidelines (Australian EPA 1995) presents a set of common closure objectives that a mining company planning waste rehabilitation should consider. The South African coal mining industry is similarly subject to a set of closure recommendations posted by the Chamber of Mines (DWAF 1992). The MEND program in Canada has produced a number of reports that document cover practices (MEND5.4.2d 2001). MEND has provided guidelines based on these reports but these are considered to be guidelines, not prescriptive regulations. Similarly there are guideline regulations under which Wismut must operate. None of these guidelines prescribe

what the cover should look like, but rather state certain minimum standards that must be achieved through the placement of a cover system.

The review concluded that mining companies are effectively left alone to decide on appropriate cover designs, and the standards of the design is governed usually by their own approved Closure Plans and Environmental Impact Statements, which in many countries are legally binding documents. In essence the mining company must employ best available technology to eliminate, minimize or reduce the impact that the waste facility has on the environment, and this is usually expected to be a long-term solution.

This is in stark contrast to designing covers for hazardous, industrial and municipal landfills, for which there are minimum design standards that are enforced by regulation. Examples of these are the South African Minimum Standards for Landfill Design (DWAF 1998), German Legislation on covers for municipal solid waste (Munnich 1993) and the US EPA design standards for hazardous waste disposal facilities (Suter *et al* 1993). In the United States there are even State Agencies that has additional regulations, for example the Alaskan Department of Environmental Conservation (Cabalka and Newton 1998).

Prescriptive regulations such as these would make it easier for a mine to know what is expected; however, no two sites are ever the same, and prescriptive regulations may need to be overly conservative, potentially making for uneconomical and/or unsuitable cover design. The performance based system of cover design currently in practice for mine waste facilities, do therefore appear to best suit all concerned. However, as long-term cover performance data becomes available and cover failures are being observed, regulators may well want to re-evaluate this approach, especially if the reasons why covers fail are not understood.

Cover Design Approach

There are no standard procedures or “*recipes*” for designing soil covers. Yanful and Lin (1998) present an approach to soil cover design in the form a flow chart. Wismut developed an in-house design approach; however, their approach focuses mostly on the selection and testing of suitable cover soils, and on the development of appropriate quality assurance and quality control procedures for the cover placement. More recently, Wels and O’Kane (2003) presented another “*typical*” approach to the design of soil covers. Their approach follows the same principles as that proposed by Yanful and Lin (1998), although details associated with each task is explained in greater detail. Neither of these approaches however, provides a step by step schematic for a cover design.

As a result of the review undertaken by SRK, a formalized approach to cover design is proposed, as illustrated in Fig. 1. This is a summary of the general steps that most practitioners follow in cover design. Since cover design is a very site specific issue, this approach should be viewed as a guide; however, all the design processes reviewed in the case studies generally followed most, if not all, of these general steps.

