Physics Considerations of Stresses in the Excavation of Large Chambers for the DUSEL water Cerenkov Detector

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The excavation and construction of the 100 kiloton fiducial volume water Cerenkov detector chambers at the DUSEL – Homestake Laboratory is a major technological and engineering challenge. These chambers will be the largest such excavations at depth done to date. In addition, the expected 40 – 50 year useable lifetime places significant demands on the engineering of these excavations. The intent of this paper is to provide a sense of the scale of this undertaking and provide a basis of comparison with other, existing long occupancy excavations at depth. In it not intended to be an engineering study nor can such a study can reliably carried out before the various rock characteristics are measured.

Physics Stress Considerations

The chamber excavation can be thought of as a domed roof that rests on a vertical cylinder. Both the base of the dome and the cylinder have a radius R. The pressure on the roof from the rock above it is ρgZ, where ρ is the rock density, $g = 9.8$ and Z is the depth below the surface in meters. Since the total horizontal area of the roof is πR^2, the total downward force exerted by the domed roof on the top annular ring of the cylinder is $(\rho gZ)(\pi R^2)$. For stability, the downward force of the domed roof must be opposed by an upward force due to the top of the cylinder. This upward force has a maximum value $2\pi Rt\sigma$, where σ is the compressive strength of the rock and t is the equivalent thickness of the cylinder wall. Of course, the cylinder wall does not have a real thickness. Rather, t is the coherence length of the rock, the distance between joints adjusted for the inclination angle of these joints.

From Eq. 1 $(\rho gZ)(\pi R^2) = 2\pi Rt\sigma$,

we get Eq. 2 $RZ = 2t\sigma/\rho g$.

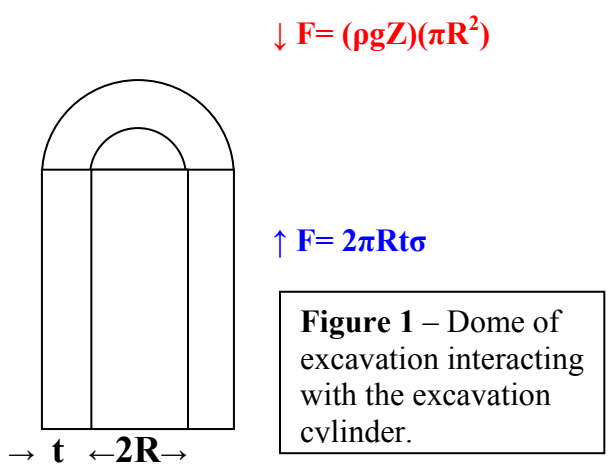

Figure 1 – Dome of excavation interacting with the excavation cylinder.

Detector	Depth (Z)	Radius	RZ
SuperKamiokande	1000 m	20 m	20,000
MegaDetector (DUSEL)	1480 m	27.5 m	40,700
SNO	2092 m	11 m	23,000

Table 1 – The "RZ" of existing large underground detector excavations, Super Kamiokande and SNO compared to the proposed MegaDetector chambers at DUSEL.

From equation 2, it is clear that the critical parameter that defines the stability of an excavation is RZ. The two existing deep underground large detector excavations, SuperKamiokande and SNO, both have RZ ≈ 20,000, see table 1. The proposed large water Cerenkov excavation at DUSEL, has a diameter of 55 meters or R = 27.5 meters and Z = 1480 meters and so RZ = 40,700, about twice that of the two existing detector excavations. This comparison just provides another demonstration that we must be very concerned with the stability of the excavation. Only one of the four parameters on the right side of equation 2, t, is under our control. The density of rock, ρ, is approximately the same at most underground laboratory sites, about 2.9 tonnes/m^3, A single measurement of the unconfined σ of the rock at the proposed DUSEL site for the large water Cerenkov detector, gave σ ≈ 180MPa. The corresponding measured unconfined compressive strength at SuperKamiokande is 149MPa. Clearly, we need additional measurements of σ both for unconfined and confined samples of rock at the proposed chamber excavation sites.

Using σ = 180MPa in the above equation gives t = 3 m. Part of this can be achieved by long and frequent cable bolts and by careful selection of the sites for the proposed excavations. The rest of the required effective t can be obtained from an appropriate internal liner.

Using the above SK σ = 149MPa, we can make a rough guess of the effective t of the rock excavation at the SuperKamiokande excavation. From equation 2, above, we have

Eq.3 "effective t" = $(RZ)\,\rho g/2\sigma = (2 \times 10^4)(2.9 \times 10^3)(9.8)/2(1.49 \times 10^8) \approx 2$ meters

Since the Super Kamiokande excavation has a 0.4 – 0.5 meter thick reinforced inner concrete liner which contributes to the total "effective t", the best we can conclude is that "effective t" of the Superkamiokande rock is greater than (2 – 0.5) or 1.5 meters.

