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Investigation of factors governing the stability of stope panels in hard rock mines in order to define a suitable design methodology for shallow mining operations

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A dissertation submitted to the Faculty of Engineering, Built Environment and Information Technology of the University of Pretoria, in partial fulfilment of the requirements for the degree of Master of Engineering (Mining)

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Ondersoek van faktore wat die stabiliteit bepaal van afboupanele in harderots myne om sodoende ‘n gepaste ontwerp metodologie te definieër vir vlak mynbou operasies

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Dissertation summary

Investigation of factors governing the stability of stope panels in hard rock mines in order to define a suitable design methodology for shallow mining operations

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Instability in stope panels in shallow mines manifests itself as rockfalls from the hangingwall. Rockfalls from unstable stope panels vary in size from rockfalls between support units, to rockfalls spanning between pillars or solid abutments, to rockfalls bridging several panels and pillars. A suitable and reliable design methodology for stable stope panels at shallow depths is therefore required. This methodology must consider all manifestations of instability in stope panels and take account of the factors governing the stability.

Very few mines design stope panels according to a systematic design procedure or methodology. Rock mass characterisation, estimation of rock mass properties, identification of potential failure modes, appropriate stability analyses and other elements of the rock engineering design process are often neglected. Instead, panel lengths are often dictated by the equipment in use and by previous experience under similar conditions. Consequently, unplanned stope panel collapses occur on most near-surface and shallow mines. Although these incidents often occur during blasting, they pose a major threat to the safety of underground workers and the economic extraction of orebodies. Hence, a rock engineering design methodology for the design of stable stope panels between pillars is of vital importance for optimum safety and production in shallow mining operations.

Using the proposed design methodology, rock mechanics practitioners and mine planners should be able to identify and quantify the critical factors influencing the stability of stope panels. The critical factors should then be used as input to the design of stable stope panels that will provide the necessary safe environment for underground personnel working in stopes.

It is concluded that the design of stable stope panels should be a **process** of defining the means of creating stable stope panels for the safety of underground workers and optimum extraction of the orebody. Therefore, a method is required whereby all rock properties, their variability, and an understanding of all rock mechanisms affecting the stability of stope spans are used as a fundamental base. A procedure for identifying the mechanisms and rock properties relevant to the

specific problem is then required. In this way, existing knowledge should be used in an optimal way to design site specific stable stope spans.

Hence, it is proposed that the design methodology for stable stope panels is a process consisting of the following steps:

1. Define objective.
2. Rock mass characterisation.
3. Estimation of in situ rock mass properties.
4. Consider an “ideal” stope panel.
5. Identification of potential failure modes.
6. Stability analyses.
7. Identify all significant hazards and assess the significant risks.
8. Geometric optimisation.
9. Determination of support requirements.
10. Design of support.
11. Evaluation.
12. Recommendation and implementation.
13. Monitoring of excavation and support behaviour to validate design and permit modifications.

Samevatting van verhandeling

Ondersoek van faktore wat die stabiliteit/onstabiliteit bepaal van afboupanele in harderots myne om sodoende ‘n gepaste ontwerp metodologie te definieër vir vlak mynbou operasies

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Sleutelterme: stabiliteit, afboupanele, ontwerp metodologie, harderots myne, vlak mynbou operasies

Onstabiliteit in afboupanele in vlak myne manifesteer as rotsstorings vanaf die hangwal. Rotsstortings weens onstabiele afboupanele varieër in grote vanaf rotsstorings tussen bestuttings eenhede, tot rotsstorings tussen pilare, tot rotsstorings oor verskeie panele en pilare. ‘n Geskikte en betroubare ontwerpmetodologie vir stabiele afboupanele op vlak dieptes word dus benodig. Sodanige metodologie moet alle manifestasies van onstabiliteit in afboupanele oorweeg en moet ook oorweging skenk aan die faktore wat stabiliteit/onstabiliteit beheer.