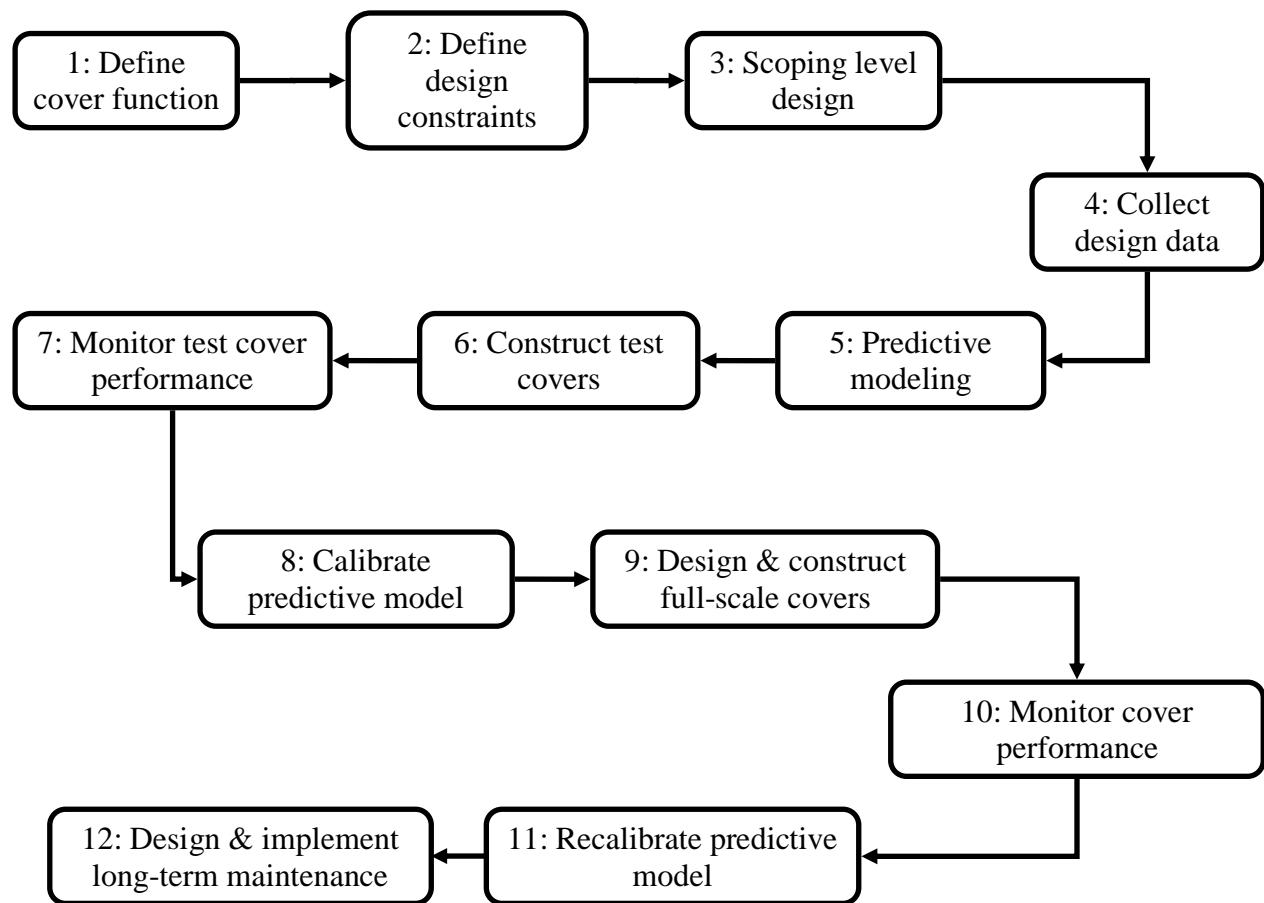


Figure 1. A proposed formalized cover design procedure as evaluated from the international cover design and construction review.

The complete formalized approach (Steps 1 through 12 in Fig. 1) has been followed successfully in a number of actual case studies; Kidston Gold Mine (Durham 2002), AA Heap Leach Pad (Zhan *et al* 2001), Les Terrains Auriferes (MEND2.22.4a 1999), Whistle Mine (Ayres *et al* 2002) and Wismut being good examples. Sites where this approach has been adopted, but not yet fully implemented (i.e. only up to Steps 7, 8 or 9), include Mt. Whaleback (O’Kane *et al* 2000), Grasberg, Kestrel Coal, Syncrude (Meiers *et al* 2002), Kaltim Prima Coal, Questa Mine (Wels *et al* 2002) and Greens Creek.

Beyond these case studies, pilot-scale work appears to be limited to research studies in the form of experimental test plots which has not led specifically to a detailed full scale design of any particular waste facility cover; for example at Waite Amulet (Yanful and St-Arnaud 1991), Sullivan Mine (Gardiner *et al* 1997), Heath Steele Mine (Yanful *et al* 1993), Myra Falls (O’Kane *et al* 1998), Bersbo Mine (Lundgren 1997), Key Lake Mine (Lee 1999), East-Sullivan Mine (Aubertin *et al* 1997) and the Potash Corporation of Saskatchewan (Haug *et al* 1991).

There are also a number of case studies where the cover construction has been completed without pilot scale work, with the cover performance based solely on uncalibrated numerical modeling (i.e. skipping Steps 6 though 8). For these case studies cover performance monitoring

is implemented in tandem with cover construction with a view to proving the design. Examples of this approach include Equity Silver (Aziz and Ferguson 1997), Golden Sunlight (Wilson *et al* 1995), and Rum Jungle (Bennet *et al* 1988).

However, by far the majority of full scale covers being constructed are done without any pilot scale testing or calibration monitoring at all (i.e. moving straight from Step 5 to Step 9 and ending there. Examples of this approach include the Vangorda waste rock pile (SRK 1994a, 1994b), Yankee- and Coral Gold heap leach pads, and the Glamis waste rock dumps and heap leach pads. Although the review identified many more sites where this approach is adopted, there is generally very little in the form of published documentation explaining the reasoning behind this decision. Drummond *et al* (2003) reports on the cover designed for the Tonopah heap leach pad, where no design was done at all. Their approach was simply to adopt a design similar to those in the surrounding areas and apply that – the premise being that if it works elsewhere, it is good.

