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The Influence of Environmental Impacts on Tailings Impoundment Design

Integrating environmental impacts with engineering costs for the design of tailings impoundments

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I would like to dedicate this thesis to my co-supervisor Professor Geriant (Gary) Alan Jones whom I have had the privilege of studying under. He has mentored me during the past four years and although difficult at times, I do not wish to have it any other way. He truly knows how to inspire a person and has the ability to provide useful input on most subjects.

Prof. Jones's research into soil mechanics led to the development of the piezocone, a powerful tool used worldwide for assessing the strength and compressibility of soft soils, tailings and other materials. Piezocone testing has changed the method of investigation of soft soils around the world and consequently the design of embankments on soft soils.

He was born on 17 October 1933 in Wales. He obtained his BA and MA degrees in engineering from Clare College, Cambridge, in the UK, in 1957 and 1961 respectively. He was awarded a PhD by the University of Natal in 1993. Gary has more than forty year's experience as an engineering consultant and is presently an extraordinary professor of geotechnical engineering at the University of Pretoria.

Gary, I thank you warmly for the tremendous amount of selfless time and energy spent helping me during the lots of good and sometime less good times during my doctoral studies.

"...the key is to find technological ways of disposing debris without ecological upset."

Robert Pirsig (Pirsig, 1999:128)

"...from a larger point of view it is only tailings deposition not the disposal that ceases and tailings management must continue until such time as the deposited tailings is assured to be permanently stable and environmentally innocuous..."

Steven Vick (Vick, 1983:324)

"Development and technological progress places increasing pressure on the earth's resources. In this aspect South Africa is no exception and many unfortunate decisions have been taken in the past, often with disastrous consequences, due to ignorance or lack of essential environmental information."

(van Riet, Claassen, van Rensburg, van Viegen and du Plessis, 1997:63)

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Summary

Mining of South Africa's gold, platinum and base metal resources has given rise to hundreds of mine residue deposits (MRDs) the footprints of which cover large areas of land. Metalliferous mines produce a substantial volume of fine-grained waste and it is estimated that approximately 12 000 ha of land is sterilised by 150 MRDs within the Gauteng province alone (Figure Ex 1).

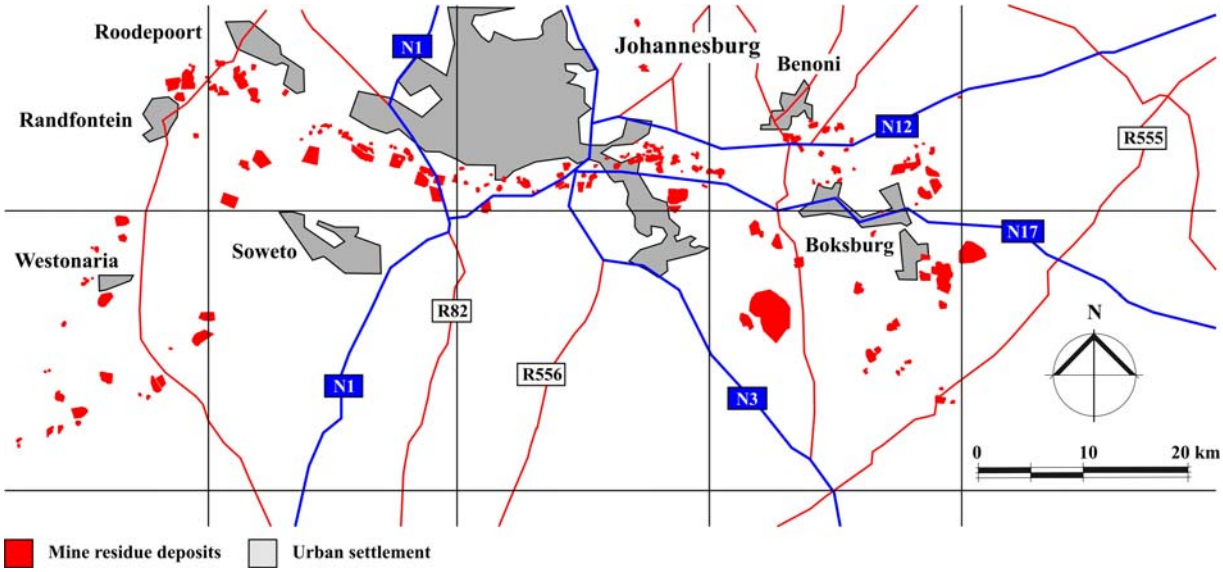

Figure Ex 1: Footprints of mine residue deposits in and around the Gauteng province (Rademeyer and van den Berg, 2005.)

