THE IMPORTANCE OF ENGINEERING DESIGN WITH REGARD TO SAFETY IN MINING

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Abstract

Mining has the reputation of being an unsafe industry. The business aim of a mining operation must be to achieve the planned production safely at the planned rate and the planned costs, to provide the planned return on the investment made. All mining excavations and operations should be planned and designed to achieve this aim in the high risk conditions, and good design of all mining components is critical. Design requirements, design methods and design criteria for mechanical and electrical components are usually clearly defined. However, this is not the case for mining excavations, and many are temporary or have a short term life. Temporary mining excavations cannot be conservatively designed since this will impact negatively on profitability, and design approaches to reduce the risk and ensure safe and effective operation become critical.

In this paper the importance to safe working conditions of a thorough ten-step design process is described, and it is emphasised that a design is not complete until monitoring has proved that behaviour is as planned and according to the design. Since risk is an integral part of mining, “acceptable risk” becomes a necessary and significant consideration in any mining project or operation. The concept of risk as an engineering design criterion is introduced and it is suggested that quantified risk, defined by mining company management and executives, provides a basis for rational engineering design. Only once acceptable levels of risk have been defined (there may be numerous risks considered - financial, moral, empirical, or other), can the design, which must take into account measures such as operations, monitoring and management, be carried out to satisfy these levels of risk. This approach matches well with a structured engineering design process and strategic planning considerations. Failure of a designed component in a mine, such as a rock fall or a conveyance, represents a failure of the design. This design must then be reviewed and revised to prevent a recurrence of the failure. Hence safety can only be ensured by an appropriate and structured design process.

1 INTRODUCTION

Mining is an unusual business in which the mining company hardly ever has any control over the price of the product that it produces, the price being determined by market forces. After a feasibility study has been completed and the decision is taken to go ahead with the mining operation, the final design, construction and implementation before the full scale planned production is achieved may take many years – 10 to 20 years for a major operation. During this time the product price has much opportunity to change, up or down. During mining the product price may also be considered to be
dynamic. These are the very high financial risk conditions under which the planning and design of mining operations must be carried out. In addition, however, mining has a poor safety record, and hence serious safety risks must also be addressed in the mine design. For these reasons, design is a very important issue in mining.

In reviewing the engineering design process, Bieniawski (1991, 1992) quotes the definition of engineering design from ABET (1987): “Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation. In addition, sociological, economic, aesthetic, legal and ethical considerations need to be included in the design process.”

If there is a key point that can be identified in this definition, it is that the design must “meet a stated objective”. This implies that a mining company should have stated design objectives as a component of its operating policy. One such policy that is often repeated is that of “zero tolerance” as far as safety is concerned. The safety record in South African mines is proof that this policy is not being satisfied. This may be regarded as an ethical issue, and it is noted that this appears in the definition of the design process given above. According to Schinzinger and Martin (2000), ethics in engineering design are directly associated with safety.

It is important to note that, as stated by Wong (2005), “Nothing can be 100% reliable and safe”, and “human beings, one day, will invariably make a mistake.” There is always some possibility or probability that a failure, accident or fatality will occur. The data in Figure 1 show that there is a probability of loss of life associated with even the most mundane activities, for example, drinking tap water.

Zero tolerance is therefore an admirable aim, but is idealistic and unrealistic. A more practical approach is to implement measures that result in reliability and safety that are at acceptably high levels. One of the measures is thorough design, to ensure that all likely hazards have been satisfactorily addressed.

2 A THOROUGH DESIGN PROCESS

Engineering design usually involves the development of a “solution” (the design) to a known “problem”. There is no unique solution, and different engineers will produce different solutions – some solutions will work better than others, but all solutions should “work”. The reason that solutions are not unique is probably because of the very wide scope of the issues involved in design.

The key input to design is required in the early stages of planning a project as indicated in Figure 2. This is when the key thinking, and most important decision making, take place. These provide the groundwork in the definition of the requirements for the design. It is well accepted that front end loading of projects is essential if they are to meet their desired performance objectives.
Satisfactory engineering design involves a design process. According to Hill (1983), as discussed by Bieniawski (1988), the design process is “a sequence of events within which the design develops logically, and a process that provides a work plan in the planning of a design programme”. Bieniawski (1991, 1992) defined the following series of design principles that encompass a design methodology.
Design principle 1: Clarity of design objectives and functional requirements. A statement of the “problem” and a statement of the design objectives, taking account of any constraints that are present, to satisfy this problem, is essential to any design process. These statements clarify the design thinking at the outset. If this is not done, different engineers may interpret the problem differently and hence may design solutions for different problems.