Cover Design Life

MEND5.4.2d (2001) suggests that long-term cover performance integrity should be ensured through appropriate design for a period of 1,000 years; however, there does not seem to be general agreement on this subject. In Australia, Normandy Mining Ltd. has taken an initiative to specify physical stability of their waste containment facilities for between 200 and 500 years. The Wismut practice is to design cover systems that will ensure physical stability for a 200 year life.

Often, however; statements are made that covers should last and continue to perform in perpetuity. At Canadian arctic mine sites, there is even a school of thought that suggests that cover designs should be designed taking into account global warming in perpetuity.

An aspect that goes hand-in-hand with the design life of a cover is the approach to maintenance and repairs. Most mine sites acknowledge that some form of cover maintenance and repair will be required; however, generally the understanding is that such commitments would be temporal, i.e. immediately following cover construction there would be an intensive monitoring period; however, over time, say 10 to 20 years no more maintenance will be required. In fact, many mine sites stipulate “*zero maintenance*” as a design standard.

Clearly, these commitments are perhaps contradictory, especially if the cover design relies on the long-term integrity of engineered components.

Cover Construction

Construction Approach

This review highlighted two important findings with respect to the mindset regarding cover construction. Firstly, the level of engineering documentation that is being kept (i.e. design reports, design drawings, project specifications, quality assurance and quality control procedures etc.) is significantly less than what is considered standard practice for conventional civil earthworks projects (e.g. roads, foundations, dams etc.). Secondly, certainly in the past, there has been a perception by some, that cover design and construction constitutes a simple landscaping exercise, and therefore does not warrant the same level of scrutiny as would

conventional civil earthworks. More recently, this attitude has changed, and cover design practitioners and mine operators are realizing that there is a distinct difference between simple reclamation covers and engineered soil covers. However, the preparation of appropriate engineering documentation is still lacking, probably due to the fact that engineered soil cover construction is a relative new technology, and therefore the tools and methods to construct these engineered covers are not yet fully established. The remainder of this section illustrates some of these issues.

Construction Methods

Soil cover construction methods are still very much in its development stage. The reasons for this appears to be twofold; Firstly, the history of soil cover construction is limited, and therefore a “*track-record*” of proven construction techniques specific to soil covers has not yet been established. Secondly, the soil cover designs presented for construction often lack fundamental basic information necessary to ensure that appropriate construction methods can be developed, such as detailed construction specifications and quality control and quality assurance documentation. This is in stark contrast to conventional civil earthworks construction, where construction practices to achieve the engineered system performance is well developed.

Construction Fleet

The majority of soil cover construction is being carried out by mining companies, using their existing operational mining fleet. Whilst this may be a logical choice, especially when considering sites where progressive reclamation is taking place, and considering the scale of construction, the soil cover designs does not appear to be matched to the fleet. In many cases, the cover design is not constructible with the mining fleet, and therefore the design is simply field fitted during construction without giving consideration to the design and subsequent cover performance implications. This problem could be successfully overcome, by acknowledging the constraints offered by the available construction fleet, and designing a cover to suit. The landscape engineering approach adopted at Syncrude, Canada is a good example of this in practice (McKenna 2002). Wismut approached their cover construction more in line with conventional civil earthworks practice. The design was completed, and subsequently a construction fleet specifically suited to match their requirements was sourced. The net effect of this approach was that it allowed them to achieve exceptional control over their design; however, their cover construction costs were some of the highest recorded.

Lack of Detailed Design Documentation

A surprising review finding was the lack of detailed design documentation, i.e. design reports and construction drawings. Few formal soil cover design reports exist. Most often, the design documentation consist of a numerical modeling report used to predict cover performance. Similarly detailed construction design drawings, stamped by a Professional Engineer are rarely produced. The design drawings used for construction therefore consist of simplified cross sections in numerical modeling reports, intended to illustrate a concept rather than guide a contractor. From discussions with larger mine operators, it would appear that for operating mines (and mines that go into scheduled closure) cover construction is seldom subjected to a formalized tender process, which would require detailed design documentation. This observation is supported by the more recent closure of derelict mines through public funding in various countries. Appropriate documentation is a pre-requisite for these types of projects. Unfortunately, the previously mentioned perception, at least in some circles, that construction of

soil covers does not require rigorous engineering scrutiny, does not foster an environment that supports rigorous engineering documentation.

Lack of Construction Specifications

Hand-in-hand with the lack of proper detailed design documentation is the lack of construction specifications when soil covers are constructed. Whilst the basic reasons, for the lack of these specifications are the same as those leading to the lack of design documentation, it is apparent that the soil cover design approach often leads to the stipulation of inappropriate and incomplete specifications, as well as in many instances unenforceable specifications.