This "effective t" at the Super Kamiokande site is a measure of the rock coherence length of that rock. If we assume that the Homestake rock has a similar coherence length, then, at least 1.5 meters of the required 3 meters is in the rock formation and the remainder must be supplied by the inside liner and by appropriate cable and rock bolting. Since the planned rock studies at Homestake may well reveal rather different rock characteristics,

we should merely use the above discussion and "effective t" values as a guide of how to think about the excavation stability and reinforcement considerations. In this evaluation, we assumed that the intent for the DUSEL excavation was a safety factor as least that at Super Kamiokande.

The above consideration also indicates that if we were to increase the diameter of the excavation, we would have to similarly increase the liner thickness. For example, a 10% increase in chamber diameter, from 55 meters to 60 meters, will increase the required "effective t" by 10% from 3 meters to 3.3 meters. Since the rock only provides an "effective t" of 1.5 meters, the liner thickness increases from 1.5 meter to 1.8 meters. It is worth stressing again that these "guesses" are not construction and reinforcement guides, but rather indications that considerable pre-excavation rock studies are rather important.

Before discussing the specifics of this liner, it is worth thinking about the sequence of events that might occur if there is a failure of the rock support structure. The interior rock wall of the excavation is semi-confined. That is, ¾ of the rock surface is in contact with the adjacent rock and thus is confined, cannot move even if its internal structure is compromised, while ¼ faces the excavation and so is unconfined, can and will move if its internal structure is destroyed. A compressive failure of a section of rock resulting in part of that rock section moving into the excavated space will immediately transfer the downward force of the dome onto the adjacent sections of rock. If the stress of these adjacent sections was already critical or close to critical before this occurrence, then these adjacent sections may become over stressed and collapse leading to a domino effect with a section by section collapse around the periphery of the excavation.

This suggests a second role for the liner, to convert the semi-confined inner rock surface into a fully confined rock structure. Confined rock compressive strength is generally greater that unconfined or semi-confined, so this step effectively increases the value of σ. In addition, by preventing inward motion of the rock, the liner can prevent the domino effect collapse described above. The requirement here is for liner "stiffness", that is, limiting liner deflection under load. This is the same as the stiffness of a beam that supports a loaded floor.

The final point worth mentioning is that this collapse danger exists during the excavation as well as after the excavation is completed. This is particularly critical since the excavation time is quite long, 4 – 5 years. That means that the liner should be installed in a section by section mode as the excavation progresses. We should not wait until the excavation is complete before installing the liner.

LINER ENGINEERING CONSIDERATIONS

From the above discussion, it is important that (1) the excavation liner is installed as the excavation proceeds. The liner (2) is in close contact with the interior rock surface of the excavation and adjust for the irregular nature of that surface. Because the liner will be installed in sections, it (3) must be self-supporting and it (4) must be protected from damage from further blasting end excavation. In addition, if possible, the inner surface of

the liner is smooth and incorporates links that permit attachment of the photomultiplier tube mounts.

There are several ways to construct such a liner. One approach is to use pre-cast sections of concrete that dovetail together in the form of a horizontal arch. This technique is commonly used in tunnel construction. Since there may be irregular gaps between the outer wall of the concrete sections and the rock wall, there will have to be a procedure for filling these gaps with rubble from the excavation as well as sprayed concrete.

A second approach is to construct a form for casting concrete and do a section by section cast of the liner. Once a given section of cast concrete has cured, the form can be lowered for the next section. An advantage of this approach over the one above is that the concrete will fill in the irregular gap between the form and the rock wall and avoid the rubble fill described above. Since the excavation is likely to proceed from top to bottom, the sections of the liner will have to be supported by links to the rock wall, that is, have steel reinforcement rods mounted in holes in the rock and that protrude into the concrete liner region.

One concern is that concrete has a typical curing time constant of about 28 days so that there is a period during which the recently cast concrete will have limited strength. Fortunately, this curing time is comparable to the time required to drill, blast and clear rubble from the next section to be excavated.

A third approach is to install a steel liner on the inside of the excavation and fill the space between this liner and the rock wall with sprayed concrete and rubble. This approach is likely to be considerably more expensive than the cast in place concrete.

A fourth approach is to use fiber reinforced sprayed concrete, shotcrete. This approach is quite similar to the cast in situ approach except for the absence of the form. The form can provide a smooth and continuous inner surface that can then be used in the construction of the water tight liner. There is some concern that the compressive strength of sprayed concrete is not as predictable as that of cast concrete. It is also not clear that except for the cost of the casting form, there is any cost or time advantage in a sprayed concrete liner over a cast in place liner.

Given the unique nature of these excavations, there will be considerable value and interest in installing stress and motion sensors in the rock walls and excavation liner and monitoring these on a continuing basis.