Design principle 2: Minimum uncertainty of geological conditions. The rock masses and conditions in which mining takes place are very variable. Mine design therefore take place in an environment of considerable uncertainty. In mining, designs are often carried out with inadequate knowledge. Minimization of uncertainty by suitable investigation of conditions will provide an environment in which more confident design can be carried out, and hence will reduce risk.

Design principle 3: Simplicity of design components. In terms of the Simplicity Principle, a design should be broken down into a series of simpler components. It is suggested here that the principle should be viewed in addition in its broadest context – simpler designs, design methods and design analyses are easier to understand and are therefore likely to be more robust. Where there is a simple way, it is to be preferred to a complex or sophisticated way, provided that it addresses the design requirements. An important step in engineering design is to develop a design model. This may be conceptual, but it is important to be able to describe the likely behaviour and the possible mechanisms of deformation and failure. Only once this has been done can appropriate design (failure) criteria be decided on, design limits be defined, required factors of safety or probabilities of failure be defined, a design model (or models) be
developed, and appropriate design analysis methods be decided upon. This will ensure that the design is appropriate, and as simple as possible.

**Design principle 4: State of the art practice.** The implication of this principle is that up to date concepts, analyses and methods must be used whenever they are appropriate.

**Design principle 5: Optimization.** Risk involves numerous factors including safety, cost, productivity, seismicity, water, labour, etc. Therefore, to minimize risk, designs must be optimized. In addition, since conditions in which mining is taking place (economic, political, price, depth, seismicity, geology, etc) change over time, it is likely that designs will need to be optimized again when conditions change. An optimized design will result from the evaluation of the outputs of alternative designs. Monitoring during the progress of mining will provide data that may facilitate design optimization.

**Design principle 6: Constructability.** If the design cannot be implemented safely and efficiently it does not satisfy this principle and therefore is also not optimized. In such cases it will be necessary to review the design and repeat, either partially or completely, the design methodology.

A design methodology or process corresponding with the above design principles is summarized in the ten steps given below (Bieniawski, 1991; 1992).

Step 1: Statement of the problem (performance objectives) [Design principle 1]
Step 2: Functional requirements and constraints (design variables and design issues) [Design principle 1]
Step 3: Collection of information (site characterization, properties and parameters, boundary conditions) [Design principle 2]
Step 4: Concept formulation (model) [Design principle 3]
Step 5: Analysis of solution components (analytical, numerical, empirical, observational methods) [Design principles 3 and 4]
Step 6: Synthesis and specifications for alternative solutions (eg shapes, sizes, locations, orientations of excavations) [Design principles 3 and 4]
Step 7: Evaluation (performance assessment) [Design principle 5]
Step 8: Optimization (performance assessment) [Design principle 5]
Step 9: Recommendation [Design principle 6]
Step 10: Implementation (efficient excavation, and monitoring) [Design principle 6]

This methodology represents a thorough design process and can be used as a checklist to ensure that a robust and defensible design has been carried out. There is often a misconception that analysis is design, and many sophisticated analyses, with little underlying validity in terms of input data and failure criteria, are often carried out. Analysis is science, whereas design is engineering. It may be observed from the above steps that “analysis”, which involves analytical (including numerical), empirical and observational methods, occupies only one step of the overall design methodology, and is bridged by design principles 3 and 4. Analysis is only a tool to obtain answers to the problem that has been posed. If the input information is inadequate, and the concept or model (including the interpretation of mechanisms of behaviour and choice of appropriate failure or design criteria) is incorrectly formulated, the answers obtained
from the analysis may be scientifically correct, but will be wrong with regard to a valid design. That is, the sophisticated analysis has provided results for the wrong problem.

Independent review during the design process provides a very important control on the quality of the design being carried out. Such an activity should be both informal and formal and could take place at various stages, depending on the magnitude of the design project. For a large project, a formal review would typically take place at regular time intervals, such as twice a year; for smaller projects, the review could be done at appropriate stages rather than on a regular time basis. The aim of the review is to ensure, independently, that the design is robust and that the design objectives are being addressed. If any shortcoming is identified in the design, it will be necessary to loop back to an earlier step in the process and reassess the design.

The engineering design process can logically be represented as a circular process, as shown in Figure 3.