The disposal of mine residue, mainly tailings, can impact on large areas of land through the change in visual landscape, the decrease in air quality, and the degradation of the water resource. MRDs are particularly susceptible to erosion giving rise to long term wind and water borne pollution. Mine residue can contain sulphide minerals which upon weathering give rise to a range of pollutants especially where there is insufficient neutralizing potential. Radionuclides are also found in drainage associated with some MRDs.

The quantitative prediction and integration of these impacts is difficult and the impacts are costly to manage and remedy.

The legacy of the impacts associated with MRDs, particularly in the long term after closure, has given rise to an increasingly complex regulatory regime. Obtaining approvals for upgrading old facilities, for the development of new facilities, and for closure plans are difficult owing to the lack of a suitable framework within which to make decisions. Since efficient development of the South African mining sector is essential, whilst maintaining a balance with an acceptable level of environmental risk, it is necessary to develop systems to facilitate transparent and effective decision making. The current state of the art of prediction and mitigation is not yet developed sufficiently to place South African regulators, in particular, in a position to evaluate and validate tailings impoundment schemes.

The research presented in this study is multidisciplinary. It integrates information from a range of disciplines, many of which have analytical structures and barriers separating them. The results of specialist studies are normally communicated to those within the discipline, and infrequently to specialists in other disciplines and even less so to stakeholders outside the planning and design team. This study describes a system to integrate different environmental impacts and engineering design aspects with the aim to present the results in a rational and understandable manner.

The research applies integrated environmental planning and design principles to the design of upstream deposited ring-dyke tailings impoundments which are widely applicable in South Africa, the result of which is an integrated environmental impact and engineering cost system for the configuration of such impoundments. A theoretical ecological and sustainable philosophical approach was adopted and used to critically evaluate, assess, and analyse environmental impacts and formulate solutions for the post-closure land use of tailings impoundments.

The research is innovative both because it envisages tailings impoundment design from the view of landscape architecture and also because it introduces the concept of visual impacts in a novel way. In essence, there must be a shift in emphasis from designing and operating an impoundment to contain tailings for a 20 year period, to the design of a man-made landform within the landscape with the end of life configuration and land use envisaged prior to construction. Generic models for the environmental impacts and engineering costs throughout the life cycle of a tailings impoundment are described such that the design can be optimised ab initio with respect to the environmental impacts and costs.

The research depends on the use of models and experimental work. The challenge was to develop a system that reflects the real world situation. Uncertainty exists regarding the detailed processes controlling and contributing to the environmental and engineering aspects. Uncertainties are incorporated into the predictions by means of following a systematic and rational approach. A systems approach ensures that the environmental problems associated with tailings impoundments are not considered in isolation but holistically.

The system for the evaluation of the life cycle of tailings impoundments with particular emphasis on post-closure land use can be used to:

- inform the stakeholders in the planning stage to consider alternative configurations;
- assist with decision making;
- provide a platform for constructive discussion with relevant authorities; and
- facilitate transparent liaison with stakeholders.

Regulators, proponents, environmental practitioners, and engineering consultants can use the system to understand better what the implications are of alternative configurations such as flattening tailings impoundment embankment side slopes and changing cover types.

Through a process of elimination the following key environmental issues that influence tailings impoundment design are:

- visual aspects;
- air quality aspects; and
- water aspects.

This study combines and integrates these environmental aspects with engineering costs.

It was recognized early on in the research that a complete model could contain a number of aspects currently not included such as heritage, tourism and the living environment. The exclusion of environmental aspects does not mean that they are in any way less important. Also, the time period for the life cycle considered in the quantification of environmental impacts and engineering costs is for a period from the start of tailings impoundment design up to 20 years after closure. Had a full set of aspects with more indicators been considered over a longer post-closure period some of the conclusions may have been different. However, the view was taken that initially only key aspects will be included and modelled for a 20 year post-closure period with the aim of creating a robust system demonstrating its efficacy.