Baie min myne ontwerp afboupanele volgens ‘n sistematiese ontwerp prosedure of metodologie. Rotsmassa karakteriseering, skatting van rotsmassa eienskappe, identifikasie van potensiële swigtingsmeganismes, toepaslike stabiliteits analises en ander elemente van die rots ingenieurswese ontwerp proses word dikwels nagelaat. Instede daarvan word paneellengtes dikwels dikteer deur die toerusting ingebruik en deur vorige ondervinding onder soortgelyke omstandighede. Gevolglik vind onbeplande ineenstorting van afboupanele plaas in meeste vlak myne en myne naby die oppervlakte. Alhoewel hierdie insidente dikwels plaasvind gedurende skiettyd, hou dit groot gevaar in vir die veiligheid van ondergrondse werkers en die ekonomiese ekstraksie van ertsliggame. ‘n Rots ingenieurs ontwerp metodologie vir die ontwerp van stabiele afboupanele tussen pilare is dus van uiterste belang vir optimum veiligheid en produksie in vlak mynbou operasies.

Rotsmeganika praktiseerders en mynbeplanners behoort die kritiese faktore wat die stabiliteit van afboupanele beïnvloed te kan identifiseer en kwantifiseer deur die voorgestelde ontwerp metodologie te gebruik. Die kritiese faktore moet dan gebruik word as inset tot die ontwerp van stabiele afboupanele wat die nodige veilige omgewing vir ondergrondse personeel sal skep.

Die gevolgtrekking word gemaak dat die ontwerp van stabiele afboupanele behoort ‘n proses te wees wat die middele definieer om stabiele afboupanele te skep vir die veiligheid van ondergrondse werkers en optimum ekstraksie van die ertsliggaam. ‘n Metode word dus benodig waardeur alle rotseienskappe en hulle veranderlikheid, en verstaan van alle rots meganismes wat die stabiliteit van afboupanele affekteer

gebruik word as ‘n fundamentele basis. ‘n Prosedure vir die identifiseering van relevante meganismes en rots eienskappe word dan benodig. Bestaande kennis behoort op hierdie manier optimaal gebruik te word vir die ontwerp van plek spesifieke stabiele afboupanele.

Die volgende proses word voorgestel as ontwerp metodologie vir stabiele afboupanele:

1. Definieër die doelwit van die ontwerp.
2. Rotsmassa karakterisering.
3. Skatting van die in situ rotsmassa eienskappe.
4. Beskou ‘n “ideale” afbouplek.
5. Identifikasie van potensiële swigtings modes.
6. Stabiliteits analiese.
7. Identifikasie van belangrike gevare en beskouing van belangrike risiko’s.
8. Geometriese optimeering.
9. Bepaling van bestuttings benodigthede.
10. Ontwerp van bestutting.
11. Evaluering.
12. Aanbeveling en implementering.
13. Monitering van uitgrawing en gedrag van bestutting om ontwerp te bevestig en om modifikasies toe te laat.

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Glossary of abbreviations, symbols and terms

Abbreviations

AGS	Australian Geomechanics Society
BL	buckling limit
cm	centimetre
DRMS	design rock mass strength
ESR	excavation support ratio
ECPD	Engineers' Council for Professional Development
FF	fracture frequency
FOG	fall of ground
FOS	factor of safety
FTA	fault tree analysis
GSI	Geological Strength Index
HR	hydraulic radius
IRS	intact rock strength
JC	joint condition
JRC	joint roughness coefficient
L	length
LGA	local geotechnical area
m	metre
mm	millimetre
MBR	Modified Basic *RMR* system
MN	meganewton
MPa	megapascal
MRMR	Mining Rock Mass Rating
NATM	New Austrian Tunnelling Method
NGI	Norwegian Geotechnical Institute
RCR	rock condition rating
RGA	regional geotechnical area

RMR	rock mass rating
RMR_{89}	Bieniawski's rock mass rating (1989)
RMS	rock mass strength
RQD	rock quality designation
RSR	rock structure rating
SAMRASS	South African Mines Reportable Accident Statistics System
SG	specific gravity
SI	stability index
SIMRAC	Safety in Mines Research Advisory Committee
SRF	stress reduction factor
TOL	tolerance
UCS	uniaxial compressive strength
UTS	uniaxial tensile strength
WRAC	workplace risk assessment and control

