Design—a strategic issue

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Synopsis

A set of six design principles for rock engineering was developed by Bieniawski: design objectives; minimum uncertainty; simplicity of design components; state-of-the-art practice; optimization; and constructability. These principles translate into a ten-step design process. Although this methodology was developed for rock engineering, it is applicable to any design process, feasibility study, etc. Diligent use of such a process will ensure that a defensible design or evaluation has been carried out. Recently a 'strategic conversation' process has been identified by Ilbury and Sunter that includes the following ten steps: scope; players; rules of the game; key uncertainties; scenarios; SWOT analysis; options; decisions; measurable outcomes; and meaning of winning. A comparison of these steps with those of the design process shows a remarkable correlation. This is perhaps not surprising since engineering design is a strategic up-front issue, and front end loading in a project is critical to achieve the expected project performance. Based on the close correlation between the strategic conversation and engineering design processes, a circular design process, rather than a linear process, is proposed. The 'circle of design' better reflects the importance of review and monitoring in the two phases of successful design and implementation—defining the design, and executing the design.

Introduction

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. 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.'

It is unlikely that anyone would dispute that engineering design is a strategic issue. A satisfactory design is fundamental to the expected performance of the engineering structure. For example, satisfactory design of a mine shaft involves many aspects including siting, shaft pillar if appropriate, rock support, lining, steelwork, hoist design, etc. If any one of these aspects is unsatisfactory, the mine is unlikely to perform to its required production capacity.

The key input to design is required in the early stages of planning a project. 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. Front end loading, and therefore also design, are part of the strategy.

The design process and the strategic planning process

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'. A defined process can serve as a checklist of activities that must be carried out to ensure that a satisfactory design

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results. The defined process or methodology can be considered as a form of quality control, which ensures that all aspects that should be taken into account in the design, are taken into account.

According to Ilbury and Sunter (2005) 'strategy is about where you are going and tactics is how you get there', and they introduce a process which they term a strategic conversation.

The design and strategic conversation processes will be dealt with in the following sections.

Design principles in rock engineering

Bieniawski (1991, 1992) dealt specifically with engineering design in the rock mechanics field. He defined a series of design principles that encompass a design methodology. Although Bieniawski developed these for rock engineering, they are applicable in principle to any form of engineering or investigation. The design principles defined by Bieniawski are summarized below.

- *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 in which mining takes place are very variable, which is true of any natural material. Rock engineering and mine design therefore take place in an environment of considerable uncertainty. In mining, which is almost always tightly cost controlled, there is usually an aversion to spending money on geotechnical investigations, with the result that geological conditions are often unknown or, at best, little known. In many mines, designs are carried out with inadequate knowledge of the *in situ* stresses, the rock material strengths and deformation properties, and the rock mass behavioural conditions.

  The minimization of uncertainty will provide an environment in which more confident design can be carried out, and hence will reduce risk. The remaining uncertainty must be taken into account in the design method, for example, by using a probability of failure approach.
- *Design principle 3: Simplicity of design components*—Designers often rush into carrying out complicated analyses using sophisticated analysis methods. These methods often require input data, knowledge of which is very uncertain. There is therefore a mismatch between the sophistication of the method of analysis and the lack of sophistication of the input data available. The use of sophisticated analysis methods often leads to the false confidence that a good design analysis has been carried out. Bieniawski indicates that, 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 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 rock engineering design is to develop a geotechnical model. This may be conceptual, but it is important to be able to describe the likely behaviour of the rock mass 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. It is to be noted that these steps are carried out before any analyses are conducted. 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 integrally 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, mineral 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 output from alternative designs. Monitoring during the progress of mining will provide data that may facilitate design optimization.
- *Design principle 6: Constructibility*—If the design cannot be implemented safely and efficiently it does not satisfy this principle and therefore is also not optimized. It will be necessary to review the design and repeat, either partially or completely, the design methodology.

Design methodology or process

The design methodology presented by Bieniawski (1991, 1992), corresponding with the above six design principles, is summarized in the ten steps given below.

- Step 1—Statement of the problem (performance objectives) [Design principle 1]
- Step 2—Functional requirements and constraints (design variable and design issues) [Design principle 1]
- Step 3—Collection of information (site characterization, rock properties, groundwater, *in situ* stresses) [Design principle 2]
- Step 4—Concept formulation (geotechnical 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 (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 geotechnical 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 a valid design. That is, the sophisticated analysis has provided results for the wrong problem. This illustrates that the other steps in the design methodology are in fact much more important than the analysis step—they are fundamental to a successful design, whereas the analysis simply follows from these other steps.