Some of the input parameters in the system are not definitive and require conservative value judgements to be applied. Future research can refine the predictive models by initiating longer term monitoring programs. Even though there are uncertainties pertaining to some of the parameters used in the study it can be stated that the approach developed and described in this thesis presents a complex problem in such a manner as to make it more useful for rational decision making.

This study demonstrates that real costs can be ascribed to environmental impacts and that these can be added to the direct engineering cost to produce a total cost model. It is from this that rational decisions can be made. For example alternative tailings impoundment configurations and post-closure land uses are compared through the valuation of environmental change which assists to identify critical aspects determining the sustainability of the proposed land use.

Although there are many challenges to the process of estimating values, this study identifies and discusses the requirements to valuate visual, air, and water impacts associated with tailings impoundments. It is recommended that the environmental impact and engineering costing system should be used to inform decision making involving the rehabilitation of existing as well as new tailings impoundments.

Key words in alphabetical order:
Air quality, configuration, decision making, environmental impacts, environmental costs, engineering costs, environmental impact and engineering cost system, integration, land use, post-closure land use, sulphate mass flux, tailings impoundment, upstream deposited ring-dyke tailings impoundments, valuation, visual perception distances, water quality.

Samevatting

Die ontginning van Suid-Afrika se goud-, platinum- en onedele metaalhulpbronne het tot honderde mynoorskotafsetsels (MOA's) aanleiding gegee, waarvan die oppervlaktes groot landsgebiede bedek. Metaalhoudende myne produseer groot hoeveelhede fynkorrelrige afval en daar word geraam dat slegs in Gauteng ongeveer 12 000 ha grond deur 150 MOA's gesteriliseer word (Figuur Ex 1, p. b).

Die wegdoening van mynreste - hoofsaaklik uitskot - kan deur middel van veranderings in die visuele landskap, die afname in luggehalte, en die degradasie van die waterbronne 'n impak op groot landsgebiede hê. MOA's is veral vatbaar vir erosie, wat langtermyn wind- en waterbesoedeling veroorsaak. Mynoorskot kan sulfiedminerale bevat wat tydens verwering tot 'n reeks besoedelende stowwe aanleiding gee, veral waar daar onvoldoende potensiaal vir neutralisering bestaan. Radionukliedes word ook in dreinering wat met sommige MOA's gepaard gaan, aangetref.

Die kwantitatiewe voorspelling en integrasie van hierdie impakte is moeilik, en duur om te bestuur en te remedieer.

Die nalatenskap van impakte wat met MOA's verbind word veroorsaak ná sluiting veral in die lang termyn 'n al hoe meer ingewikkelde regulerende stelsel. Goedkeuring vir die opgradering van ou fasiliteite, vir die ontwikkeling van nuwe fasiliteite, en vir sluitingsplanne is moeilik om te verkry weens die gebrek aan 'n geskikte raamwerk waarbinne besluite geneem kan word. Aangesien die doeltreffende ontwikkeling van die Suid-Afrikaanse mynsektor noodsaaklik is, solank 'n balans met 'n aanvaarbare vlak van omgewingsrisiko gehandhaaf word, is dit noodsaaklik om stelsels te ontwikkel wat deursigtige en doeltreffende besluitneming vergemaklik. Die huidige stand van sake wat voorspelling en versagting van skade betref is nog nie voldoende ontwikkel om veral reguleerders in staat te stel om slikdamskemas te evalueer en te bekragtig nie.

Die navorsing wat deur hierdie studie voorgelê word is multidissiplinêr. Dit integreer inligting uit 'n reeks vakgebiede, waarvan verskeie deur analitiese strukture en versperrings geskei word. Die resultate van spesialisstudies word normaalweg aan dié binne die dissipline oorgedra, en selde aan spesialiste in ander dissiplines, en nog meer selde aan insethouers buite die beplanning- en ontwerpspan. Hierdie studie beskryf 'n stelsel om verskillende omgewingsimpakte en ingenieursontwerpaspekte te integreer, met die doel om die resultate op 'n rasionele en verstaanbare manier voor te lê.

