The Sydney Opera House Underground Parking Station

By P. J. N. Pells

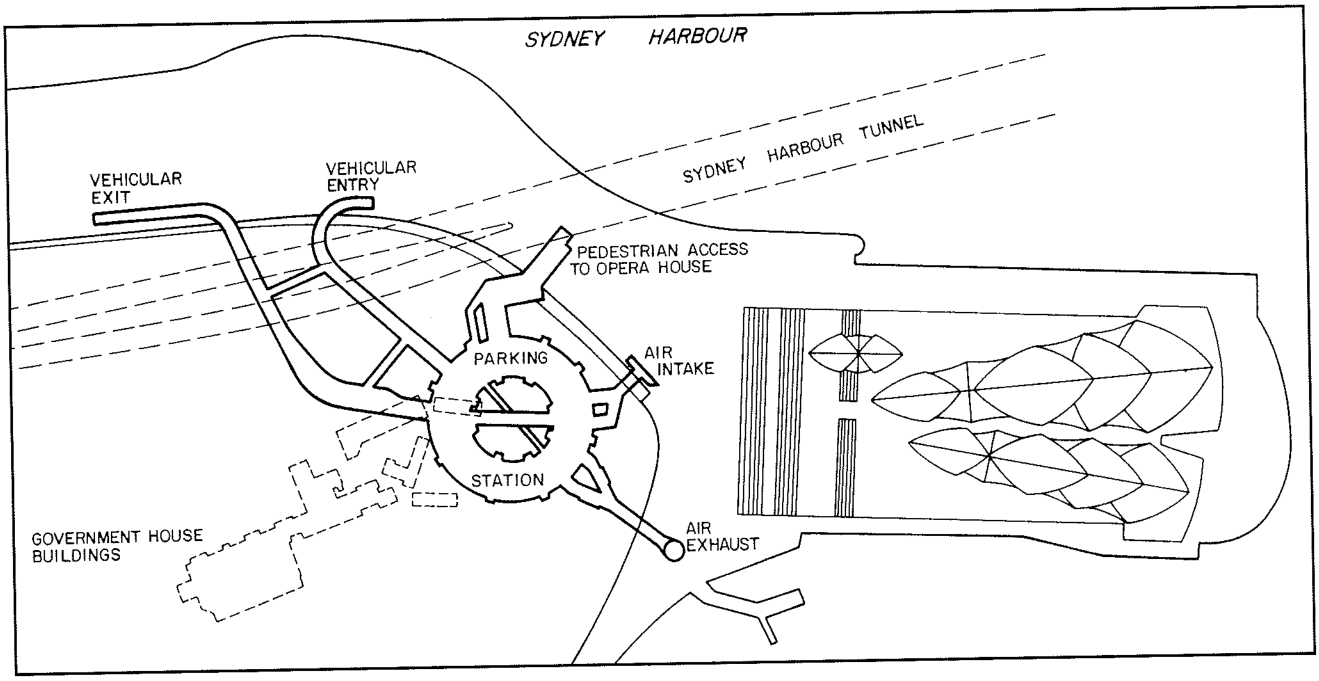

Figure 1. Location plan of underground parking station.

