Risk Management for the Construction of Large-Deep Caverns Facilities at the Deep Underground Science and Engineering Laboratory

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1.0 Introduction:

Physicists conducting large experiments are very familiar with the need to manage risk. Risk is inherent in many technical tasks that routinely constitute a large fraction of a research program. However, at the Deep Underground Science and Engineering Laboratory (DUSEL), where researchers call for the construction of large-span underground space, deep underground, substantial and largely unfamiliar risks are introduced to the project risk registry. The geotechnical factors that give rise to many of these new risks must be well characterized and addressed early in the project cycle if optimal siting and design decisions are to be made and practical solutions identified.

2.0 Deep Underground Science and Engineering Laboratory (DUSEL) Site

2.1 Homestake Mine Setting

The DUSEL is to be sited within the footprint of the old Homestake Mine, Lead, South Dakota, USA, in a series of heavily-folded, meta-sedimentary rock units, consisting primarily of schists, phyllites and amphibolites. These units contain faults, fracture zones and dyke structures. At depth, some fracture zones yielded hot water under pressure, and overstress behaviour related to mining activity was been reported [1]. During the later stages of mining, a seismic monitoring system was installed. This system allowed burst locations to be pin-pointed and supported changes in stoping methods to better predict and control the on-set and limit the adverse effects of burst behavior.

Figure 1: Schematic Cross-Section of the Homestake Gold Mine
The fractured nature of the rock mass and the level of in situ at depth will both play key roles in determining the behavior of the rock mass at DUSEL. Early investigation of local conditions are required in order to identify better ground conditions within the mine volume prior to selecting candidate sites for performing the underground science and engineering experiments.

2.2 Rock Mass Units Accessible from the 4850 Level

Much of the early construction work, including excavation of the larger cavern space, is currently planned to take place on the 4850 level of the DUSEL facility in either the Yates (amphibolites) or Poorman (schist-phyllite) formations. Pending access for site investigation work, early estimates of ground support on this level have been based on rock mass data collected over the life of the mine. Steed and Cavahalo [2] used such data to estimate representative Q-system parameters [3] to quantify the factors of block size, inter-block friction, and active stresses. The three parameters are reported for the Yates and Poorman formations on the 4850 level in Table 1.

Table 1: Preliminary Rock Mass Q Parameters for the Poorman and Yates Formations

<table>
<thead>
<tr>
<th>Q Parameters</th>
<th>Q Factor</th>
<th>Yates</th>
<th>Poorman</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block Size</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RQD</td>
<td>85</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Jn</td>
<td>6</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Inter-block Strength</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jr</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Ja</td>
<td>0.75</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Water Pressure &amp; Rock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength:Stress</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jw</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>SRF</td>
<td>5</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Q-Index</td>
<td>15.1</td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>

The block size (RQD/Jn) and inter-block friction (Jr/Ja) parameters shown in the table were estimated by reference to rock core logs and surface outcrop. A maximum Stress Reduction Factors (SRF) for each rock unit was estimated at the perimeter of excavations based on the use of mine-specific strength and in situ stress measurements. A joint water factor (Jw) of one was adopted as being representative of mine conditions during operation. Dewatering of the 4850 campus level was completed in 2009 and it is anticipated that the rock mass will be fully drained below the base of the 4850 level excavations prior to the start of excavation work.

Figure 2: Cavern in the Yates Formation (Source: Brookhaven National Laboratory)
At the Homestake Mine, the Yates formation lies adjacent to units that bear gold mineralization. Although the Yates unit itself is barren, it does house several mine shaft and tunnel openings. The Yates was also used as the host unit for an earlier neutrino experiment. The cavern within which the experiment was housed is shown in Figure 2. Past experience in the Yates unit largely confirms the preliminary Q-parameter values, as it was reported to have performed well as the host rock mass for the siting of a number of permanent mine excavations.

3.0 Large Caverns for Physics

3.1 The Long Baseline Programme

The international High Energy Physics community is currently charting the course for a new era of experimental physics. In the US, planning spotlights the development of a world class neutrino program. A cornerstone element of this plan is the Long Baseline Neutrino Experiment (LBNE). The geo-engineering scope of this experiment can be succinctly characterized as comprising the construction of new neutrino beamline tunnels and chambers at Fermilab, located near Chicago, Illinois, and "megacavern(s)" at DUSEL. The capital cost for this experiment is estimated to be well in excess of half a billion dollars.

The megacavern(s) will be significantly larger than any previously constructed for physics purposes. The balance of this paper will discuss the DUSEL site and the geo-engineering risks associated with designing and constructing such large caverns at depth underground.

