# Vibration assessments for the Sydney LPG Cavern from construction piling for the adjoining Bulk Liquids Berth 2, Port Botany, Australia

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## ABSTRACT

The Sydney LPG Cavern is an underground storage facility comprising unlined excavations in rock. The cavern is owned and operated by Elgas Limited (Elgas). Sydney Ports Corporation (SPC) has recently completed the construction of a second Bulk Liquids Berth (BLB2) at Port Botany, to the immediate west of the Sydney LPG Cavern (BLB2 was transferred to NSW Ports on 1 June 2013 as part of the 99 year lease for Port Botany and Port Kembla). The BLB2 structure incorporates 136 large diameter driven piles and at the BLB2 design stage, Elgas advised that the LPG Cavern and its operations are sensitive to ground vibrations. The magnitude and possible adverse effects of vibrations caused by pile driving at BLB2, on the Sydney LPG Cavern and its operations, therefore required geotechnical assessment. As well as assessing impact mechanisms, the work included predictive analyses for comparison with the allowable maximum vibration limits nominated by Elgas. A detailed geotechnical model of both sites was compiled, enhanced by a knowledge of conditions encountered during the Sydney LPG Cavern investigation, design and construction phases, that were attended by Author 1. The FE programme Plaxis dynamic feature was utilised for vibration modelling, which indicated that pile driving could be carried out at BLB2, without exceeding the stringent ppv limits at Cavern level nominated by Elgas. The geotechnical feasibility of the BLB2 project was thereby confirmed.

*Keywords:* LPG, deep unlined rock caverns, piling, vibration, dynamic analysis.

## 1 INTRODUCTION

Sydney Ports Corporation (SPC) has constructed a second Bulk Liquids Berth (BLB2) to service the Port of Botany Bay, Australia. The BLB2 site is located to the immediate west of the Sydney LPG Cavern, which is owned and operated by Elgas Limited (Elgas). The Sydney LPG Cavern is an underground storage facility comprising unlined excavations in rock. The LPG Cavern and its operations are sensitive to ground vibrations such as can accompany pile driving.

The BLB2 structure incorporated 136 large diameter driven piles. The magnitudes and possible effects of vibrations caused by pile driving at BLB2, on the Sydney LPG Cavern, therefore required analyses for comparisons with nominated vibration limits, to assess the feasibility of the proposed BLB2 design and construction methods at the designated BLB2 location adjoining the Cavern.

## 2 THE SYDNEY LPG CAVERN

The Sydney LPG Cavern was excavated by drill and blast methods during the period 1996 to 1999 with commissioning occurring between January and May 2000. The Cavern comprises four (4) parallel interconnected LPG storage galleries which are 14m wide, 11m high and 230m long. The cavern crown is at RL-124m and the floor is RL-135m, beneath Molineux Point, located entirely within horizontally bedded Hawkesbury Sandstone strata. Each gallery is approximately rectangular in shape, with an arched roof and rounded corners in the floor.

The gas containment principle relies on the hydraulic pressure of groundwater surrounding the Cavern to be maintained at a level that is higher than the operation pressures within the cavern. To insure against any possible de-saturation of the surrounding rock mass, the Cavern incorporates an overlying water curtain gallery, (RL-106m to -109.5m), comprising interconnected 4m wide, 3.5m high tunnels and a network of radiating, pressurised water injection drill holes located 15m above the LPG storage galleries. The function of the water curtain gallery can artificially maintain rock mass saturation around the cavern, in the event of any future depletion of the natural groundwater regime. An isometric view of the Sydney LPG Cavern is shown in Figure 1.