![Engineering circle or wheel of design (Stacey, 2005)](image)

This circular format draws from the similarity with the strategic planning process introduced by Ilbury and Sunter (2005) and demonstrates the very close correlation between the processes of logical strategic planning and thorough engineering design.
As indicated above, review and monitoring are very important inputs to the design process, which can result in looping back to earlier steps in the process – this looping back is represented by the “spokes” of the wheel in the circular process. Logically, therefore, implementation (excavation and construction), the final step of the engineering design process, which includes review and monitoring, should be positioned at the centre of the circle of design. Review and monitoring are extremely important aspects of design since they allow design shortcomings to be detected at the earliest possible stage, and also allow validation of the design. Review should take place at every step, as indicated by the spokes, to ensure that the stated objectives of the design, defined in Step 1, are being satisfied at each step. If the design objectives are not being satisfied, it is necessary to revert to earlier steps in the process to correct the situation. As shown in Figure 3, the engineering design process can be divided into two phases: defining the design (the very important front end loading part), and executing the design (the implementation of the design at various levels of detail). It is in the first phase, defining the design, that most value is created (see Figure 2). Front end loading determines, to a very great extent, whether a project will be successful or not in returning the performance expected, on time and on budget.

Minimisation of uncertainty involves investigation to provide input data for engineering design. In mining it is common that design information is lacking due to a reluctance to spend money on obtaining such data. As stated by Wong (2005), “Reliability cannot be predicted without statistical data; when no data are available the odds are unknown.” Generally the greater the uncertainty, the greater the risk. This emphasises the importance of step 3 of the process in generating value for the mining project.

In summary, the above design process can serve as a checklist of activities that must be carried out to ensure that a robust and defensible design results. Diligent application of this defined process or methodology is a form of quality control and will ensure that all aspects that should be taken into account in the design, are taken into account.

3 STATED OBJECTIVES OF DESIGN

To achieve a satisfactory design, it is critical to know the objectives of the design. In a safety context, an aim will clearly be to avoid injuries and fatalities. However, this is an unquantified aim, which is not satisfactory as a design objective, since it is impossible to design something that is 100% reliable and safe. Therefore, from an engineering design point of view, what percentage reliability is acceptable – 99%, 95%, 90%, etc? It has been suggested that quantified risk should be used as a rock engineering design criterion (Stacey et al, 2007), and Steffen (1997) and Steffen and Terbrugge (2004) have planned and designed rock slopes on the basis of risk. A quantified risk provides the engineer with a tangible basis for design. Stating a quantified risk will require mining management and mining company directors to commit themselves and their company to an “acceptable risk”, which could be a statement in their company policy document. This is appropriate since it is the function of company executives and management of any company to be aware of and decide on the levels of risks they can tolerate for that company. As indicated by Martin and Schinzinger (1983), ethics and risk are linked, and the identification of risks is the first
step: “Thus, for engineers, assessing risk is a complex matter. First, the risks connected to a project or product must be identified. This requires foreseeing both intended and unintended interactions between individuals or groups and machines and systems. Second, the purposes of the project or product must be identified and ranked in importance. Third, the costs of reducing risks must be estimated. Fourth, the costs must be weighed against both organisational goals (e.g., profit, reputation for quality, avoiding lawsuits) and degrees of acceptability of risks to clients and the public. Fifth, the project or product must be tested and then either carried out or manufactured.”

There is nothing new in the consideration of acceptable risk. Eurocode 7 (Eurocode7, 1997), dealing with geotechnical design in civil engineering, includes a requirement for a statement on the level of acceptable risks: “the assumptions, data, calculations and results of the verification of safety and serviceability shall be recorded in a Geotechnical Design Report. The level of detail of Geotechnical Design Reports will vary greatly, depending on the type of design. For simple designs, a single sheet may be sufficient. The report should normally include the following items, with cross-referencing to the Ground Investigation Report and to other documents which contain more detail:

A description of the site and surroundings.
A description of the ground conditions.
A description of the proposed construction, including actions.
Design values of soil and rock properties, including justification, as appropriate.
Statements on the codes and standards applied.
Statements of the level of acceptable risks.
Geotechnical design calculations and drawings.
A note of items to be checked during construction or requiring maintenance or monitoring.
The Geotechnical Design Report shall include a plan of supervision and monitoring, as appropriate. Items which require checking during construction or which require maintenance after construction shall be clearly identified in the report. When the required checks have been carried out during construction, they shall be recorded in an addendum to the report.

The suitability of the construction procedures and the sequence of operations shall be reviewed against the ground conditions which are encountered and the predicted behaviour of the structure shall be compared with the observed performance. The design shall be assessed on the basis of the results of the inspection and control. If necessary, the structure shall be redesigned.
It shall be checked that the principles used in design are appropriate for the geotechnical features of the ground which are encountered.”
This extensive quote has been included here to illustrate the detail that is required in a thorough design. It can be seen that the requirements in this code match very well with the ten step design process described above.

