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Stress Induced Roof Collapses During Construction of the Sydney LPG Storage Cavern

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Summary: This paper discusses the experience of the authors with two large failures that occurred in the roof strata of a storage facility for LPG which was being constructed deep below the ground surface in Hawkesbury Sandstone in the Sydney Basin, NSW, Australia.

Examination of the failure areas showed that each had been subject to severe distortion of the roof strata resulting in failure of the support systems. It was apparent that the strata had been subject to high lateral stresses and that the impact of these stresses on the roof of the excavation, coupled with the unique requirements for gas tightness, had contributed to the failures.

This paper describes the two roof failures and the particular geotechnical conditions associated with each.

INTRODUCTION

During winter, past experience was for the storage of Liquefied Petroleum Gas (LPG) for the Sydney market to be depleted to only a few days capacity. To address this situation, Elgas Limited constructed an underground storage facility at Molineux Point, Port Botany which is now capable of storing 65,000 tonnes of LPG.

Early in the construction period, the project was interrupted by two major roof falls, which resulted in the suspension of all underground works. Full resumption occurred some five (5) months later by which time an alternative roof support strategy had been agreed by all parties.

Excavation for the storage facility was carried out by Concrete Constructions Group Limited (subsequently the Walter Construction Group) under contract to Elgas Limited. The design was prepared by the French firm, Société Française de Stockage Géologique (Geostock). The contract for construction was awarded in March 1996 and construction commenced in May 1996. The storage facility was commissioned in June 2000. Project management was by C.J. Zanelli Pty Ltd. The authors were engaged as technical advisors to Elgas Limited.

DESCRIPTION OF THE UNDERGROUND STORAGE FACILITY

Figure 1 presents an isometric view of the completed LPG storage facility. It comprises four parallel storage galleries, the crowns of which are located at a depth of 124m beneath the ground surface. Each gallery is approximately rectangular in shape, with an arched roof and rounded corners in the floor.

Each gallery is approximately 230m long, 14m high and 11m wide. They are joined by smaller connection galleries 5.5m square in section, which alternate from connecting across the tops and bottoms of the main galleries. The galleries are unlined and rely on the pressure of the surrounding groundwater for gas containment.

A water curtain gallery comprising interconnected 4m wide, 3.5m high tunnels and a network of radiating water filled injection drill holes is located 15m above the LPG storage galleries to ensure saturation of the bedrock.

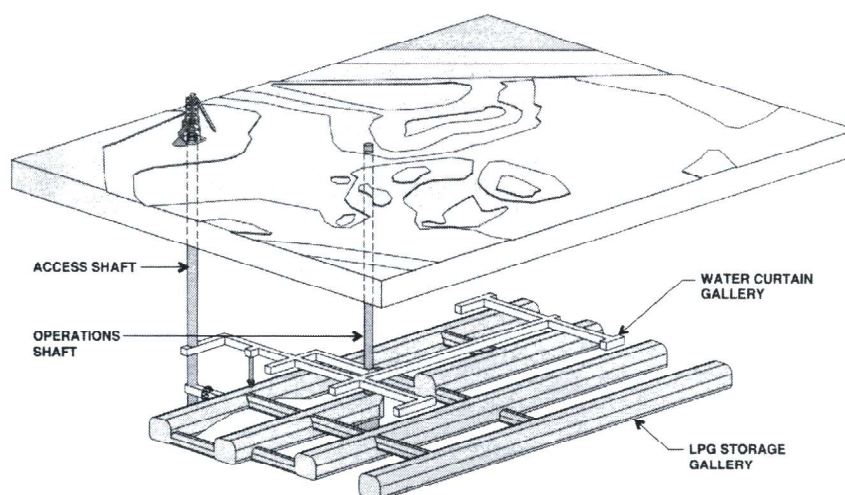


Figure 1. Isometric View of Underground Storage Facility

GEOLOGICAL SETTING

Molineux Point is centrally located along the coastal margin of the major structural basin known as the Sydney Basin. This Basin is a structural trough, in which a thick stratigraphic sequence of sedimentary rocks was formed by successive episodes of deposition during the Permian and Triassic Ages.

The Hawkesbury Sandstone is one of the four main stratigraphic units which comprise the Sydney Basin. It dominates much of the landscape in and around the City of Sydney and it also comprises the bedrock strata beneath Molineux Point and its environs. It is a flat-lying quartz sandstone sequence that was formed by a large braided river system that transported quartzose sand into the Basin. This fluvial environment of deposition is reflected in the internal sedimentary structure of the Hawkesbury Sandstone which displays three (3) different facies types, namely the 'massive sandstone facies', the 'sheet sandstone facies' and the 'shale (or mudstone) facies'.