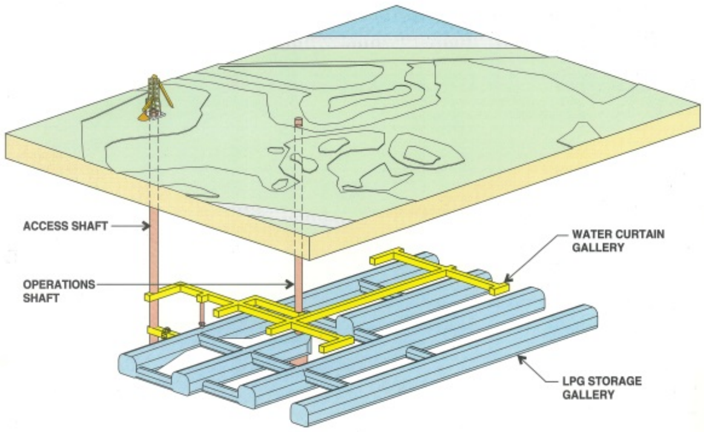


*Figure 1. Isometric View of Sydney LPG Cavern.*

The combined effects of the natural hydrogeological conditions at cavern level and injection from the water curtain gallery resulted in significant water inflows to the storage galleries during construction. A grouting programme was required to reduce the magnitude of cavern seepage inflows. The Hawkesbury Sandstone is characterised by a very low primary (inter-granular) permeability, due to the presence of a clay-rich matrix cement and recrystallization during diagenesis. The migration of groundwater through the bedrock sequence at the site had been confirmed by site testing to be controlled by flow along fractures and rock mass defects. The adopted grouting programme therefore sought to reduce permeability through the controlled injection of cementitous grout into bedding plane seams and joint plane defects around the Cavern. In so doing, hydraulic gradients were optimised and seepage inflows to the Cavern were controlled, to a nominal 40m$^3$/day. A photograph of Cavern conditions during construction is presented as Figure 2.

*Figure 2. Storage gallery top heading excavation prior to trimming showing Hawkesbury Sandstone strata, groundwater inflow, rock bolt roof support and temporary safety mesh.*

## 3 NOMINATED PILING VIBRATION LIMITS AT CAVERN LEVEL

The closest BLB2 pile location is 70m (in plan) from the northern end of the LPG Cavern, with a direct distance of 120m from pile tip to cavern crown. Elgas and their cavern designers (Societe Francaise De Stockage Geologique – "Geostock") nominated a maximum peak particle velocity (ppv), attenuation limit of 1mm/sec at LPG Cavern level, with a "never to exceed" value of 3mm/sec. These stringent limitations are consistent with the German Standard DIN 4150 – Part 3 (1999) "Effects of Vibration on Structures." The value of 3mm/sec is the limit recommended by that Standard to protect "particularly sensitive" structures. Associated damage referred to in that Standard includes "… even minor non-structural effects such as superficial cracking in cement render, the enlargement of cracks already present, …", as discussed below.

## 4 POTENTIAL ADVERSE VIBRATION IMPACTS AT CAVERN LEVEL

A review was undertaken of elements of the LPG Cavern and its operations, that could potentially be adversely impacted by vibrations. From a geotechnical perspective there were two potential elements at risk identified.

### 4.1 Roof Stability

Past direct experience during the construction phase of the Cavern strongly suggests that the DIN limits for sensitive structures will provide conservative threshold limits against any reduction in roof stability within the Cavern. During the construction phase partly excavated galleries were repeatedly subjected to vibrations emanating from nearby blasting used to advance the face of the top bench initially and then followed by removal of the lower benches. Whilst records are not available of the actual vibrations experienced repeatedly by the walls and roof of the Cavern, conservative estimates would indicate vibration levels far in excess of the proposed DIN Standard limits without instigating instability. Cavern roof support was achieved with 5m long rock bolts on a 1.5m grid spacing, with some additional bolting for local geological conditions. Since that time it is to be assumed that, as per design criteria for the Cavern, there has been no significant deterioration in the rock bolts supporting the roof structures so that the expectation is that these same rock bolts can satisfactorily support the roof without instability, when subject to vibrations constrained to be within the DIN Standard recommendations for sensitive structures.

### 4.2 Cavern Groundwater Inflows

It was our assessment that the element at risk most vulnerable to damage from vibrations is the grouting that has been carried out within the sandstone bedrock to control the hydraulic gradients for groundwater inflow into the Cavern. The grout exists as thin brittle, cementitous infill to fractures in the rock mass comprising the Cavern roof and walls. The integrity of the cementitous grout is critical to both gas containment and groundwater inflow control. Even fine cracks within the grout could feasibly result in increased groundwater inflow, with associated implications for pumping operations and water treatment requirements. The grout is hence seen as a critical component of the Cavern and its operations, which requires protection. Furthermore, the relevance of the application of the above-mentioned DIN Standard to the Cavern is considered to be confirmed, based on the similarity that exists between cement render and plaster in sensitive buildings and the cementitous grout in bedrock fractures around the Cavern.

It was agreed by all stakeholders that detailed modelling of piling vibrations between BLB2 and the Sydney LPG Cavern was required, for quantification purposes and to enable comparison and review with the maximum allowable vibration limits nominated by Elgas.