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 a formal one that could take place at various stages, depending on the magnitude of the design project. For a large project, the 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.

Monitoring is an extremely important aspect of design. It could range from being purely visual to the use of sophisticated instrumentation. One of the main aims of such monitoring should be to check whether the mechanism of behaviour of the designed structure or opening is as expected and whether the design criteria used were appropriate, i.e. to determine that the design is valid. If the behaviour and/or criteria are not as expected then it will be necessary to loop back to an earlier step in the process and reassess the design. It may even be necessary to carry out a completely new design. The sooner that monitoring information or data can be obtained the better, since costly errors and consequences will then have the best chance of being avoided.

Strategic planning process, and discussion

Ilbury and Sunter (2005) have recently published a book on strategic planning, *Games foxes play—planning for extraordinary times*. In this book they describe a strategic planning process that they term a 'strategic conversation'. They propose the following ten-step process in their 'strategic conversation'.

- Step1—Scope of the game
- Step 2—The players
- Step 3—Rules of the game
- Step 4—Key uncertainties
- Step 5—Scenarios
- Step 6—SWOT analysis
- Step 7—Options
- Step 8—Decisions
- Step 9—Measurable outcomes
- Step 10—The meaning of winning.

What is remarkable about this process is its uncanny correspondence with Bieniawski's engineering design process. A comparison of the two processes is summarized in Table I below.

Since design is a strategic issue, the correspondence is perhaps not surprising. However, such direct correspondence has not been observed with other strategic planning approaches.

Ilbury and Sunter (2005) consider that 'circles of conversation' are most effective, since they avoid the linear approach commonly adopted in strategic planning sessions in which dominant individuals may drive the process in the direction that they favour—'When the strategic conversation is circular, it flows like a current through the heads of all the people sitting around the table, creating its own field of alignment.' Their conversation model is expressed in the form of a circular chart, shown in Figure 1.

After viewing this circular process approach, it is considered that the engineering design process should similarly and logically be represented as a circular process, as

Table I

Comparison of design and strategic conversation processes

Design process	Strategic conversation process
Statement of the problem	Scope
Requirements and constraints	Players
	Rules of the game
Collection of information (minimization of uncertainty)	Key uncertainties
Concept formulation	Scenarios
Design analysis	SWOT analysis
Alternatives	Options
Evaluation optimization	Decisions
Recommendation	Measurable outcomes
Implementation (construction, excavation)	Meaning of winning

shown in Figure 2. Review and monitoring are important inputs to the design process, which can result in looping back to an earlier step in the process—this looping back would form the 'spokes' of the wheel in a circular process. Again, the similarity with the strategic conversation process is remarkable. Ilbury and Sunter (2005) state, '… the direction of the process is circular, i.e. a conclusion reached later on in the conversation can lead to a review of earlier material'. 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 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 1, the strategic conversation process is divided into two phases: defining the game (the real strategic part) and playing the game (the implementation or more tactical part), with five steps of the process in each phase. Similarly, 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). In this case, the first phase will contain four steps and the second six steps, as shown in Figure 2. The first phase, 'defining the design', represents the extremely important front end loading phase of projects, during which most value is created. 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 budget.

The strategic conversation approach allows issues for potential action (IPAs) to be noted and addressed at an appropriate time during the process (Ilbury and Sunter, 2005). Similarly in engineering design, design IPAs arise, and these can be addressed much more easily if the thinking in the design process is circular, with the review and monitoring function centred at the hub of the circle of design.

Figure 1—The conversation model (Ilbury and Sunter, 2005; Chart 7)

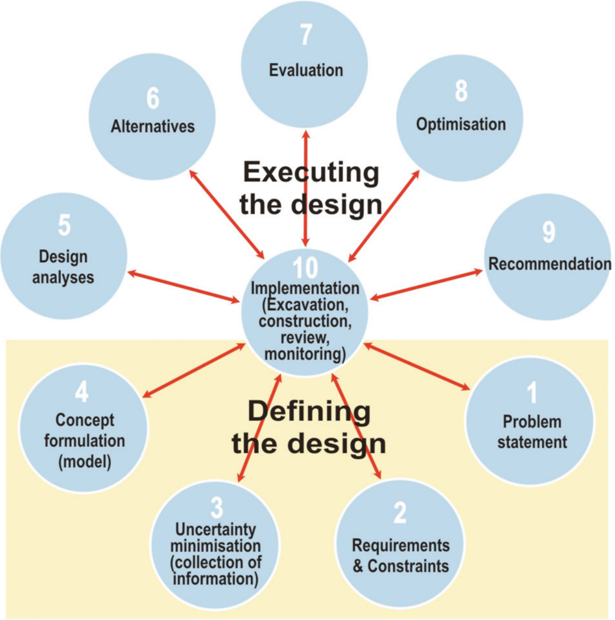

Figure 2—The engineering circle or wheel of design

Strategic and design considerations for vertical pit mining

As a small-scale example of some strategic conversation and design considerations, the unique case of vertical pit mining is considered in this section.