Site Geology

Nine deep cored boreholes comprising a total length of 1,713m were drilled around the storage cavern. The drilling confirmed that the cavern would be excavated in intercalated sheet facies and massive facies strata. The massive facies sandstone beds are typically homogeneous in grain size and massive in structure. They typically range in thickness from 1 to 5m. By comparison, the sheet facies strata generally range in thickness from 0.5m to 2.0m and they are characterised by closely spaced internal crossbeds, inclined at angles ranging from 15° to 30° from horizontal.

The boundaries between massive facies and sheet facies strata range from being planar and horizontal concordant bedding surfaces to curvilinear and undulose discordant erosional surfaces. These boundary surfaces also vary from being tight and intact planar contacts to undulating or curvilinear low strength partings or clay seams.

EXCAVATION PROCEDURE AND INITIAL ROOF SUPPORT

The excavation for the storage galleries was carried out using a drill and blast technique. Initially this occurred via the excavation of a top heading some 5.5m high followed by removal of the bottom bench. Excavation commenced in Gallery A which was closest to the access shaft. Other faces were progressively opened as access was provided via the cross connection galleries. The four galleries were then worked simultaneously once full access had been achieved (Refer to Figure 2).

The initial roof support comprised 4.0m long solid bar rock bolts on a 2.0m x 2.0m grid pattern, grouted in place using resin capsules. However, as work proceeded, it became apparent that because of voids created by the opening of bedding planes due to roof convergence, some of the grout was being lost into the voids along the bedding planes resulting in incomplete encapsulation of the bolts. The designers were concerned at this situation as it violated one of the 'gas tightness' criteria for the storage facility.

The roof support was then changed to a system of 4.0m long, hollow, high tensile steel rock bolts which were initially anchored using a mechanical expanding shell at the top end of the bolts followed by the application of cement grout applied through the hollow stem once the face had advanced and roof convergence had ceased. Further, in an attempt to minimize roof sag before the bolts were installed, the procedure for face advancement was altered from full face "drill and blast" to the initial removal of a pilot heading followed by the removal of side strips. This system of face advancement was being used in Gallery A when the first of the major roof falls occurred.