## 5 GEOLOGICAL AND PILE VIBRATION MODELS

Some initial pile vibration modelling had been carried out for Sydney Ports Corporation; conducted using geotechnical finite element software Plaxis. In accordance with the then current design for the BLB2 structure, two types of pile were analysed, both hollow steel tubes with 20mm wall thickness; one of 800mm diameter and the other 1200mm diameter. The Plaxis model employed axial symmetry with a single vertical pile situated at the centreline. Using this approach, raked piles were not able to be analysed. The model extended radially for a distance of 120m with the closest cavern wall modelled at a 65m radius from the pile. Two different types of pile driving hammer were modelled: Hydraulic hammers - IHC S-150 and HHK-16S; Vibrating hammers; ICE 416L and MS-16HFV. The calculations were performed for two (2) strokes of the hydraulic hammers and for five (5) cycles of the vibrating hammers. Three (3) separate cases of pile tip location were analysed for each pile and for each hammer type:

Case 1 - Pile Tip at -19m

Case 2 - Pile Tip at -27m

Case 3 - Pile Tip at -38m

Ground conditions and the sub–surface profile were based on information from an offshore borehole at the BLB2 site. The idealised subsurface profile comprised:

| | | |
|---|---|---|
| RL | -15m to -19m | Loose to Medium Dense Sand |
| | -19m to -27m | Dense to Very Dense Sand |
| | -27m to -32m | Loose to Medium Dense Sand |
| | -32m to -38m | Dense to Very Dense Sand |
| | -38m to -150m | Class III grading to Class I Medium to High Strength Hawkesbury Sandstone. |

It may be noted that the results included cases where the sand stiffness was reduced by a factor of 2 and the bedrock strength by a factor of 10, and a thin sand layer case was modelled with the top of rock occurring at -27m, and that there was no modelling of the shale layer subsequently included in our expanded modelling.

Review of the results showed that the maximum vibrations induced in the wall of the cavern occurred for the vibrating hammer, particularly for Case 1 where, except for the low stiffness case, the magnitude of the transmitted vibration from the vibrating hammers was of the order of 5 times greater than the corresponding case with the hydraulic hammers. The reason for this is uncertain and may well be related to the frequency assumed for the hammer and assumptions made affecting the natural frequencies of the soil and bedrock strata as well as the assumptions made for damping of materials.

Subsequent calculations were carried out which minimised the influence of damping whilst using realistic values of the elastic parameters for the soil and rock based on experiences with the construction of the Elgas cavern facility. In any event, undue focus on the use of vibrating hammers was likely to be unwarranted because informal discussions with industry personnel and indeed past experience suggested that vibrating hammers were unlikely to be employed with such large piles, particularly given the requirement to found in dense sands. The other somewhat surprising result was that of all the situations analysed, the largest vibrations were always recorded for the case where the pile tip first entered into the moderately dense sand. This surprising result was likely related to the assumption made for the entry of the pile tip into the sand, that is, the “attachment” assumed at the nodes between the pile and soil surface, and the effect this may have in inducing resonance in the sand layer. Given that the pile driving force assumed at the point of entry into the sand (in the Plaxis model assumed as 1,000kN over a period of 0.02 secs and essentially equal to a real force on the pile of some 3,770kN because of the assumed axial symmetry) may have been too high for this early stage of the pile installation. It would appear more reasonable to assume this level of force when the pile has penetrated to a greater depth (see also below). This applies in particular to the hydraulic hammer but may also be applicable to the vibrating hammer where the frequency and amplitude of vibration may need adjustment according to pile penetration.

Notwithstanding any qualification that may be appropriate for consideration of the vibrating hammer for such large piles, and/or the fact that the largest transmitted vibrations occurred when the pile first entered into the sand at a high level, the results themselves (that is, the highest of the readings) can be seen to fall within the vibration limits that had been nominated by Elgas.

### 5.1 Expanded Modelling

GHD Geotechnics was then required to carry out separate modelling to that already carried out in order to independently evaluate the magnitude of the vibrations likely to be transmitted into the Sydney LPG Cavern from the BLB2 pile driving activities.