Redford and Terbrugge (2000) describe the mining of a small, shallow orebody at Inyala Mine in Zimbabwe by means of a vertical pit. This project is appropriate to use as an example in this paper since it was the first time that this mining method had been used (therefore requiring strategic considerations) and there were critical design aspects involved (therefore requiring the application of a thorough design process).

Vertical pit mining is applicable for the mining of relatively small orebodies with vertical geometries, such as small diamond pipes. It avoids a large amount of waste stripping, and removal of ore and transporting of equipment and materials is by means of a crane or other device. At Inyala Mine a Blondin cable hoist was used.

Redford and Terbrugge (2000) describe the project as follows: 'Anglo American Corporation Services Limited (AAC), acting on behalf of Zimbabwe Alloys Limited (Zimalloys), called for tenders for conventional open pit mining by contractors of the Inyala Mine 'Airfield Block' …

The pit was designed … on geotechnical information available at the time …. sidewall slopes adopted were 58° in the …. gneiss rock footwall, and 45° in the …. siliceous serpentinite conditions elsewhere. …

‘The pit operations were planned to exploit two chromitite ore lenses, each approximately 30 m long by 9 m wide, with a waste middling of some 10 m, at an apparent dip of 80°. Pit production comprised 155 000 t, with 2 500 000 bcm waste …

‘In parallel with the conforming bid preparation, an alternative proposal was developed and priced, adopting the vertical pit principle. Based on the geotechnical information provided, the proposal envisaged an oval shaft, with plan dimensions of 41 m and 32 m…. such a shaft would recover an estimated 147 000 t of chromitite ore to a mining depth of 95 m, together with a further 25 000 t of low-grade material… Shaft sidewalls would be supported by means of a combination of 300 kN, 10 m long cable anchors, rockbolts, mesh and mesh-reinforced shotcrete….. A budget cost of …$4.8 million was quoted for the alternative, almost half that of the lowest conventional bid submitted.’

Additional drilling was subsequently carried out, which showed poorer rock qualities and a greater orebody footprint. Sidewall support costs increased substantially because of the weaker rock mass conditions. The contractor was appointed and the vertical pit was mined successfully to a depth of 78 m. The reduction in the price of chromitite ore was the reason that the mine did not progress to the planned depth of 95 m.

Strategic conversation approach

In this project, the strategic conversation steps could have been considered as follows.

- *Step 1: Scope*—A small asset to be mined using an appropriate mining method. How does this match with the mining company’s stated objectives, policies, etc.?
- *Step 2: Players*—Mining companies, contractor, designer, existing miners/employees and dependants, the local population, the broader population, the government. These would include players for, against and neutral.
- *Step 3: Rules of the game*—Safety, environmental acceptability, laws, contracts, economic factors, required return on investment, production and profit targets, etc. These include the normative or moral rules of the game, the descriptive rules and the aspirational rules (Ilbury and Sunter, 2005).
- *Step 4: Key uncertainties*—Orebody definition, chrome price, geotechnical information (particularly in the waste rock), mining method, social, environmental and technical issues, quality control performance, government policies, tax, politics, etc.
- *Step 5: Scenarios*—The mining scenarios are open pit mining, vertical pit mining, underground mining, and no mining.
- *Step 6: SWOT analysis*—A SWOT list, as suggested by Ilbury and Sunter (2005) can be prepared as in Table II. It is probable that many more points could be included in such an analysis.
- *Step 7: Options*—From the SWOT analysis, one might choose only two options: – open pit mining and vertical pit mining. Underground mining was probably never a significant option.
- *Step 8: Decisions*—The tenders received for conventional open pit mining (Redford and Terbrugge, 2000) showed that conventional open pit mining of the deposit was not economic. There were also additional risk factors, indicated as threats in the SWOT analysis, that could have made the conventional pit even less economic. Vertical pit mining was therefore the only possibility. The decision-making process at this stage, on the part of the owner, should normally involve a risk analysis.
- *Step 9: Measureable outcomes*—Milestones, production targets, costs, profit, meeting defined key performance indicators, ‘satisfaction’.
- *Step 10: Meaning of winning:*
  - – All stakeholders satisfied?
  - – Owner: return on investment.
  - – Contractor: technical satisfaction and satisfactory profit.
  - – Designer: design proven, satisfactory income.