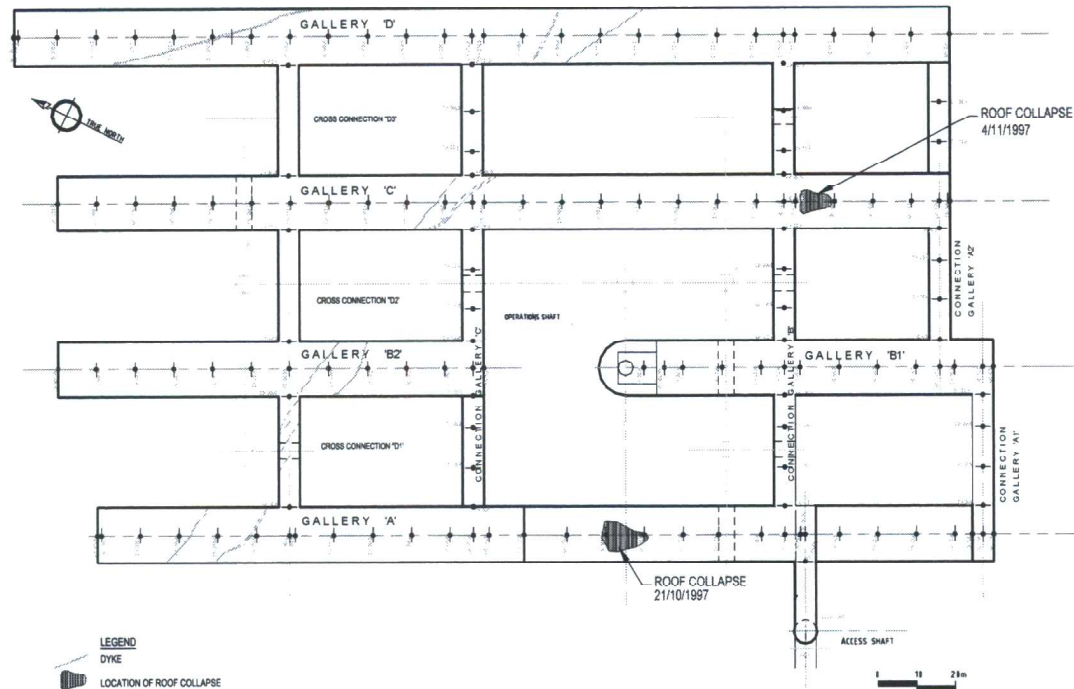


Figure 2. Plan of Storage Facility

ROOF COLLAPSE IN CAVERN GALLERY A

Description of The Roof Collapse

The collapse occurred either during or immediately after the perimeter blast of the western strip at chainage 096m, when the pilot heading was at face chainage 104m. The collapse occurred from chainage 089m to 102m and over a roof span width of up to 7m (refer to Fig 2). The failed material ranged in thickness from 1m to 1.5m into the roof in sheet facies sandstone strata. At the time of the failure none of the rock bolts had been grouted.

Observations at the Failure Site

The following observations were made during the course of our inspections (Refer to Figures 3 and 4):-

1. The roof collapse debris covered a cavern floor area measuring approximately 12m x 10m and included a number of relatively intact, large sandstone slabs up to 1.5m in thickness.
2. Some rock bolts were observed protruding upwards through the failure mass. These remained complete with bearing plates, nuts and threaded metal cones. However, on most bolts the top ends had pulled out of the shell "gripping" mechanism. Numerous other rock bolts could be seen to be bent and partly buried within the debris. Other bolts were observed protruding from the crown. These protrusions were about 1m in length and all but one was devoid of bearing plates and end fittings.
3. Visual observation in open rock bolt holes showed lateral displacements on bedding planes of up to 10mm to 15mm. The direction of movement of lower beds had been towards the centre of the opening. Detailed inspection of the roof also showed striations along the bedding planes consistent with this relative displacement across the beds.
4. Towards the centre of the failure area, zones of compression induced shear failure could be deduced from areas of freshly spalled rock in the roof. At one location in line with the west wall of the pilot heading a "dome" had been formed in the roof as a result of compression induced shear in the roof strata.

5. The surface of the failure area elsewhere comprised gently undulating bedding planes that were characterised by some localised orange-brown iron oxide staining. This surface was generally dry. The outline of the failure area was defined by individual bedding plane exposures which were cutoff by steeply dipping to subvertical, clean, curved to conchoidal fractures that had propagated between bedding planes at different elevations in the roof.
6. Numerous clean, subvertical, wavy fractures were observed to be either aligned with or emanating from drilled blast holes on the side walls of the failure site. Some of these fractures were wavy to curvilinear and parallel with the shape of the excavation between the cavern wall and the pilot heading.
7. Dry, pre-collapse grout (see later) was observed at a number of locations on bedding planes.



Figure 3. Roof Collapse in Gallery A showing portion of roof collapse debris and protruding rock bolts.

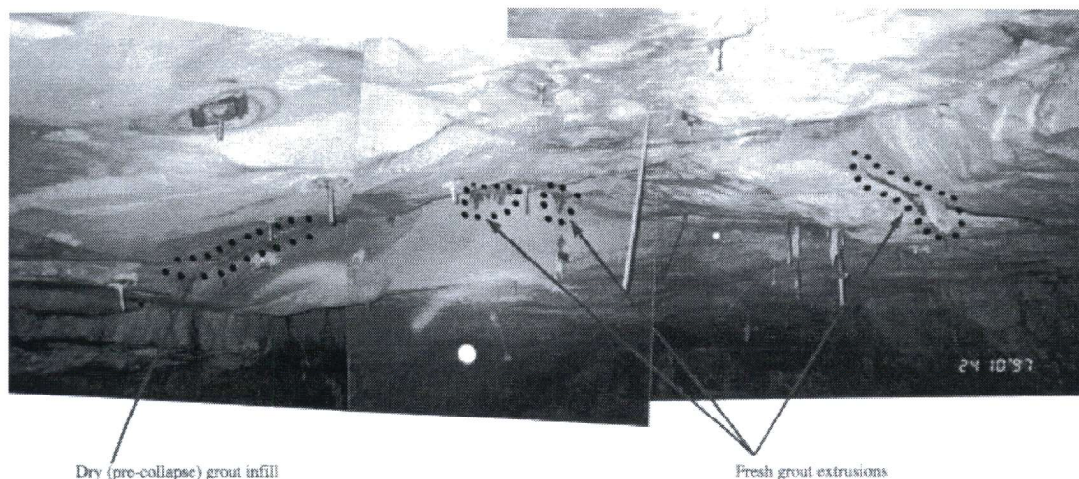


Figure 4. Roof Collapse in Gallery A showing failed roof area

Geology of the Failure Site

The failure site was characterised by a sequence of fresh, strong, medium and coarse grained, sheet facies sandstone strata, with individual bed thicknesses that ranged up to 1.7m. Some strata were prominently cross bedded. Cross bed dip angles typically ranged from 16° to 22° from horizontal. Some cross beds displayed silty, micaceous and carbonaceous coatings.