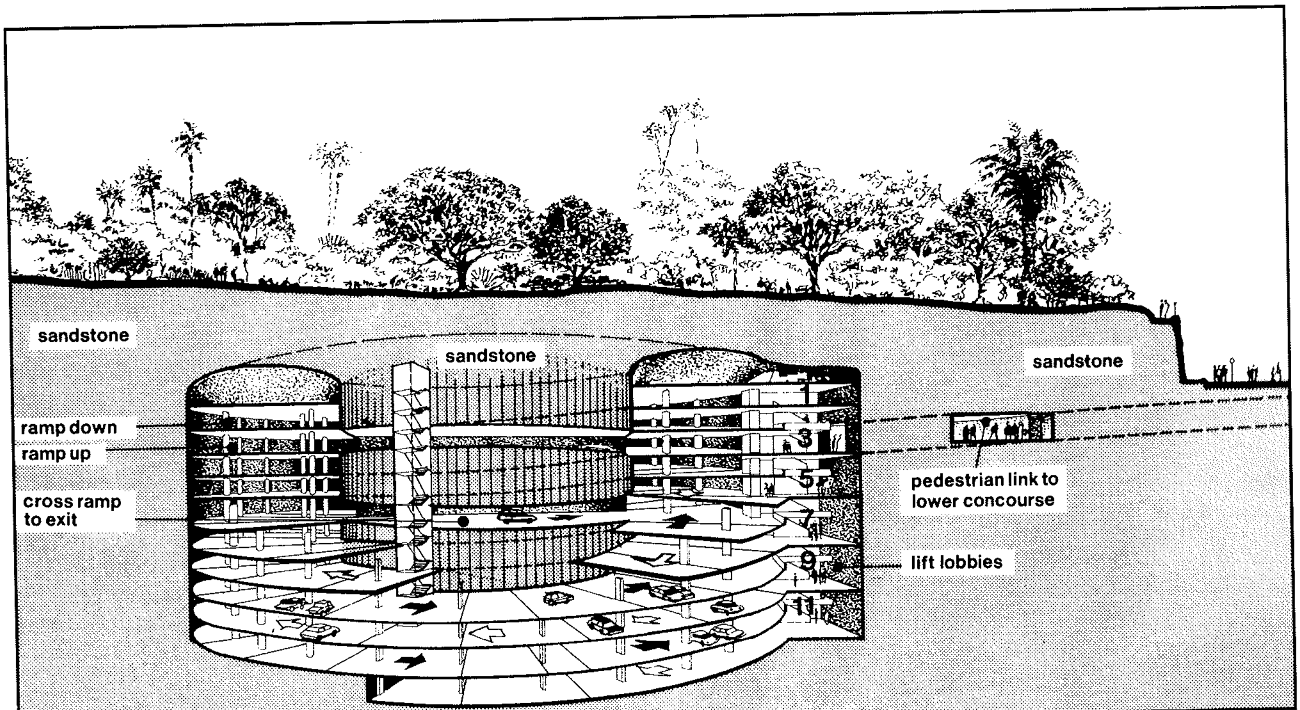

Figure 2. Artists sketch of the double helix structure.

The Sydney Opera House car park, known as the Bennelong Point Parking Station, is unique in shape and size and has established a number of firsts during its construction.

- It is the first helical underground parking station. The huge doughnut-shaped cavern, with a span of up to 19 m and an outer radius of 75 m, contains a 12 story free-standing double-helix concrete structure which, while providing 1100 parking spaces, will not provide long-term support for the rock cover (see Figures 1 and 2).
- It is possibly the widest shallow-cover rock cavern in the world (see Figure 3). The roof spans between 17.5 m and 19 m and comprises between 7 m and 8 m of variably weathered Hawkesbury sandstone, a rock which ranges in strength from 15MPa to about 40 MPa.
- Bulk excavation saw what was probably the first underground use of a Caterpillar D10N equipped with an Impact Ripper.

The roof is the key feature of the cavern. It is not supported with a formed concrete arch but rather, internal reinforcement comprising tensioned Macalloy bar anchors up to 7.5 m long and untensioned galvanised dowels up to 4.5 m long. There are about 2000 anchors and dowels in the roof. Design of the reinforcement system involved the development of a new design method which is described in a paper presented at the 7th ISRM Congress, Aachen, 1991 (Reference 1). The important design features of the roof are:

- the roof is almost flat, as this is found from both analytical studies and experience to be appropriate in horizontally bedded strata with a relatively high horizontal stress field ($\sigma_h / \sigma_v \approx 2$ to 5)
- the capacities and distribution of the reinforcing elements were designed so as to tie together the horizontal beds of sandstone (ranging in thickness from 1 m to 3 m) to act as a single pseudo-elastic no-tension linear arch.
- the roof surface is covered with a 150 mm skin of reinforced shotcrete and fibrecrete which acts as a membrane between the reinforcing elements.

Other special challenges in this project were:

- portions of the underground excavations are beneath outbuildings of Government House (see Figure 1).