Die navorsing pas beginsels van geintegreerde omgewingsbeplanning en -ontwerp op die ontwerp van slikdamme toe. Die resultaat is 'n geïntegreerde omgewingsimpak- en ingenieursonkostestelsel wat gebruik kan word om tipiese stroomop gedeponeerde ringdyk slikdamme te konfigureer. 'n Teoretiese ekologiese en volhoubare filosofiese benadering is aangeneem en gebruik om omgewingsimpakte krities te evalueer, te takseer en te ontleed, en om oplossings te formuleer vir die nasluitingsgrondgebruik van slikdamme.

Die navorsing is vernuwend omdat dit slikdamme vanuit die oogpunt van landskapargitektuur beskou en ook omdat dit die beginsel van visuele impakte op ‘n nuwe manier bekendstel. In wese moet daar ‘n klemverskuiwing plaasvind vanaf die ontwerp en bedryf van ‘n opdamming om uitskot vir ‘n periode van 20 jaar te bevat, na die ontwerp van ‘n mensgemaakte landvorm in die landskap waar die konfigurasie en grondgebruik aan die einde van die leeftyd daarvan reeds vóór konstruksie oorweeg word. Generiese modelle vir die omgewingsimpakte en ingenieursonkoste dwarsdeur die lewensiklus van ‘n slikdam word beskryf, sodat die ontwerp van die begin af ten opsigte van die omgewingsimpakte en onkoste geoptimaliseer kan word.

Die navorsing steun op die gebruik van modelle en eksperimentele werk. Dit was ‘n uitdaging om ‘n stelsel te ontwikkel wat ‘n werklike situasie sou weerspieël. Daar bestaan onsekerheid ten opsigte van die gedetailleerde prosesse wat die omgewings- en ingenieursaspekte beheer en tot hulle bydra. Onsekerhede word by die voorspellings ingelyf deur ‘n sistematiese en rasionele benadering te volg. ‘n Stelselbenadering verseker dat die omgewingsprobleme wat met slikdamme gepaard gaan nie in afsondering nie, maar eerder holisties oorweeg word.

Die stelsel vir die beoordeling van die lewensiklus van slikdamme met besondere klem op nasluitingsgrondgebruik, kan aangewend word om:

- insethouers reeds in die beplanningstadium aan te moedig om alternatiewe konfigurasies te oorweeg;
- besluitneming te vergemaklik;
- ‘n podium te bied vir opbouende besprekings met die betrokke owerhede; en
- deursigtige skakeling met insethouers te vergemaklik.

Reguleerders, voorstanders en konsultante kan die stelsel gebruik om die implikasies van alternatiewe konfigurasies, soos die afplatting van die kantwalle van slikdamme en die verandering van bedekkingstipes, beter te verstaan.

Deur middel van uitskakeling is die volgende belangrike omgewingskwessies wat die ontwerp van slikdamme beïnvloed, vasgestel:

- visuele aspekte;
- luggehalte-aspekte; en
- wateraspekte.

Hierdie studie kombineer en integreer hierdie omgewingsaspekte met ingenieursonkoste.

Reeds vroeg in die navorsing het dit duidelik geword dat ‘n volledige model verskeie aspekte wat tans nie ingesluit is nie, soos erfenis, toerisme en die lewende omgewing, sou kon bevat. Die uitsluiting van omgewingsaspekte beteken nie dat hulle enigsins minder belangrik is nie. Die uitgangspunt was egter dat slegs sleutelaspekte ingesluit sou word, met die doel om ‘n kragtige, doeltreffende stelsel te skep.

Sommige invoerparameters in die stelsel is nie finaal nie en vereis dat konserwatiewe waardebepalings toegepas word. Toekomstige navorsing kan die voorspellingsmodelle verfyn deur langtermyn moniteringsprogramme in te stel. Hoewel daar onsekerhede bestaan wat sommige van die parameters in die studie betref, kan dit gekonstateer word dat die benadering wat in hierdie tesis ontwikkel en beskryf word ‘n ingewikkelde probleem op só ‘n wyse aanbied dat dit rasionele besluitneming

vergemaklik. Hoewel die gebruik van die stelsel nie ‘n aanvaarbare uitslag kan waarborg nie, sal dit waarskynlik die konflikte ten opsigte van slikdamkonfigurasie verminder.