An example of inappropriate design specifications is cover thickness. Soil cover designs are often based on numerical modeling results and generally optimal cover thickness are determined without consideration of constructability. Furthermore, cover thicknesses are typically specified as an absolute number, without consideration of variance (tolerance). Such a specification is clearly not realistic.

The performance of a soil cover naturally rely on the soil properties, such as particle size, plasticity, water retention and saturated hydraulic conductivity. Whilst there is often very detailed consideration of these properties during the design stage of the cover (especially if numerical modeling is conducted), the importance of these properties appears to be lost in developing construction specifications, leading to incomplete specifications. For example, other than for Wismut, only the Rain Mine case study (Shepperd Miller 2001) had the moisture retention properties of the cover materials included in the specifications. Considering the fact that the success of store-and-release covers is almost entirely dependant on this property, this appears to be a serious omission. Soil water retention properties are of course not easily and quickly measurable in the field; however, some simple indicator tests such as particle size distribution can be used successfully if the appropriate confirmation testing was completed at the design stage.

Another example of incomplete specifications is the practice of specifying a single grain size distribution, as listed in the numerical modeling report. In fact, in only two case studies other than Wismut, i.e. Vangorda Dump, Canada (SRK 1994b), and Rain Mine, USA (Shepperd Miller 2001) was the cover material size fraction specification given as an envelope of allowable particle size distributions. In the Heath Steele test cover (Yanful *et al* 1993), and the Yankee heap leach pad cover (SRK 2001) the material specification was stated as upper brackets of particular particle sizes, which indirectly implies an envelope of allowable particle size distributions.

Unenforceable construction specifications are perhaps another reason why quality control is not carried out. For example, at one site, the construction specification called for a clay barrier to be compacted (and moisture conditioned) to achieve the design saturated hydraulic conductivity of 10^{-10} m/sec. The specification also called for field moisture content and hydraulic conductivity tests during construction. The mine however did not have water to spare, and subsequently no moisture conditioning could be done (this fact was known at the design stage). The quality control data shows that the field moisture content is consistently lower than optimum and the field saturated hydraulic conductivity is 10^{-8} m/sec on average. The opposite problem was encountered at another mine, where moisture control was specified, but since the material was too wet it had to be dried out. The almost 2,000 mm of rain per year at that site

however prevented this from happening and field permeability tests show values one to two orders of magnitude higher than the design specification.

Another example of unenforceable specifications which are commonly used, is the use of laboratory derived saturated hydraulic conductivities as the field specification. The review did not find a single case study where the construction specification for field permeability has an equivalent laboratory hydraulic conductivity specified that has been calibrated. Irrespective of these limitations, the reality is that measurement of field or laboratory permeability is rather complex, expensive and time consuming. A better approach would be to correlate the state of soil compaction and moisture content to permeability through testing and pre-construction trials. Compaction can then be the measurable field parameter, which would be significantly more practical and enforceable.

Lack of As-Built Documentation

The review concluded that even if quality control is done during construction, it is not documented in as-built reports, and therefore there are few official records documenting cover construction. Notable exceptions to this are covers constructed in the USA, where the submission of an as-built report is a regulatory requirement; and Germany, where detailed construction and quality control documentation must be submitted for approval by the regulator. As-built reports for covered heap leach pads in Nevada were included in the review, and although the reports were acceptable to the regulator, it certainly contains much less information that would an as-built report for any other conventional civil engineering earthworks project. Through verbal communication it was established that this is a common occurrence with completed covers under this regulation in the USA.

Example of an Approach that Yield Good Success

Wismut arguably has one of the most rigorous approaches towards developing and setting construction specifications. Once candidate soil cover materials have been identified, full scale testing, using the actual construction fleet is conducted to determine exactly how the soils can be conditioned to achieve the design criteria stipulated for the cover. With this data, a specification is written which describes both the target conditions (i.e. compaction), as well as the method to achieve this. This is unusual, since most specifications provide either the target values or the method, but not both. These specifications are material, site and location specific, i.e. if a specific layer is constructed from more than one borrow source, there will be individual specifications for each material type. Likewise, different specifications apply to side slopes and top surfaces and/or benches. Specifications developed by Wismut are multi-faceted in that there are specifications for gradation, plasticity, compaction (including moisture content and density), water retention properties and saturated hydraulic conductivity. This means that merely achieving the required compaction specification is not adequate if the material grading falls outside of the prescribed specification. Wismut ensures that these strict specifications are enforced by applying a strict quality assurance program during construction.