3.1 Design Criteria for Physics Caverns

Many requirements for underground physics are similar to those developed for other end-uses, where there are shared needs for long-term stability and space for access, operations, equipment and infrastructure. However, stricter demands may be imposed in experimental areas to ensure that the enhanced levels of excavation alignment, foundation stability, cleanliness, and water- and climate-control are met to provide for trouble-free installation and operation of the installed experiment. For the most sensitive apparatus, extra demands may be added to reduce background radiation, radon gas concentration and modify ground-motion characteristics.

LBNE detectors, based on the use of water Cherenkov particle detection technology, will add particular engineering demands for span and watertightness. As currently conceived, these detectors will be housed in caverns up to 60-m in span, built at depths of up to 1.5 kilometers. The detector space will need to be equipped with a lining that provides for the containment of large volumes of ultra-pure water over multi-year operating periods. In order to meet strict purity specifications these pools will likely incorporate a reliable composite waterproofing and drainage membrane system. Construction of these facilities at depth, within the confines of an old mine, is likely to prove expensive and risky. The design solution will not only need to meet criteria for stability and watertightness, but also underpin the development of reliable estimates of construction duration, budget and contingency. Firm understandings of cost, time-to-physics and risks are all needed before the affordability of the experiment can be realistically evaluated within the context of a national research budget.

3.2 Past Performance of Water Cherenkov (wC) Detectors in Underground Settings

The large-deep cavern(s) required to house LBNE detectors have combinations of span and depth that are largely unprecedented within the domain of mining and civil engineering. However, larger, free-standing openings have been observed in nature, and mined within the context of block caving operations, and there appears to be no intrinsic reason why such large spans cannot be constructed cost-effectively in the Yates rock unit present on the 4850 Level of the Homestake Mine.
In addition to the excavation challenges of span and depth the engineering team will also need to devise robust design solutions that can achieve the isolation and near-watertight containment of large volumes of ultra-pure water and the protection of Photo-Multiplier Tubes (PMT’s). PMT’s are partially evacuated glass tubes used to observe light emitted from neutrino particle interactions taking place within the body of the water pool. The PMT’s may need protection from water over-pressures phenomena, induced by other near-field DUSEL activities, e.g. blasting.

Figure 3. Irvine-Michigan-Brookhaven (IMB) Detector (Source: University of California, Irvine)

The engineered lining system(s) constructed within the cavern must also provide for the near-watertight containment of the target water mass, and ensure that groundwater cannot infiltrate into the pool during periods of filling, maintenance, drainage or repair. Composite line-drain systems may be required if the target water mass is doped with potential groundwater contaminants. An example of a liner for a rectangular mined excavation is shown in Figure 3.

Figure 4: Super Kamiokande (Super-K) Detector (Source: University of Tokyo)
Figure 4 shows PMT’s mounted around the perimeter of the Superkamiokande (Super-K) water Cherenkov Detector. The Super-K Detector water pool is housed in a steel-lined concrete vessel roughly 40 meters in diameter and 60 m deep. The Super-K detector is located at a depth of over a kilometre in the Kamioka Mine, Japan.

Reference to past experience staging large water Cherenkov experiments such as the two shown in Figures 3 and 4, underlines the need to focus on developing robust solutions that can mitigate against critical failure mechanism. Water Cherenkov detector components have proven highly vulnerable to failure. Specifically, water containment systems have leaked, [4] PMT’s have imploded [5], and support apparatus has been damaged by ground motion [6]. Damage in the two latter instances was attributed to in-pool overpressure and mining-induced seismic activity, respectively. Failures to properly design and install robust water containment systems and protect key pieces of equipment may result in major experiment downtime, high repair costs, and severe disruptions to the overall research programmes. In one of the cases above, lining failure resulted in the termination of an entire research programme. Water leaks and PMT implosions may both be considered high severity risks or showstopper events that should receive focused early attention within the context of the overall design process.

Risk analysis is a critical element of the overall LBNE design and construction process. Integrated plans will need to take into account both the excavation and lining aspects of the structure. The early design tasks and siting decisions necessary to support concept development will need to be guided by feedback from risk analyses and interpretations of site investigation data sets. It is during the conceptual stage of the project that the widest range of optimization options can be explored for a minimal expenditure of resources, to a maximum effect, including the mitigation of risk.