Hierdie studie demonstreer dus dat werklike onkoste aan omgewingsimpakte toegeskryf kan word en dat hierdie koste by die direkte ingenieursonkoste gevoeg kan word om ‘n totale kostemodel te produseer. En dit is hieruit waar rasionele besluite geneem kan word. Byvoorbeeld, alternatiewe slikdamkonfigurasies en nasluitingsgrondgebruike word vergelyk deur omgewingsveranderings te evalueer, en dít help om kritieke aspekte ten opsigte van die volhoubaarheid van die voorgestelde grondgebuik te bepaal.

Hoewel daar baie uitdagings bestaan wat waardebepaling betref, identifiseer en bespreek hierdie studie die vereistes wanneer visuele, lug- en waterimpakte wat met slikdamme gepaard gaan, geëvalueer moet word.

Sleutelwoorde in alfabetiese volgorde:
Besluitneming, ingenieursonkoste, integrasie, konfigurasie, luggehalte, nasluitingsgrondgebruik, omgewingsimpakte, omgewingsimpak- en ingenieursonkostestelsel, slikdam, sulfaatmassavloeiing, valuasie, visuele waarnemingsafstande.

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I deeply appreciate the selfless input and assistance of the following persons during the past couple of years, listed in alphabetical order:

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Elizabeth Marsden	(Anglo Platinum)
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John Wates	(Fraser Alexander)
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Pierre Rousseau	(personal capacity)
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The overall system described in this study required specialist input and predictive modelling of various aspects. People who provided input and assistance require acknowledgement and a special word of mention. Hennie Geldenhuys (AngloGold Ashanti) provided background information on the case study site, ERGO Daggafontein tailings impoundment. Permission was also granted to photograph the impoundment as part of the visual perception study.

Mader van den Berg (UP) assisted with the field work and manipulation of the photographs as part of the study to quantify visual perception distances for tailings impoundments. The nominal group technique (NGT) study method was used and required the participation of experts, mentioned in alphabetic order in Appendix A.1, as well as students and academic staff.

The engineering cost model, commissioned as part of this overall study, was developed in collaboration with Caroline Holmes (SRK) (Holmes, 2006). The engineering cost model is based on a system for the costing of environmental mine closure liabilities described by Rademeyer, Jones and Rust (2003). The engineering cost model includes the specific variables required to allow integration with the environmental aspects.

Hanlie Liebenberg-Enslin (Airshed Planning Consultants) provided assistance with the predictive modelling of the air quality impacts (Liebenberg-Enslin, 2006). The roughness height parameter used in the airborne dust dispersion from area sources (ADDAS) model was calibrated as part of this study. This involved field work and required the iterative comparison of predicted results with monitoring data until key parameters were calibrated. The calibrated air quality models used predict the change in dustfall for the various tailings impoundment configurations as part of the overall system requirements. The calibrated models can be used in future to assess the environmental impacts of impoundments with comparable physical tailings properties.

Similarly, the development of the analytical sulphate mass balance model was undertaken in collaboration with Koos Vivier (AGES) as part the input requirement of the overall system (Vivier, 2006).

The following computer software is used:

- ARC/INFO™ geographic information system software is used to spatially represent visual perception influence zones.
- Airborne dust dispersion from area sources (ADDAS) software is used to calculate particulate emission rates. The United States Environmental Protection Agency (US EPA) approved industrial source complex short term (ISCST) Breeze Version 3 dispersion modelling software is used to compute spatial ambient particulate concentrations. Air quality results are mapped as isopleths using Surfer Version 7.
- Both the engineering cost model and analytical sulphate mass balance model uses Microsoft Office™ EXCEL 2003 spreadsheets to analyse information and perform calculations.
- Maps are compiled using ARC/INFO™ geographic information systems software, Corel Draw 12™, Corel Photopaint 12™, and MapSource Version 6,8,0.
- All other text, tables and graphs in the thesis uses the Microsoft Office™ 2003 Suite.

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