Whilst, this rigorous approach has proven to be successful to ensure good cover performance, it is expensive. It is certainly not suggested that the Wismut practice should be the model for cover construction everywhere; however, undoubtedly approaching the cover construction phase with the same attention to detail as the design stage must allow for a better end product, especially if the cover performance relies on engineered modifications to the soils.

Cover Performance Monitoring

Based on the review data, SRK concluded that there are two basic approaches to evaluating and monitoring cover performance. These have been defined as “*macro*” and “*micro*” monitoring. Macro monitoring entails measurement of water quality and flow data from seepage or overland flow discharged from waste facilities (i.e. a measurement of site wide waste load), independent of the actual cover system, whilst micro monitoring entails actual monitoring of the cover system itself.

In most cases however, the standards against which cover performance is measured, consist of downstream water quality target concentrations set on a case by case evaluation. The onus lies on the mining company to prove that their design will ensure compliance to the water quality standards set for that site. The South African coal industry is a good example of this system in practice. Receiving water bodies in watersheds impacted on by the mining industry are monitored and an assimilative capacity for each is determined based on the downstream water use. It is therefore recognized that the mining industry has an impact on the environment, and the maximum allowable contaminant load that any receiving water body can receive without impacting the downstream water use is calculated. Each mine in the watershed is then assigned a pro-rated portion of that waste load, based on production numbers. The system is regulated through measurement of the contaminant loads emanating from each site. The mine must ensure compliance with this assigned contaminant load, by whatever means, including possibly soil covers.

For some sites compliance are also measured via other mechanisms, i.e. achieving low radon emissions for radioactive waste (DOE 2002) or specific final land use requirements, i.e. pasture (Rykaart *et al* 2002).

Direct performance monitoring of the cover system in the form of flux measurements through the cover (MEND5.4.2d 2001) is generally used to evaluate the processes that influence the cover system performance, and to assist in setting target performance criteria for downstream water quality monitoring. The review did not identify any case studies where this level of performance monitoring as used for the purpose of compliance monitoring.

The review confirmed that field trials and detailed cover performance monitoring are considered extremely important in developing appropriate site specific cover design criteria. There is however a healthy recognition that data from these test facilities should be very carefully evaluated to ensure that it has not been skewed though improper equipment selection (Rykaart 2002; Wates and Rykaart 1999; Lee 1999).

One element that warrants special mention is lysimeters. Many case studies list the use of lysimeters to directly measure infiltration through the cover system and these measurements are used to evaluate the cover effectiveness. Bews *et al* (1999) illustrated the complexities involved in lysimeter design, and showed that in order for a lysimeter to correctly measure infiltration through a cover it has to be specifically designed for each application. The dimensions and fill material of the lysimeter are therefore critical components towards successful lysimeter application. Experience with this aspect as well as a review of lysimeters documented in case studies leads to the conclusion that many cover performance results are based on inadequate lysimeters, often making the interpretation of data difficult.

Cover Performance

There is a wealth of cover performance data reported in the literature, especially with respect to infiltration through covers. Long-term performance data (about 20 years) are also starting to become available, which are particularly useful to evaluate the actual benefit of soil covers.

Interpretation of cover performance data, especially with the intent of comparing performances of different cover types are however quite difficult, for a number of reasons. Firstly, there not standardized performance monitoring methods that would allow for direct data comparisons. Often measured parameters between sites differ, and performance comparisons have to be made through secondary reduction of the data to a mutual parameter, i.e. one site may measure the water level fluctuations beneath a cover using piezometers, whilst another site may have seepage data from a series of underdrains. Both these data sets can indirectly yield a measure of the flux through the cover, which can then be used as a measure to compare their performance. Secondly, soil cover performance is highly complex and will vary widely depending on site specific physical and environmental factors. Therefore, performance data cannot be interpreted without keeping those factors in mind. Thirdly, and perhaps the most controversial, is determining the accuracy of performance data. The use of bottom lysimeters to directly measure cover flux values, is a good example of the problem. Recent advances in lysimeter design have confirmed that lysimeter data is only relevant and accurate if the lysimeter was specifically designed for its application. Therefore, potentially, a large volume of the data published and being used as indicators of cover performance to date may be incorrect.

Notwithstanding the limitations mentioned, and, by applying good judgment, it is possible to draw some interesting conclusions with respect to the cover performance data that is available.