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- the cavern is within 60 m of Sydney Harbour and extends 28 m below sea level.
- all work had to be done without disrupting the surface other than for the two 9 m wide access tunnels which have to pass over the Sydney Harbour Tunnel and have, in places, rock cover as low as 2.5 m.

In addition to the main cavern, 16 tunnels had to be excavated ranging in span from 2 m to 12 m (see Figure 3). These include:

- the two main vehicle entry and exit tunnels
- the main pedestrian concourse which links directly to the opera house
- four vehicle tunnels through the core of the "doughnut"
- two air supply tunnels
- two air exhaust tunnels

Excavation

Excavation of the access tunnels and the crown section of the main cavern was achieved primarily by a Mitsui S200 roadheader. This machine proved to be the first roadheader which could cut the high silica content Hawkesbury Sandstone (75% to 85% silt and sand size quartz) with both reasonable productivity and pick-wear rate. Attempts were made to use an AM65 in

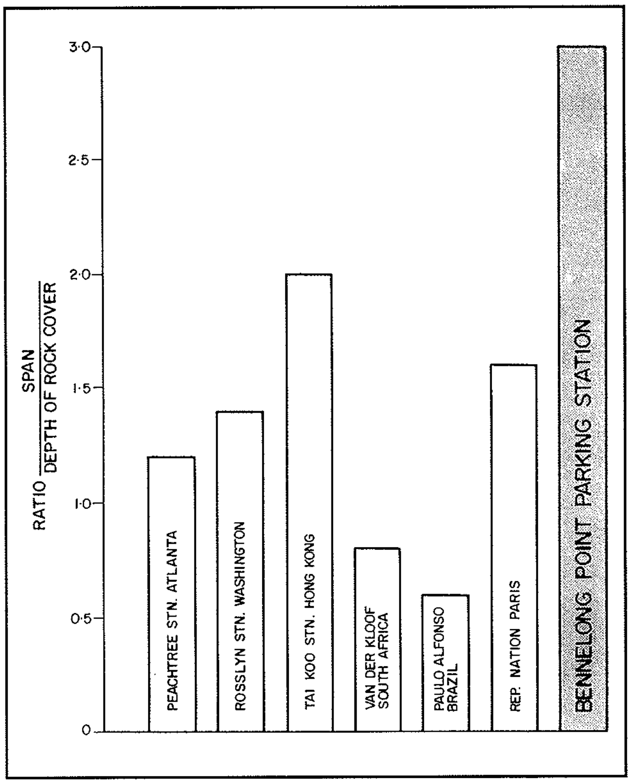


Figure 3. Comparison of rock cover versus span for several large near-surface rock caverns.

Roadheader Model	AM65	S65	S200
Instantaneous cutting rate m^3/hour	10	3.5	10-12
Pick wear rate/m^3	0.7 to 0.8	0.25	0.1

Table 1

parallel with the Mitsui but, as in previous Sydney tunnelling projects, pick-wear rates were unacceptably high. A second S200 machine was brought onto the site and a small S65 machine was also used for a 1.6 m wide tunnel required for diversion of an old stormwater tunnel. Table 1 summarizes productivity and pick-wear data.

The crown section of the main cavern was excavated by successive widening from an initial outer 6 m wide heading. Support was installed as the heading was widened from 6 m to 10 m to 15 m to 18 m. Careful monitoring of roof deflections, rock anchor loads and roof delamination was undertaken as the span increased, as a check against design assumptions. Once the crown was fully excavated and supported, a D10 bulldozer fitted with an impact ripper was used for bulk excavation. The cavern walls were trimmed by two Kato HD1250 30 tonne excavators and one Kato HD900 fitted with Montabert hydraulic impact breakers. These were also used to cut slots up the cavern walls for ventilation risers and for excavation of the lift shaft (see photographs 1 and 2).

Corrosion protection of the anchors and dowels in the crown of the main cavern and in the various service tunnels involved the following philosophy:

1. The tensioned Macalloy bars are epoxy coated and full column grouted in a high early strength Portland cement based grout.
2. The untensioned dowels are hot dip galvanised and also full column cement grouted.
3. A number of the anchors are fitted with vibrating wire load cells for long-term monitoring.
4. All major support elements in the main cavern are accessible and can be replaced if significant degradation due to corrosion occurs in the long term.