Table II

SWOT analysis

Scenario	Strengths	Weaknesses	Opportunities	Threats
Open pit	Established method Understood Flexibility – e.g., production capacity easily increased, pit design can change	High stripping ratio Large surface area affected Limited design options for small pit	‘Conventional’	Slope failure Waste stripping increase Increased pit limits Dilution
Vertical pit	Established in civil engineering (basements) Selective mining Reduced area, and environmental effects Perceived lower cost	New mining method Unproven to depth envisage Limited flexibility—no negative wall angles Limited production capacity	Lower cost Reduced volume of mining Use of civil contractor	Wall collapse Poor quality control Potential loss of mine
Underground	Established approach Probably no surface effects	Infrastructure requirements – shaft etc. Small orebody	Limited	N/A
No mining	No risks	No use of asset	N/A	N/A

- Employees and dependants: employment, income, living standards.
- Local population: income, environment.
- Government: export earnings, tax income, use of national asset.

Circle of design approach

The design process begins once the decision step of the strategic process has been completed. The steps below deal with the geotechnical aspects. There would be similar processes for other aspects such as mining, environmental, etc.

- *Step 1: Problem statement*—Vertical pit mine, depth defined, production rate defined.
- *Step 2: Requirements and constraints*—Walls must be stable; critical to safety, but also, if a failure was to occur, it would probably be uneconomic to continue mining. Quality control of blasting and support installation and monitoring of behaviour are critical to successful mining.
- *Step 3: Uncertainty minimization*—Collection of information to enable the following: definition of rock materials present; definition of rock mass properties; definition of rock mass geotechnical zones; definition of strength properties of rock/rock mass.
- *Step 4: Concept formulation*—Geotechnical model incorporating rock mass zones and their expected strength properties, and the expected behaviour and potential failure mechanisms. Concept of support to ensure stability. Influence of three dimensions. Definition of design criteria, e.g. factors of safety, probabilities of failure, acceptable deformations, acceptable extents of failure, etc. Blasting requirements, timing of support installation, sequencing, etc. Monitoring requirements.
- *Step 5: Design analyses*—Analyses of the geotechnical model or models developed in Step 4, considering the range of material/rock mass properties and alternative support geometries/quantities. Prediction of behaviour and expected deformations, and identification of corresponding monitoring requirements. Identification of critical areas from the analysis results and corresponding specific monitoring requirements. Use of alternative analysis methods.
- *Step 6: Alternatives; and Step 7: Evaluation*—Consideration of the alternatives analysed and evaluation of the results. Decision on acceptability of the extent of analyses carried out.
- *Step 8: Optimization*—Optimization of the outputs obtained from the design analyses and ranking of chosen alternatives.
- *Step 9: Recommendation*—Decision on method and quantity of support, support installation requirements, quality control requirements, stability monitoring requirements, recording and reporting requirements (blasting, construction, inspections, monitoring) etc.
- *Step 10: Implementation (review, monitoring)*—Excavation and production. Monitoring and reporting are critical.

Note that interim review is necessary at all stages, particularly at steps 3, **4**, 6 and 7, and **9**. Highlighted steps are particularly important. If the performance is not as expected from the design analyses, the design must be reviewed at the earliest possible opportunity, since it is not feasible to install additional or different support at higher levels in the pit walls when the pit bottom has progressed downwards.

The activities identified in the ten steps above were essentially what were carried out during the design process for the Inyala Mine vertical pit, and the project proved to be successful, as described by Redford and Terbrugge (2000).

Conclusions

In this paper the engineering design process developed by Bieniawski (1991, 1992) has been compared with the strategic planning approach described by Ilbury and Sunter (2005). In the latter, the ten steps in the strategic conversation process show remarkable correlation with Bieniawski's logical design process. This is perhaps not surprising since engineering design is a strategic up-front issue, and front end loading in a project is critical to achieve the expected project performance.

Based on the close correlation between the strategic conversation and engineering design processes, a circular design process, rather than a linear process, is proposed. The 'circle of design' better reflects the importance of review and monitoring in the two phases of successful design and implementation—defining the design, and executing the design.

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