4.0 A Strategy for Early Risk-Guided Mitigation

4.1 Risk Management

As can be surmised from the budget number quoted earlier in the paper, the resources required to build the LBNE facilities at DUSEL will be high and carry significant contingency. DUSEL activities, in general, and LBNE work, in particular, will include a level of risk above and beyond that normally associated with the design and construction of a surface-based project of similar size and complexity.

LBNE construction would consume a major portion of any research agency’s annual budget. In supporting such projects, an agency is effectively placing “many eggs in one basket.” Before funding such projects, an agency will likely require strong, objectively-based reassurance that construction can be completed on time and to budget. Setting realistic values of contingency for cost and schedule that can cover the occurrence of industry-typical and project-specific risk events is key if the project health is to be adequately protected from cost overrun and delay through construction completion.

4.2 Contingencies for the LBNE Caverns

A contingency profile for a typical underground project is shown in stacked histogram form at different stages of development from conceptual design through to construction completion in Figure 5. Contingencies in the figure are allocated to a baseline estimate to cover risks associated with the external approval process and four internal categories of risk that are managed on-project relative to design, estimating, procurement, and construction. For an underground project that is designed and managed by an experienced team, the construction contingency is typically the largest allocated element. As indicated in the figure, construction contingencies associated with ground unknowns are those that remain within the contingency estimate for the longest period of time.
Attention is drawn to the pre-concept phase, where key decisions are made to develop an initial basis-of-design. These upfront decisions will typically support a first estimate of construction cost, time and contingency. It is during concept development when design decisions have the greatest impact on project outcomes. Regrettably, it is all too often the case that at this early point in time resources, in general, and access to expert advice, in particular, are most limited.

Of course, the schematic figure represents an over-simplification of a contingency setting process based on a simple accumulation of risk-categorized contingencies. However, the graphic does underline the positive influence that early geo-engineering and constructability input may have on the project’s risk profile. Such an analysis may help explain why a few dollars more spent on early site investigation, geo-interpretation and constructability may result in major contingency reductions - a common goal for all projects and particularly important for publicly-funded, complex works, for where uncertainties is high and risk tolerance limited.

4.3 Siting and Constructability Considerations

In rock engineering practice, the siting of subsurface structures is often constrained by non-technical requirements, unrelated to ground conditions or construction preferences. Consideration of end-uses, land-ownership, rights-of-way, water and mineral rights, environmental acceptability, and local politics, can all dictate the adoption of less technically-desirable or cost-effective alignments and/or design options. At DUSEL, there are few such constraints and geotechnical and excavation engineers will be afforded opportunities to seek out zones of better ground and sites more conducive to the use of miner-preferred construction options. In addition, although variations in cavern orientation, size, and shape may all impact the performance of the detector, there are options that could potentially represent opportunities to lower cost and reduce risk. A wide range of factors need to be considered before choices in cavern site, alignment, size, shape, and access layouts can be undertaken with confidence, as shown schematically in Figure 6. The trade-offs between detector performance and geo-engineering preferences, shown in the figure, should be objectively performed during the early design period before decisions are made and optimization value lost or reduced.
From a geo-engineering perspective, early attention should be placed on obtaining the site investigation data necessary to characterize the host ground mass and guide decisions on risk reduction. To support risk reduction, the initial phase of site investigation work on the 4850 level of DUSEL has focused on identifying and probing rock volumes in the Yates formation and delineate potential cavern sites that are remote from existing mine workings and geo-structural features (faults, contacts, dykes, fracture zones). Zones of high or low stress adjacent to mine workings and areas of water inflow are also being identified and avoided in what is effectively a process of elimination that will result in the short-listing of a best-qualified cavern site(s).

From an excavation engineer's perspective, attention will also need to be paid to key constructability aspects to make sure that the large caverns can be located in close proximity to other laboratory openings and infrastructure, where costs to support the investigation, construction and operation can be reduced and better shared between DUSEL partners.

5.0 Conclusions

The construction of large caverns at depth adjacent to old mine workings is likely to be expensive and risky. In particular, the construction of the large-deep cavern(s) required to house LBNE detector(s) will place significant demands on the surrounding rock mass and lining structure(s). In particular, the design and construction of water containers that will maintain high levels of water purity and protection against PMT's implosion will be critical to the success of the experiment.

Although good ground conditions are anticipated to be available at locations within the mine project, viability can be greatly enhanced if early attention is paid to the collection of critical pieces of site. This data can help identify critical risks and guide early design decisions.
To be competitive with other research proposals the LBNE design team is focused on an early optimization process that should result in a cost-effective, low risk, fully-integrated mine and line solution.

6.0 References