Instrumentation of the cavern included:

- multipoint extensometers installed from the ground surface prior to cavern excavation
- inclinometers installed around the perimeter and in the core prior to excavation
- sag measurement points on the cavern roof
- a subsidence grid on the ground above the cavern
- a piezometer network

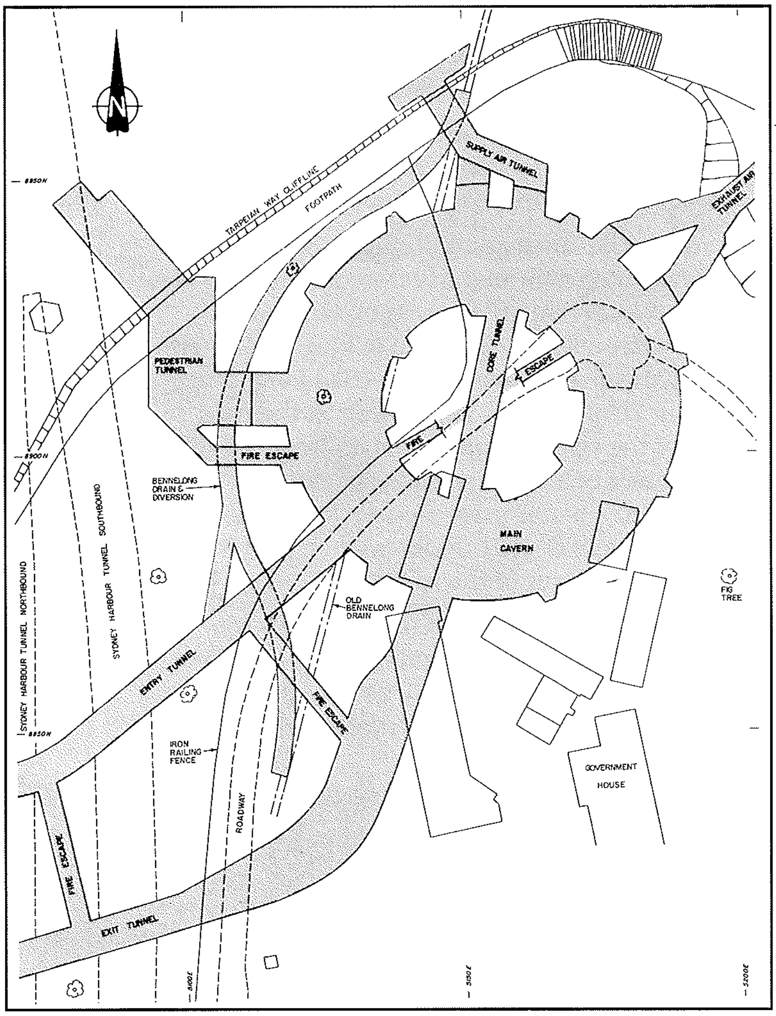


Figure 4. Main cavern and service tunnels.