Whilst a decision on an acceptable financial risk may be relatively easy, quantifying an acceptable risk of an injury or a fatality is much more emotional. However, such risks are dealt with routinely in the insurance industry, and the consideration of probability of loss of life is standard practice in the design of large dams and nuclear power plants.

The stated objectives defined in terms of acceptable risk will determine the extent of work involved in the following steps of the design process. For example, in an entry mining method, prediction of the occurrence of rock falls will be essential, and therefore detailed information on the rock mass will be necessary to allow appropriate design of support. Investigations of the rock mass and considerations of rock mass stability, rock mass behaviour, mechanisms of failure, and stability and support design analyses are likely to be detailed and extensive. If, however, the mining method is a non-entry method, the probability of loss of life in the stope is zero, and much less detailed investigation and analysis may be acceptable – the risk is that of loss of, or damage to, equipment. Wong (2005) states, “Making things safe and reliable costs money. Engineers will always need to cost the price of failure for comparison.” It is the latter part of this statement that is important. If the cost of failure (direct costs, costs of rehabilitation, lost production, loss of ore, etc) is significant, value may be created by spending the money necessary to ensure safety and reliability. Cost cutting as a method of improving profitability is common in the mining industry, and may be effective over the short term, but in the longer term often results in the destruction of value. It is to be noted that there can be many combinations of measures to control risk (eg, extent of investigation data, amount of monitoring, mining method, mechanisation, remote operation, automation, etc). Therefore, large uncertainty in design input data may be countered by conservative design and extensive monitoring to achieve the required level of risk. Alternatively, detailed input data and design with only limited monitoring may achieve the same level of risk. The important result of the design must be to achieve the desired acceptable risk at the best value, ie the best long term cost.

4 AN EXAMPLE OF CAVERN EXCAVATION AND SUPPORT

Before dealing with a real example, consider the following hypothetical situation: a mine manager’s house has a carport which was designed and constructed in the 1950’s when cars were smaller and narrower. However, mining times have been good and the manager has a Hummer, which is a very tight fit in the carport. After golf one Saturday, the manager returns home with less care than usual and, on entering the carport, knocks down one of the support poles, the roof collapses and the vehicle is damaged. The mine personnel rehabilitate the carport using the original design. As can be expected, the same thing happens regularly weeks and months later. Would the manager be happy to allow this situation to continue? What are the options to reduce the risk? The following could be considered:

- Do not park the Hummer in the carport (ie, a non-entry system, so that there is no risk of damage and injury).
• Replace the Hummer with a Smart (ie, use different equipment, such as mechanisation of an operation).
• Change the design of the carport. There are several options: place the support poles wider apart to facilitate entry (ie, change the support design - change prop spacings); redesign the roof structure so that it is stable in the event of loss of one support pole (ie, change the support design - areal support to the hangingwall to ensure stability if a prop is knocked out); design a carport with a suspended roof, without multiple support poles (ie, change the support design - use rockbolt support for the hangingwall).
• Do not park in the carport after golf and other meetings (ie, reduce the number of personnel in the hazardous situation).
• Make sure that no substances that could impair mental concentration are consumed before parking the vehicle (ie, prevent personnel affected by alcohol and drugs from entering the mine).

This analogy is not intended to be facetious, but to emphasise that a bad or inappropriate design must be changed, or that, if a hazardous condition exists, actions must be taken to reduce the risks posed by that hazard. If an accident occurs due to failure of some component, then this is an indication that the design of the component is faulty and should at least be reviewed. If the design does not work (the occurrence of an accident proves that it is not satisfactory), then it must be reviewed and changed, or other measures put in place to avoid a repeat accident. All of the options identified above are part of the design.

Now for the real example. In the mining industry, failures are rarely documented satisfactorily since apportionment of blame may be undesirable to many individuals involved. This lack of documentation of failures is unfortunate since it means that underlying causes of problems are not identified, which is to the longer term detriment of the industry. Failures are the best source of learning for future engineering improvement. The example that follows, the excavation and support of caverns, comes from the civil engineering industry. In this industry, projects are almost always completed by contractors appointed in terms of a contract, and disputes often arise in such contracts. The resolution of the disputes usually involves detailed analysis of “what went wrong” and the dispute is settled in terms of the procedures defined in the contract. In the example to be presented briefly below, the dispute went to arbitration, but, part of the way through the arbitration, was settled by mediation. The results of a mediation remain confidential and the conclusions given below are therefore a personal interpretation.