Symbols

A, B and C	parameters used to describe RSR, RMS and N'
C	cohesion
D_e	equivalent dimension
d_2	thickness of foliated rock mass column
E	Young's modulus
E_M	rock mass modulus
f_m	the maximum horizontal stress in a Voussoir beam
f_m'	the smallest calculated value of f_m in a Voussoir beam
f_{av}	the average horizontal stress in a Voussoir beam
f(x)	the equation for the horizontal reaction force locus in a Voussoir beam
g	gravitational acceleration (9,81 m/s^2)
I_y	moment of inertia of the cross section of a rectangular beam of unit width

J1	primary joint set
J2	secondary joint set
J_a	joint alteration number
J_n	joint set number
J_r	joint roughness number
J_v	the volumetric joint count or the sum of the number of joints per unit length for all joint sets
J_w	joint water reduction factor
k	$\sigma_h : \sigma_v$
m	Hoek-Brown material constant
m_i	Hoek-Brown rock mass parameter for intact rock
m_b	Hoek-Brown rock mass parameter *m* for rock mass
m_r	Hoek-Brown rock mass parameter for residual strength
M	the moment generated at the abutment due to the vertical loading on the beam
M_w	the moment generated at the abutment
M(x)	the load on the beam at *x*
N	rock mass number (Goel *et al* , 1996), or the ratio of true to effective beam thickness
N'	modified stability number
N_{min}	the lowest value of *N* for which solution possible is
N_{max}	the highest value of *N* for which solution possible is
N'	value of *N* associated with smallest calculated value of f_m
NX	size core = 54,7 mm diameter
Q	Barton's rock quality index
Q'	Modified rock quality index
q	load per unit width of beam (N/m^2)
s	Hoek-Brown material constant
s_r	Hoek-Brown rock mass parameter for residual strength
S	span
S_1, S_2, S_3	mean joint spacings for major joint sets
T	beam thickness

$V(x)$	the shear force acting on the beam at x
W	total load acting on beam, or shear force
$W(x)$	load distribution on the beam
w_1, w_2	uniform loads on beam (force/unit length)
Z	the moment lever arm after deflection
Z'	value of Z associated with smallest calculated value of f_m
Z_o	the moment lever arm before deflection
Z_o'	value of Z_0 associated with smallest calculated value of f_m
σ_h	horizontal stress component
σ_v	vertical stress component
σ_n	normal stress
σ_1	major principal stress
σ_m	maximum horizontal stress due to the vertical beam loading
σ_2	intermediate principal stress
σ_3	minor principal stress
σ_c	uniaxial compressive strength of the *intact* rock
σ_T	uniaxial tensile strength
σ_{cr}	UCS for intact rock
σ_z	vertical stress, or fibre stress, or axial stress
σ_y	horizontal stress
σ_b	buckling stress
ρ	rock density
ν	Poisson's ratio
ε	strain
γ	unit or specific weight
δ	midspan deflection
η	deflection
η_{max}	maximum deflection
ϕ	angle of internal friction
ϕ_b	basic friction angle of joint surface
μ	coefficient of friction
τ	shear stress acting on stope

τ_{xy}	shear stress acting on transverse section through beam
ϕ	friction angle
$\tau_{e\ top}$	the shear stress acting on the top of the beam as a function of the position x
$\tau_{e\ bottom}$	the shear stress acting on the bottom of the beam as a function of the position x

Terminology

anchor

The means by which a device is secured to the host rock.

beam

Is a structure supported at one or more points and subjected to external forces.

capacity

Is the strength or resisting force of the structure.

coefficient of friction

A constant of proportionality, μ, relating the normal stress and the corresponding critical shear stress at which sliding starts between two surfaces.

cohesion

The shear resistance at zero normal stress, or intrinsic shear strength of the material.

compression failure

Normal forces exceeding the compressive strength of the material.