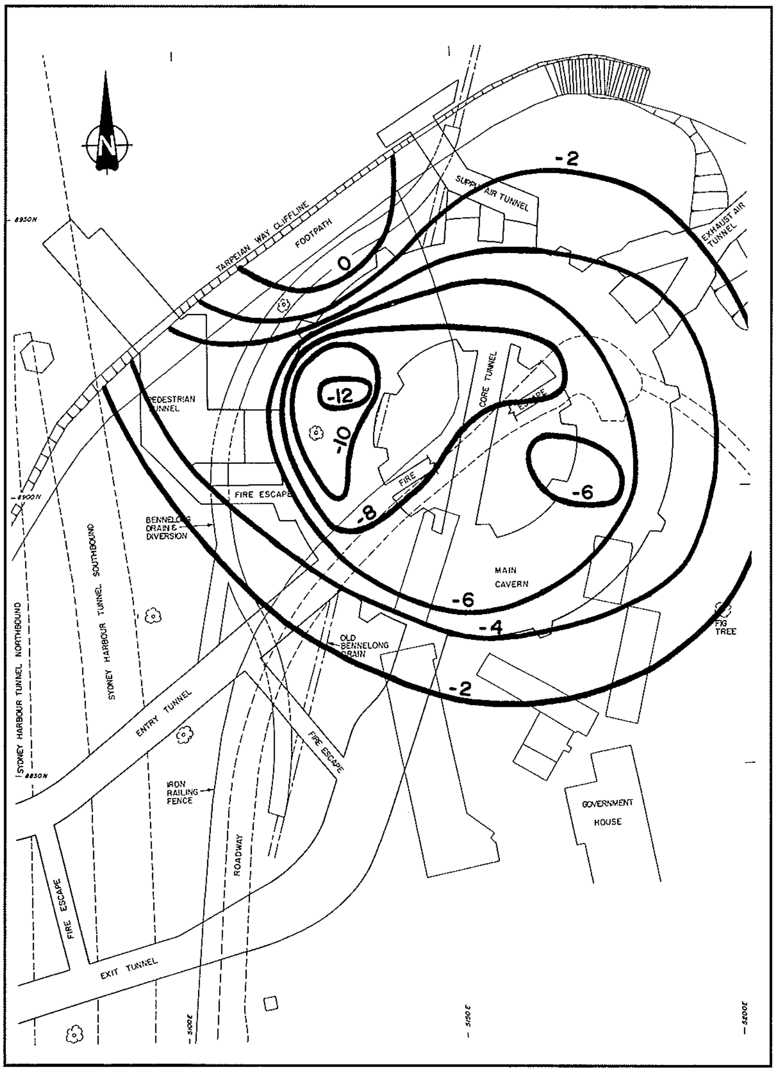
Main cavern design calculations predicted roof sag of about 15mm at full span and also settlement above the core of about 8mm. Monitoring showed that the roof rock deflected as a unit, with surface settlements being only a few millimetres less than internally measured roof sag. Contours of ground movement at the completion of excavation are given in Figure 5. These showed excellent agreement with design predictions (Figure 6).

Excavation of the cavern and associated tunnels, involving some 130,000 m^3 of sandstone, started in late 1990 and was completed in April 1992. The twelve story concrete helix was completed in September 1992 and the parking station is expected to open March 17, 1993, six months ahead of schedule.

References

Pells, P.J.N., H.G. Poulos and R.J. Best (1991). "Rock Reinforcement Design for a Shallow Large Span Cavern." *7th International Congress on Rock Mechanics, (Aachen)*, A.A. Balkema, 1193-1198.

Figure 5. Contours of surface settlement.



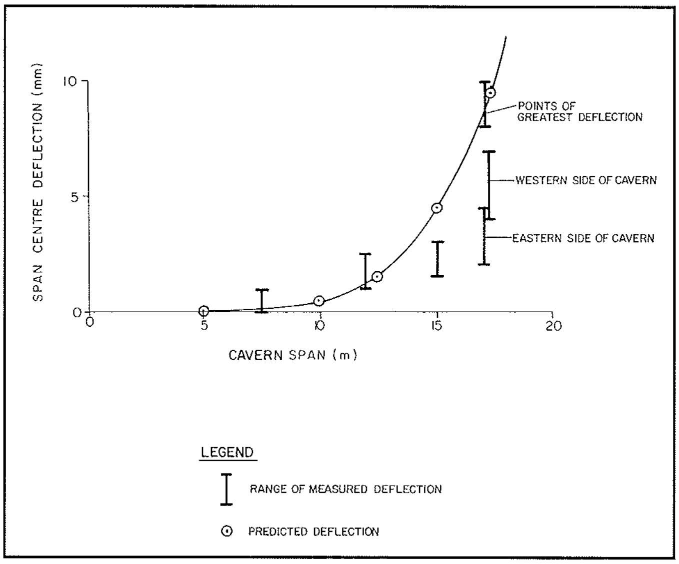


Figure 6. Predicted and measured roof sag.

Below: Lift shaft and ventilation risers.