The project involved the excavation of a series of liquefied petroleum gas storage caverns as shown in Figure 4, each with a span of 14m and a height of 11m, at a depth of about 150m below a harbour.
During the excavation of the caverns a large rock fall occurred, involving about 180 tonnes of rock. About two weeks after this major rock fall a second significant rock fall, about 20 tonnes, occurred and the behaviour represented a major safety risk. Consequently, the works inspector closed the operation until the designers could satisfy him that the rock support design would ensure stability and safety. The result was that there was a two month delay to the project as the support was redesigned, and the new support specified involved about four times as much steel as the original support. The additional support and activities, including claims for delays and other factors, approximately doubled the cost of the project and substantially increased the construction duration, delaying the planned inception of the facility.

During preparation for the arbitration, the activities involved in the designer’s investigation and design were reviewed thoroughly. A good site investigation was carried out under the direction of the designers. This identified the importance of crossbed surfaces in the rock, which could provide problems for roof stability. There was abundant local knowledge of the rock mass in which construction was to take place, and a relevant large underground excavation was under construction at the time of the cavern design. The design of the support for this excavation had been published, and its construction was available for a visit and inspection at the time of the cavern design. There were many relevant exposures of rock in cuttings that could be inspected. High horizontal stresses were known to exist, and “popping” had been reported in basement excavations and tunnels in the rock mass. The conclusion is that there was a large amount of information available as input into the cavern design.

The design was reviewed independently by local consultants for parties that might be affected such as local authorities. The following are quotes from some of these reviews: “... significant zones could exist around the caverns where ... the strength
criteria ... for the rock mass are exceeded”; “... stress induced spalling [expected] to occur 50% to 60% of the time”; “... a significant risk of rock wedges in the range of 18T to 200T” occurring “in the crown and shoulders of the cavern”; “... the geological model appears to be too simplistic and probably incorrect, particularly in terms of the geological structures”. These review comments could have been expected to prompt the designers to carry out a review of their support design. However, this was not done before the contract commenced.

During excavation, before the main rock falls occurred, a small rock fall caused damage to equipment and another represented a near miss as far as an accident was concerned. Popping/spitting from rock surfaces due to stress was also experienced.

The review of the design process involved shows that it was significantly flawed (the relevant steps of the design process in Figure 3):

- The site investigation provided good information and warnings regarding stability, which were not heeded (step 3).
- No use was made of the abundant expertise available regarding the rock type involved, nor of the abundant rock exposures in the area, nor of the cavern under construction at the time (step 3).
- Mechanisms of behaviour were not interpreted satisfactorily, ie the engineering model for design was not satisfactory. The direct implication of this was that the design criteria were not appropriate (step 4).
- Many analyses were carried out, but these tended to be more in the form of interesting scientific analyses rather than targeted engineering analyses from which design decisions could be made (steps 5 to 8).
- Perhaps most importantly, review of design was not carried out at all as a result of numerous occurrences, indicating a serious lack of monitoring feedback (spokes of the wheel of design). The review comments referred to above should have led to some design review (many of the predictions in the reviews actually occurred subsequently). The initial small rock falls, and similarly the popping and spitting experienced, should have led to a review of the adequacy of the rock support (step 10).

The conclusion of the dispute was very costly to the designers. The example is an illustration of a significant breakdown in the application of a logical design process, which resulted in an inadequate design and potentially in very unsafe conditions.

5 CONCLUSIONS

Design involves a process that starts with a clear statement of the objectives of the design and ends with the monitoring of behaviour to confirm that the design is valid and meets the stated objectives. Failure of a designed component in a mine is an indication of failure of the engineering design, which often results in unsafe situations. Therefore, when a failure occurs, to ensure that the mine will be safe in the future, it is essential that the design is reviewed and corrected to prevent a recurrence of the failure. The
diligent application of the ten step design process described in this paper will ensure that a robust design has been carried out. The definition of the stated design objective is essential, and it is suggested that the mining management and executives should quantify this in terms of the risk that is acceptable to them. These stated acceptable risks will then serve as quantified criteria for rational engineering design.

The repeated occurrence of failures in the mining industry, for example, the frequent rock falls and associated accidents, represents a failure of design. The design should be reviewed after each failure and revised to correct the deficiency in the design and ensure that safe conditions are achieved. The continued occurrence of rock fall accidents proves that the support designs, monitoring and operating procedures are unsatisfactory and require revision to ensure safety in the mines. The use of quantified risk as an engineering design criterion as part of a thorough design process should promote much more rational design, which should, in turn, result in much safer mines.

REFERENCES


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