compressive stress

Normal stress tending to shorten the body in the direction in which it acts

consequence

The degree of harm, the potential severity of the injuries or ill health, and/or the number of people potentially affected.

convergence

The reduction of the distance between two parallel surfaces, usually the hangingwall and footwall. It is similar to closure, but technically referring to the elastic component of closure.

demand

Is the stress or disturbing force in a structure.

dowel

A full contact, non-pretensioned device. (This term is often reserved for non-steel tendons such as wood or fibreglass.)

empirical

Relying or based on practical experience without reference to scientific principles.

failure

The condition in which the maximum strength of the material is exceeded or when the stress or strain requirement of a specific design is exceeded.

fall of ground

Fall of a rock fragment or a portion of fractured rock mass without the simultaneous occurrence of a seismic event.

fault tree technique

Is a systematic method for acquiring information about a system. The information so gained can be used in decision making. It can also be defined as a deductive failure analysis which focuses on one particular undesired event and which provides a method for determining causes of this event. The undesired event constitutes the top event in a fault tree diagram and generally consists of a complete or catastrophic failure. Careful choice of the top event is important to the success of the analysis.

field stresses

The stresses which exist in a rock mass before an excavation is made. At a distance sufficiently far away from any underground excavation, the field stresses will be equal to the virgin stress.

geotechnical parameters

The parameters describing the technical response of geological materials.

hazard, cause, fault, threat

Something which has the potential to cause harm e.g. hangingwall, methods of work, etc.

instability

Rock can strain, yield, deteriorate and ultimately disintegrate under the influence of stress, gravity and vibration. Instability and failure can be defined as any limiting point in this progress.

keyblock

A block that can be removed from a rock face without breaking intact rock.

method

Special form of procedure, or the orderly arrangement of ideas.

methodology

The science of method, or a body of methods used in a particular branch of activity.

near-surface mining

Mining at depths less than 100 m below surface.

outcrop

The exposure of the bedrock at ground surface.

pillar workings

Underground excavations separated by rock left in situ during the mining process to support the local hangingwall, roof, or to provide regional stability to the mine or portion thereof.

plane stress

A triaxial stress field with one of the principal stresses, e.g. $\sigma_z = 0$ and $\tau_{zx} = \tau_{zy} = 0$ is defined as the condition of plane stress.

Poisson's ratio

The ratio of shortening in the transverse direction to elongation in the direction of an applied tensile force in a body.

primary or top faults

The primary categories in which the hazards to safety and health will be considered.

principal stress

A unique set or sets of unique directions mutualy perpedicular to each other in which all the shear stress components are zero. The normal components of stress acting along these directions are called the principal stresses.

probability

Is the objective measure of the likelihood of occurrence of random events (variable) and as such provides quantitative assessments of system adequacy. If an experiment can result in any one of N different equally likely outcomes, and if exactly n of these outcomes correspond to event A, then the probability (P) of event A is: $P(A)=n/N$. Also, $0 \leq P(A) \leq 1$.

risk

Is the product of the probability of occurrence of a hazard and the effect or magnitude of the damage that would be caused by the hazard.

rock mass

Rock as it occurs *in situ*, including its structural discontinuities.

rock structure

The nature and distribution of structural features within the rock mass.

rockbolt

A steel rod placed in a hole drilled in rock for the purpose of reinforcing rock in the periphery of an excavation. One end of the rod is firmly anchored in the hole by means of a mechanical device and/or grout, and the threaded projecting end is equiped with a nut and plate which bears against the rock surface. The rod can be pretensioned.

roofbolt

A general term encompassing rockbolts, dowels and friction rock stabilisers.

shallow mining

Mining at depths less than 1000 m below surface.

shear failure

Failure in shear when the forces parallel to a plane exceeds the strength of the material in that direction

span

Diameter of largest circle which can be drawn between pillars and walls.

stability

See definition of instability.

topography

Natural or artificial surface features of a district.

virgin stress

Also known as the primary state of stress. It is the stress in the rock mass before it is disturbed by man-made works.

Young's modulus

Modulus of elasticity, *E*.