## ***Caves and caverns: stability***

***Description:*** Man-made caverns have been constructed for a diverse range of uses. For the purpose of this review, it is convenient to divide them into those designed for short-term access, such as mines, and those designed as long-term structures.

Mines are man-made openings designed for the commercial extraction of minerals. The oldest mines are the Neolithic (2,000 to 4,000 BC) flint mines in the Chalk in England and northern Europe dug to depths of 6 -14 m (Barber & Topping, 1999), some of which still remain open today. Lead and silver were first mined around 1,500 - 2,000 years BC at the Laurion mines in Greece, where shafts were sunk to a depth of 111 m (Shepherd, 1993). Subsequent improvements in pumping methods for removal of water, and increased mechanisation, have led to the sinking of larger and deeper mines. The deepest working mine is currently in the Witwatersrand of South Africa (3.5 km deep), and the deepest in Europe is the 1.4 km deep Outokumpu mine in Finland. However, mines are by definition usually designed to remain open for only a short period during mineral extraction and are then allowed to close naturally. It could be argued therefore that they are not very good analogues of repository openings, which have longer design lifetimes, even though many mines have actually remained open for very long periods.

Other man-made underground openings have been specifically designed for long-term utilisation. Examples of these include tombs, underground cities, road / rail tunnels, hydroelectric schemes, strategic military facilities, underground storage facilities, radioactive waste and astrophysics laboratories etc.

The Egyptians began excavating underground tombs in bedded limestone during the Eighteenth Dynasty (about 1,500 BC). Underground Buddhist temples were excavated into basalt lavas of the Deccan Traps, near Ajanta, India, from the C2$^{nd}$ BC to the C10$^{th}$ AD; at Ellora from the C5$^{th}$ to C10$^{th}$ AD; and at Sittanavasal from the C9$^{th}$ AD. In Cappadocia, Turkey, the underground cities of Kaymakli and Derinkuyu were excavated in a Tertiary rhyolite ash-flow tuff. Derinkuyu has a footprint of ~4 km$^2$ and housed 15,000 to 20,000 inhabitants throughout much of the first millennium AD. North of the underground cities at Goreme, churches were excavated into the same rock unit during the C9$^{th}$ to C13$^{th}$ AD. One of the churches has suffered collapse of the cliff face but otherwise the remaining churches are intact. Ten underground villages are inhabited today in Tunisia, 20-40 km south of Gabes. The largest has a population of 6,000. Some of the villages have been continuously occupied for 900 years (Stuckless, 2000; Simmons, 2002). These domestic and religious structures demonstrate long-term stability of man-made caverns measured in hundreds to thousands of years, but it should be noted that they are all at relatively shallow depths in unsaturated rock.

In 1995 and 1997 UK Nirex Limited undertook a review of long-term man-made caverns at repository depths below the water table (Geo-Engineering, 1995; 1997). A database of 450 long-term man-made caverns, with spans more than 10 m, was compiled. It was recognised as preliminary and incomplete, and excluded most mine caverns, as these are deliberately designed to be short lived. The frequency of these long-term man-made openings showed a sharp reduction with increasing depth, especially below ~500 m (see Figure 1). However, it also clearly showed that there was precedence for long-term man-made caverns at repository depths (300 - 1,000 m).

The Nirex study also considered whether there was precedence for repository-sized openings at appropriate depths. The span (width), length and height of the openings were all considered, but the most relevant was span. With some obvious exceptions there is a tendency for decreasing span with increasing depth. However, even at a depth of 1,000 m, there is precedence for openings with spans of up to ~17 m, which is larger than the dimensions proposed for the vaults in most repository concepts. It should be noted that spans reflect in part the ultimate use of the cavern and not necessarily the maximum span possible. The review of mine openings showed that there was precedence for much larger span openings but that these were not necessarily constructed for long-term use. However, all the long-term man-made caverns considered at repository depths were relatively recent, having been constructed since the 1940s (see Figure 2). Thus, even for these purpose-built, long-term facilities, direct precedence is limited to 60 years.