Summary of Performance Data

Cover performance data, such as that illustrated in Fig. 2, are now starting to become available. The figure illustrates reliable cover performance data for four case studies in the form of percolation measurements, i.e. infiltration that passes through the cover (this data is expressed as a percentage of the Mean Annual Precipitation (MAP)). In all cases there has been a significant increase in infiltration over time. The increased infiltration appears to be as a result of increased hydraulic conductivity of the cover material. The obvious question is why are these trends observed, i.e. are they as a result of inevitable natural physical changes that occur in exposed soils, or are the changes perhaps due to improper construction practices? The answer to this question is not clear; however, Figure 2 does demonstrate three interesting trends. Firstly, in all four case studies the infiltration increased, and did not decrease, suggesting an irreversible process. Secondly, in two case studies the increase was rapid, i.e. a sudden jump within a one year time frame, suggesting a trigger event of some kind. Finally, the remaining two case studies suggest a gradual increase in infiltration over time, suggesting progressive changes.

In all four the demonstrated case studies the design infiltration rate was in part reliant on a specific soil hydraulic conductivity, which was to be achieved through compaction. Therefore, the change in hydraulic conductivity which leads to increased infiltration constitutes a failure of the cover.

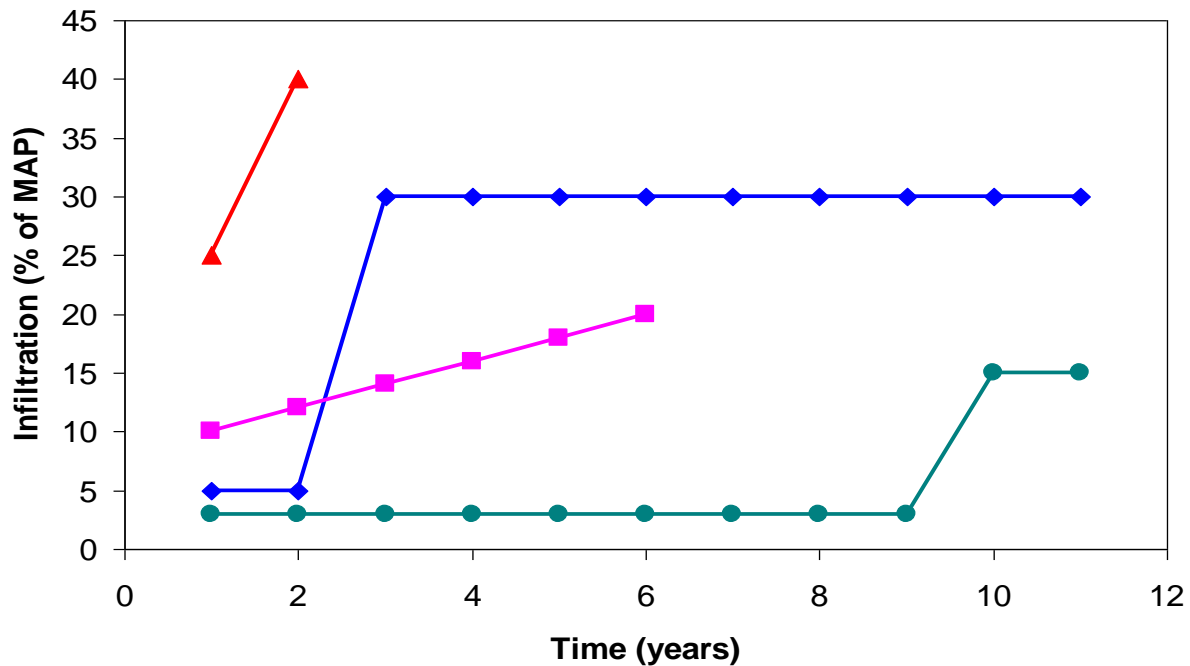


Figure 2. Four case studies for which long-term monitoring data shows persistent increase in infiltration over time.

Increasing hydraulic conductivity of the cover material over time, as well as the difference between the design specification and that measured in situ is depicted in Fig. 3 for 14 case studies. Clearly, differences of one to three orders of magnitude between design and measured values are not uncommon, and as a result covers are not performing as intended (especially, since allowance for such changes are generally not considered in the designs). Perhaps these changes are to be expected, since soil covers are dynamic, and soil properties should change over time, especially when these soil covers are subjected to wet/dry and freeze/thaw cycles. However, irrespective of these facts, when a soil cover is designed to a specific hydraulic standard for a given lifetime, that standard should be met; otherwise the cover constitutes a failure.

The obvious conclusion would be to suggest that successful cover performance would have to be done based on some inherent natural site specific soil hydraulic conductivity, and, that if the design relies on engineered soil properties then failure may be inevitable. This would undoubtedly be true for soil covers that do not rely on any form of compaction, such as store-and-release covers. However, if this approach was adopted, then barrier covers, which may rely on an engineered compacted soil layer, should never be constructed.