Bedding planes that separated individual strata were variable from subhorizontal and relatively planar to undulating. Some bedding planes were observed to be thinly coated with carbonaceous silt and clayey sand. Some bedding planes were tight, pebbly to conglomeratic and included irregular shale clasts.

The roof of the cavern at the failure site and the strata in which the roof collapse occurred, comprised further overlying fresh, sheet facies sandstone strata. The roof strata were also characterised by undulating bedding planes, some of which had localised, thin, silty carbonaceous coatings and some were locally iron oxide stained.

Subsequent Endoscope Investigations

The roof of the failure area was subject to an examination with an 8mm diameter fibre optic endoscopic camera (endoscope) used either in failed and empty rock bolt holes or purpose drilled holes. The conditions observed in these endoscope holes were plotted onto surveyed cavern profiles, onto which geological observations were also mapped. The measurements taken through the centre of the failure zone at chainage 095m are presented on Figure 5.

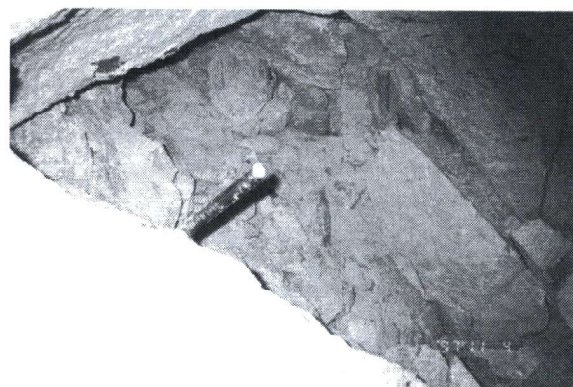


Figure 6. Roof Collapse in Gallery C showing sheared rock bolts in roof collapse debris

4. The surface of the failure area in the crown of the cavern comprised a planar to gently convex-downwards bedding plane surface, which was partially thinly coated with light grey clay and carbonaceous silt. Bedding plane exposures were locally stepped across by clean, inclined to subvertical, planar to conchoidal fractures that generally defined the outline of the failure area. Cementitious grout was also observed on some bedding plane surfaces.
5. Water seepage was occurring from the roof in the central eastern portion of the failure area.
6. Visual observation in an open rock bolt hole in the roof above the failure area indicated a lateral displacement of 5mm to 10mm on a bedding plane at a measured height of 1.0m above the failure surface.

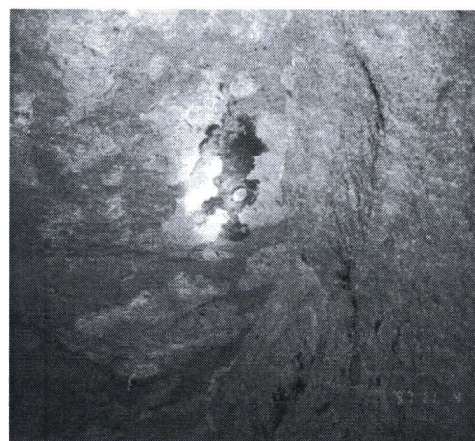


Figure 7. Roof Collapse in Gallery C showing sheared rock bolt and carbonaceous striations on bedding plane in roof.