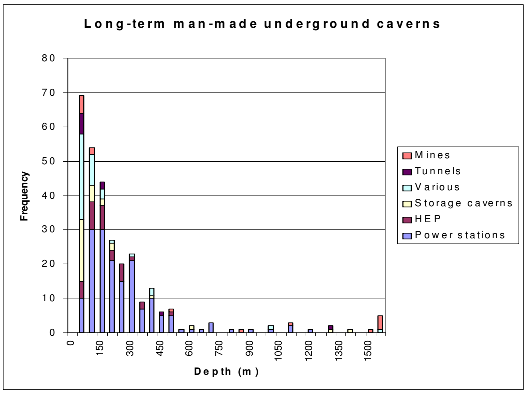


Figure 1: Frequency of long-term, man-made caverns as a function of depth.

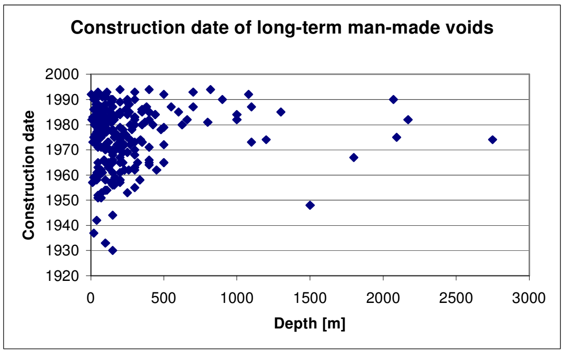


Figure 2: Construction date versus depth.

The Nirex precedence study showed that 90% of human activity in terms of underground construction occurs at less than 500 m depth and this is confirmed by an independent study by JNC of man-made caverns in Japan (JNC, 2000). Repositories constructed below these depths are therefore much less likely to be intercepted by such 'human intrusion'.

In summary, there is ample evidence for relatively shallow man-made caverns lasting for several thousand years. The examples are all in generally strong rock, mostly limestone, basalt and volcanic tuffs, and constructed above the water table. Construction at greater depths is a relatively recent phenomenon and therefore there is less precedence extending back more than a few decades for deep, non-mine, caverns.

***Relevance:*** The study of the stability of man-made caverns is relevant to all repository concepts. It demonstrates that there is precedence for construction of repository-scale caverns at depths considered for repositories in a wide range of rock types. The information is relevant to the stability of the EDZ.

***Position(s) in the matrix tables:*** This study belongs to the NF Rock/EDZ -Barrier Containment/Physical Integrity box of the Near-field matrix table.

***Limitations:*** Most man-made caverns were constructed during mining activities and were not designed for long-term stability. Only in the last 60 years have large underground caverns been constructed with long design lifetimes so that there is relatively little precedence for the long term stability of such caverns. In this context, refer to the parallel study on the Stability of Natural Caverns.

***Quantitative information:*** Quantitative data on cavern size, depth, age and construction methods are available.

***Uncertainties:*** Uncertainties in most of the data used are not stated, but most are generally considered reliable in the current context.

***Time-scale:*** The study is relevant to the human (0 – 100 years) and historical (100 – 1,000 years) time-scales.

***PA/safety case applications:*** None known for the UK. Used in the Yucca Mountain Project by the U.S. DOE.

***Communication applications:*** None known for the UK.

***References:***

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***Added value comments:*** Man-made cavern analogues offer the opportunity to address frequently asked questions from the general public concerning the stability of underground openings. Their main use, therefore, would be in communication.

***Potential follow-up work:*** The information presented here is generic. It would be possible to find particular examples of man-made caverns that more closely match specific repository concepts in terms of rock type, size, depth etc.

***Keywords:*** Man-made caverns, mines, tunnels, bunkers, EDZ stability

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