This does not make sense, since engineers routinely design and maintain engineered soil hydraulic conductivities in conventional civil earthworks, such as earthen dam clay cores. There are many documented case studies where dam cores were excavated decades after construction, and the engineered integrity of the core was still perfectly in tact. Therefore, it is possible to rely on engineered enhancement of soil. This integrity however relies on adequately protecting the engineered soil against forces of nature, and ensuring that the structure is rigorously constructed in accordance with the level of engineering performance required.

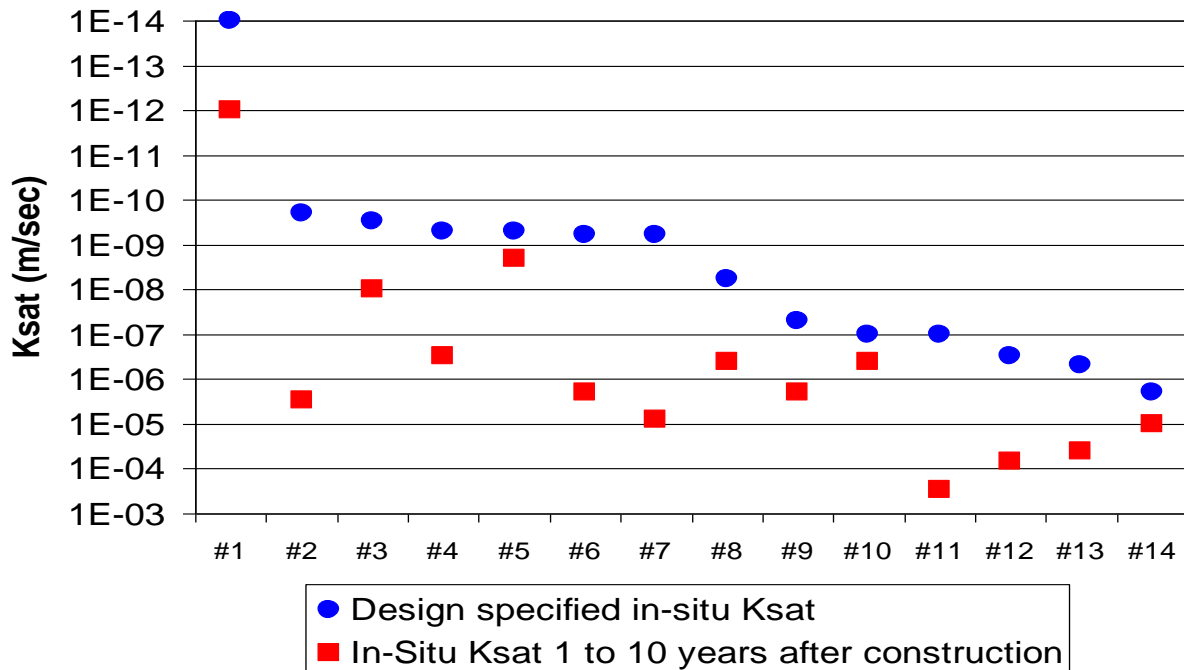


Figure 3. Case studies demonstrating how actual field measured hydraulic conductivities vary from those specified during the design stage.

Long-Term Cover Maintenance

The review confirmed that information on soil cover maintenance, short or long-term is scarce. Some covers have specific maintenance plans, for example the Richmond Hill cover has to be regularly inspected and any trees that has germinated must be removed (van Zyl 2002). DWAF (1992) reports on annual grass cutting of covered coal spoil heaps in South Africa. There are also numerous examples of covers that have undergone annual repairs due to erosion; however, there does not appear to be any particular maintenance standards.

The general approach to maintenance is to “deal with the problems if and when they occur”. Furthermore, the only aspects of cover maintenance that are addressed are erosion and vegetation. Aspects that have found to require maintenance, but that are rarely acknowledged upfront includes sediment transport, settlement (both from consolidation and thaw) and physical degradation (as a result of wet/dry or freeze/thaw cycles).

Cover Construction Costs

Construction costs for soil covers over mine waste facilities are highly site specific, mostly driven by the availability (i.e. haul distance) of the cover material, the size of the construction fleet, the level of complexity of the cover, whether the mine is doing progressive reclamation or if the reclamation is done after mining has ceased.

Figure 4 summarizes a small number of case studies for which cover construction costs are available. These are not directly comparable in all cases, since data on exactly how they have

been derived are scarce; however, the trends in the data appear consistent. Simple reclamation covers cost are the least expensive, generally less than US \$20,000/ha. Simple single layer infiltration reducing covers can be up to US \$100,000/ha, whilst multilayer complex infiltration reducing covers can be up to US \$500,000/ha. Based on the costs evaluated during the review the median cover cost is in the order of US \$68,000/ha.

