Lessons learned from large failures: multiple causes include adverse design, geology, and support

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Large tunnel and rock cavern spans that have failed for 'geological' reasons, or because of design errors, are the main focus of this presentation. The effect of adverse and sometimes unexplored geology will be illustrated. We will need to recognize that pre-investigations might miss some important detail, despite an exceptional frequency of core drilling. Usually, this is of minor importance and does not mean that failure will occur. Being wise after an event, which is always much easier, one might generally question why cross-hole seismics is not performed more frequently to obtain between-borehole information. Prior to construction, the need for this in a particular, but at that time unknown location, cannot of course be foreseen.

It is apparent that really large failures seldom result from just one or two oversights, but are caused by a multitude of adverse factors working together. Small failures might be caused by designer or contractor short-cuts, or more likely by failure to log 'today's' conditions and react with more support. The really big failures are due to faulty design, and therefore inappropriate support, but sometimes just the multiple effects of some exceptionally adverse and unanticipated 'geology', aided by a remarkably adverse location, preventing the natural and needed arching. All or many of the following represent a rich assortment of possible reasons for failure underground: oversimplified design method assumptions that are erroneous, erroneous details of sub-surface topography, ignored details of surface topography, anisotropic low-strength jointing, the presence of unexpected discontinuities with adverse properties, and finally the use of deformable and weak temporary support like lattice girders.

It seems that a really massive failure may involve about five or more adverse factors. With sufficient factors involved, fatalities may be a regrettable consequence, besides the huge economic losses. Surprisingly, whether or not a tunnel or cavern reaches this point of ultimate collapse might not depend on real-time interpretation of the instrument readings. This is because reaction to a new and exceptional rate of deformation may be too late when too many unknown adverse factors are already combined. A state of 'guaranteed failure' may be reached *despite* instrumentation warnings.

The cavern and tunnel collapses that are generalized in the above paragraphs are specifically from the world of city metro, motorway ring-road tunnels, and hydropower caverns. They will be added to by reference to the largest open-pit slope failure to date, which showed the mechanism of progressive failure and an adverse pit shape, resulting in an absence of large-scale tangential stress. Failure was located in the 'unstressed' nose, and comprised 150 Mt of waste rock and ore. The tunnel and cavern failures include two 140 m tunnel collapses, two 35 000 m^3 progressive cavern collapses, and a 15 000 m^3 total collapse. A relative absence of sufficient tangential stress (arching stress) can be blamed in each case, and if the shear strength or designed support are in question, massive failure may result.

Figure 1. (a) A fatal metro cavern failure due to an undiscovered hidden ridge of rock weighing up to 15 000 t, (b) a motorway tunnel failure due to an over-optimistic symmetric and isotropic design with light lattice girders, but an actual inhomogeneous and anisotropic 'geology', (c) a fatal hydropower cavern collapse due to failure to adjust the support when encountering a fault on the 'left' side of the arch, (d) an adverse 'nose' in the huge open-pit failure that no doubt contributed to the 150 Mt rock avalanche, contrasted with a stable 'circular' pit.

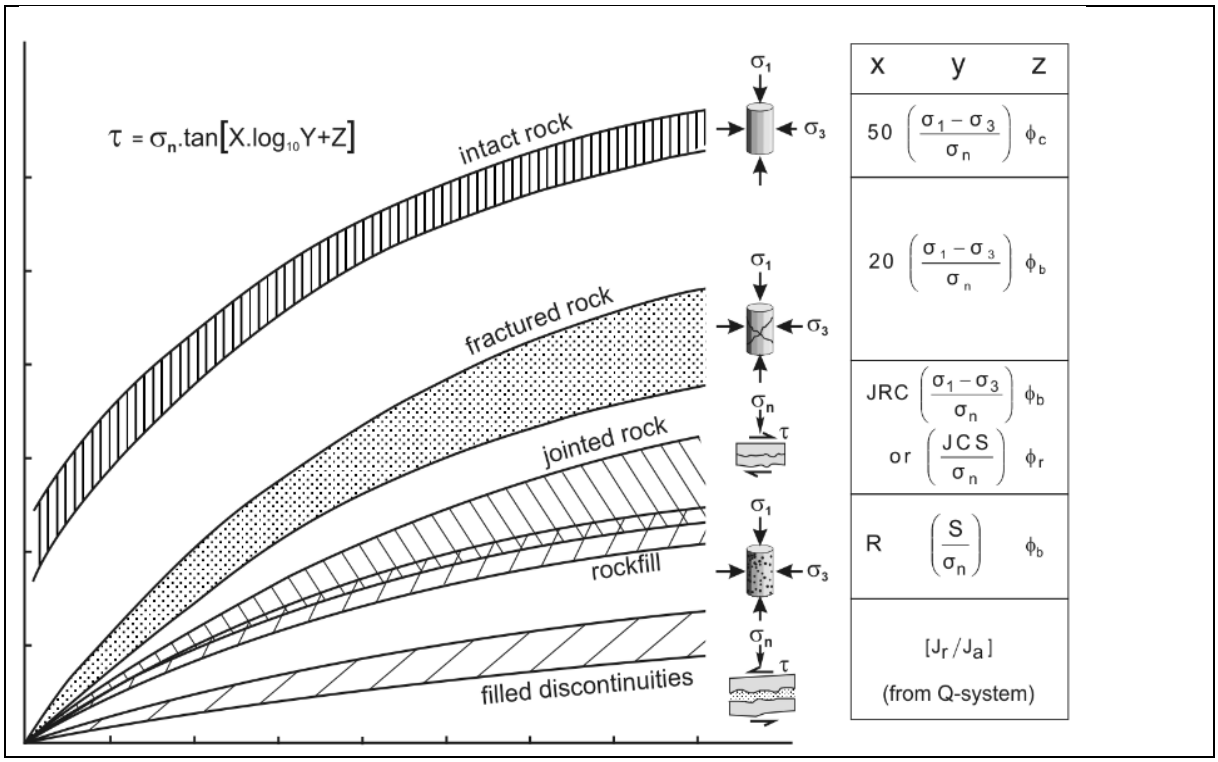

Figure 2. In the four failures shown in Figure 1 it is very likely that the initially resisting shear strength was not in the form of the Mohr-Coulomb relationship $\tau = c + \sigma_n \tan \varphi$, but more likely of the form $\tau = c$ <u>then</u> $\sigma_n \tan \varphi$. The frictional strength φ may need replacing by a nonlinear and effective-stress-dependent frictional strength. Intact bridges fail at small strain, new rough fractures take over the resistance to failure, then the smoother natural joints, and finally the weakest filled discontinuities. Progressive failure is a 'natural' process that needs to be prevented by robust design assumptions: never by isotropic continuum assumptions.

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