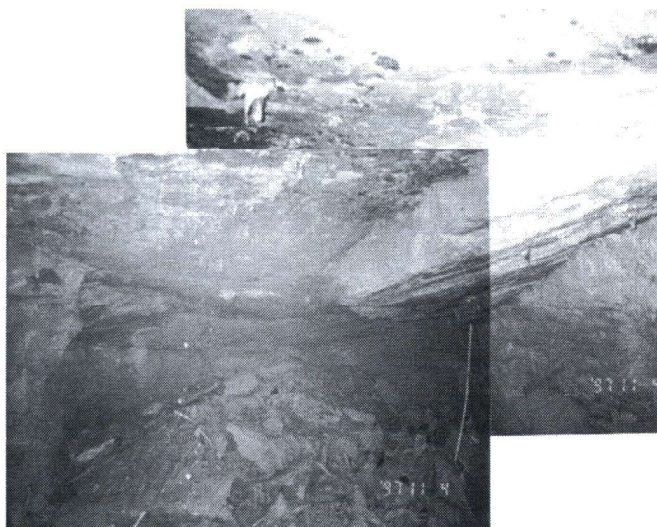


Figure 8. Roof Collapse in Gallery C showing western shoulder and localised bed thinning in central roof area.

Geology of the Failure Site

The strata exposed in the sidewalls and roof at the failure site comprised a sequence of fresh, strong, medium and coarse grained, sheet facies sandstone beds, with individual bed thicknesses ranging from approximately 0.3m to 2.5m. The strata were generally cross bedded, with cross beds being concave and characterised by shallow dip angles that ranged from 12° to 20° from horizontal. Cross bed surfaces ranged from clean to thinly coated with carbonaceous and/or micaceous silt.

Bedding planes that separated cross bed sets and adjoining strata varied from being subhorizontal and planar to gently undulating. Bedding planes were typically characterised by thin coatings of light grey clay and/or carbonaceous silt.

The failed section of roof comprised a tabular mass of rock that extended from the western sidewall to approximately the cavern centreline. This consisted of two or more individual strata up to 0.5m thick with a combined maximum thickness of approximately 1.2m.

Bedding planes exposed in the upper shoulder areas displayed ripple-marked laminations with micaceous and carbonaceous coatings. Shearing movements and detachment had occurred along these planes during the roof collapse, as was evidenced by striations on surface coatings which were oriented towards the centre of the failure site.

Subsequent Endoscope Investigations

Due to safety requirements and the subsequent prolonged closure of the gallery after the roof collapse, it was not possible to commence endoscope investigations in the failure site until February 1998. These results are not reported because other episodes of roof instability had also occurred during this interim period in and adjacent to the failure site, which would have superimposed on the effects of the initial roof fall.

INFERRED MECHANISMS OF ROOF FAILURE

Storage Gallery A

From the observations made of the failure site it could be deduced that the roof strata were initially fractured by compression induced movement along the bedding planes, resulting in the initial loss of arch support of the lower roof beam(s) and the transfer of the major component of the weight of these strata onto the rock bolts. Calculations then show that because of the thickness of the roof beam(s), the weight to be supported would have been at the limit of the load carrying capacity of the bolts. It then appears that overload of at least some of the bolts occurred either as a result of disproportionate sharing of load or as a result of additional load induced in the bolts by dilation along the bedding planes (likely a combination of both) causing some rock bolts to fail at their anchorage points. Once these bolts had failed, a "domino" effect of load transfer would have caused the remainder of the bolts to fail. It is considered likely that the above sequence of failure occurred very quickly following removal of the side strips.

Storage Gallery C

The bedrock which fell from the roof comprised part of a bed which had separated from the roof along a bedding plane. Inspection of the failed rock on the floor of the gallery showed that the bolts had been fractured at the location of the bedding plane involving both bending and reduction of the cross-sectional area of the bolt i.e "necking" (Refer to Figure 6). One of the bolts had been fractured across a very short gauge length at the location of the bedding plane while in several others the fracture was located a short distance above the bedding plane in what had previously been the underside of the overlying bed in the roof. The mode of failure was indicative of the bolts having been subject to both shearing and tension forces which in turn, were indicative of a relative movement of the underlying bed towards the centre of the cavern and dilation across the bedding plane as a result of this horizontal movement.

Inspection of the remaining rock in the roof showed that the thicker remaining section of the roof beam at the side had also moved along the overlying bedding plane, as could be deduced from fresh striations in the roof (Refer to Figure 7). This movement was seen to comprise both movement along and widening of the bedding plane. A section of this remaining slab also fell from the roof a short time after the inspection.

From the above description, it is apparent that failure had been the result of a compression induced movement along the bedding plane towards the centre of the opening, resulting in what appeared to have been the simultaneous fracture of the bolts at the location of the bedding plane and fracture and detachment of the roof beam where it became thinner towards the centre of the cavern (Refer to Figure 8). Collapse of the roof beam was then time delayed and occurred as a result of bending induced tension from cantilever action of the beam.

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