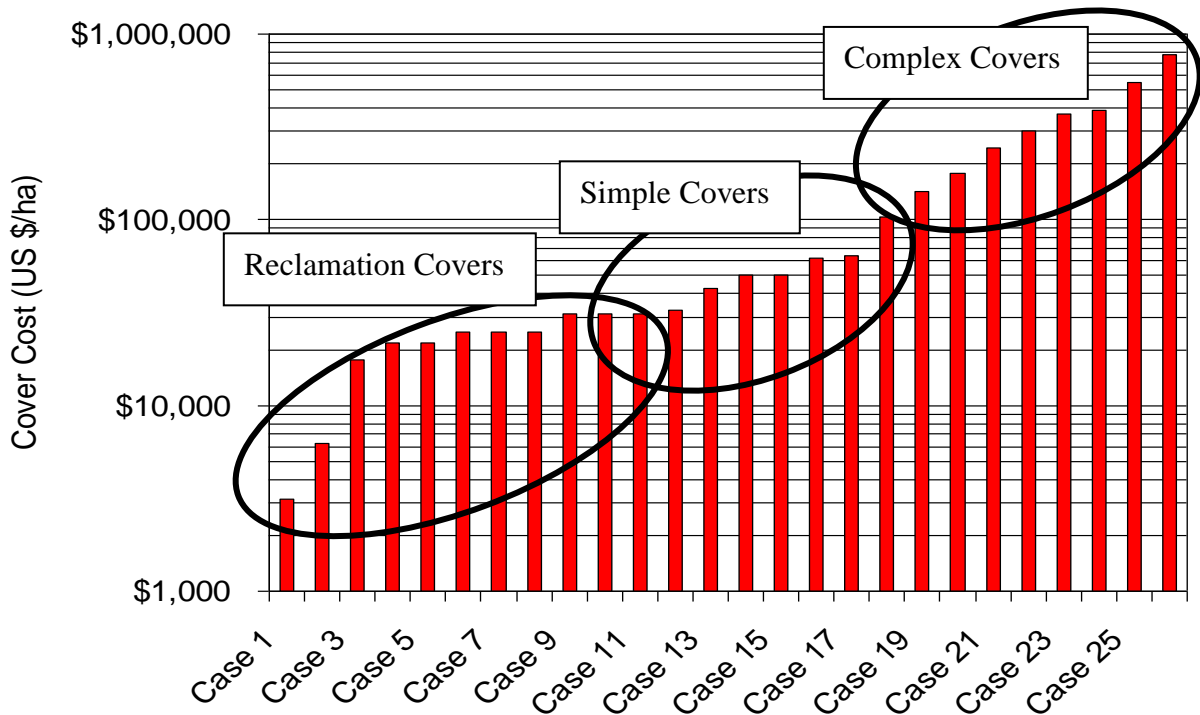


Figure 4. Summary of cover construction costs for case studies where reliable data is available.

Conclusions

The review has pointed out some interesting facts about the current soil cover design and construction practices. Significant effort appears to be going into the design of soil covers, and some great advances have been made in terms of numerical modeling for example. There is a great appreciation for the complexity behind how soil covers work, and the science of understanding how these unsaturated soil systems function is well developed (at least in temperate climates). However, there appears to be a disconnect between these highly sophisticated design philosophies and the practicality of constructing covers that are expected to perform in accordance with the design, for undetermined time periods.

Part of the reason for this disconnect is the historic mindset, that soil cover construction is equivalent to basic cosmetic landscaping, and as a result rigorous construction standards similar to those in use for conventional civil earthworks construction has not been developed. This has led to a situation where highly technical designs were “*simplified*” by construction teams without consideration of the design requirements and subsequent performance implications. Likewise, since the cover designers were not challenged to make their designs more

constructible, the designs have not evolved, such that practical enforceable construction procedures can be developed.

More recently, as long-term cover performance data is becoming available, there is recognition that many covers are not behaving as they were designed. Since many of these “failures” can be traced back to changes in the soil properties, specifically saturated hydraulic conductivity, it appears as if the approach to design and construction of soil covers should be considered much more seriously. Certainly, the review findings suggest that this change in approach is in fact starting to occur.

This review has confirmed that there is a significant wealth of valuable information on cover design and construction, many of which has not been publicly distributed. As soil cover design and construction practices continue to evolve, practitioners should strive to share these valuable experiences, such that the limitations of soil covers, and their failures can be understood. Only then can we ensure that we implement the appropriate mitigation measures.

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