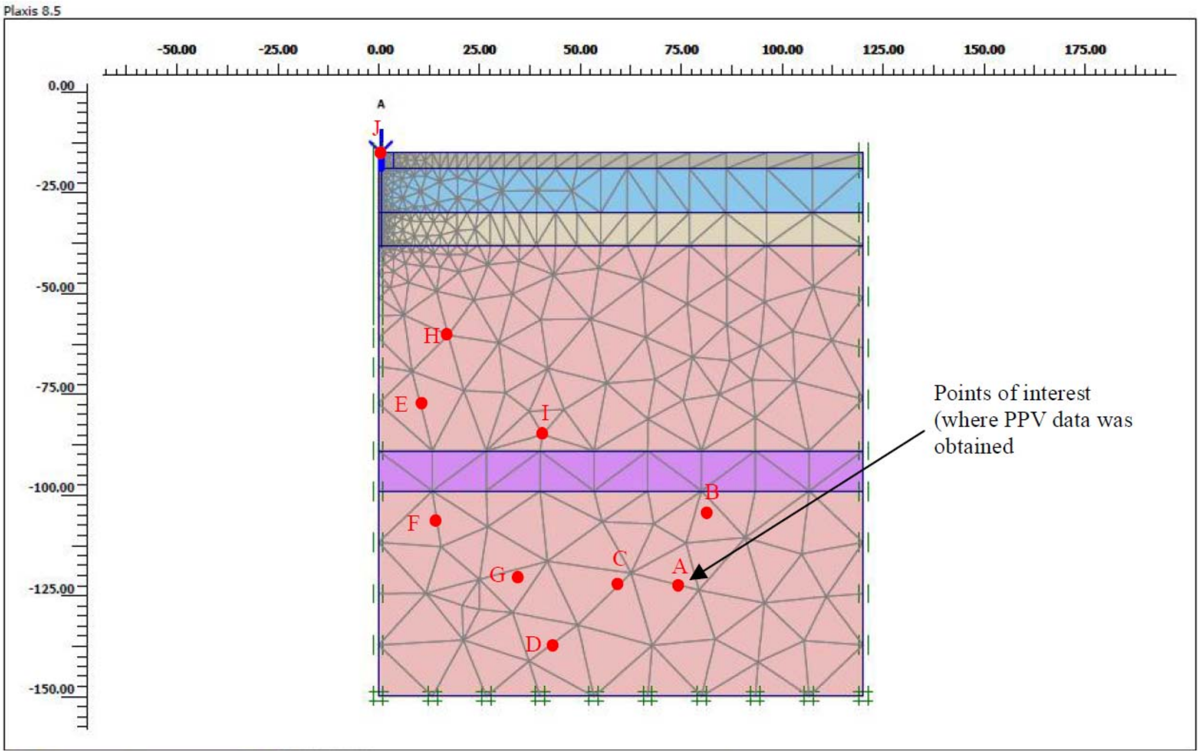


*Figure 3. Mesh employed for Plaxis dynamic analyses showing the location of the pile for Case 1, the modelled shale layer and locations of selected points of interest for Analysis 5 see Table 1.*

#### 5.1.1 Refinements to Geotechnical Model

Finite Element program Plaxis was again used for this modelling and an axisymmetric model established (see Figure 3) which would be capable of both duplicating the previous model (so as to allow a comparison of results to be made) and then expanding this model to incorporate more points of interest, as well as the geological features and conditions which were known to exist at the site from earlier involvement of Author 1. Also, we had available the range of material parameters that had been obtained from the exhaustive testing previously carried out for the design of the Cavern. These refinements included provision for a 10m thick shale sequence located directly above the Water Curtain Gallery and extending over virtually the entire site, (comprising essentially slightly weathered to fresh, moderately strong to strong shale, classifying as either Class II or I Shale on adopted Sydney Basin Classification systems); the confirmation of the sandstone within which the Caverns is constructed as Class I; and the modification of the consistency of the overlying sand layers as essentially dense to very dense sand. A further variation was made (as one of the alternative analysis cases) where the depth to bedrock was reduced to coincide with the bottom of the dense sand layer at RL-27m. This higher level of bedrock correlates with the higher level of sandstone bedrock, RL-24.3m that was documented by Author 1 during construction of the Operations Foreshaft at the Cavern.

#### 5.1.2 Hard Driving

As part of our study a preliminary review was made of the pile driving hammers that were considered likely to be adopted on the BLB2 project. The conclusion from this study was that:

Whilst a variety of hammers have been reviewed (both hydraulic and vibratory), our study concentrated on the use of a hydraulic hammer for the project for the reasons expressed above. Further, whilst it was accepted that the final choice of a hammer would only be known when the contractor was appointed and work started, the conclusion from our preliminary review, was that the energy output from a Junttan 16t hammer would be a reliable indicator of the maximum energy required to install the piles. Delivery of the maximum energy would result in a varying pile force applied to the top of the pile depending upon the ‘ease’ of penetration of the pile into the sub-surface. For example, it was likely that a relatively large penetration will occur initially when a pile first enters into the sand, requiring only the application of a small force at the top of the pile, but that this would then change at depth under “hard driving” conditions, where the pile penetration, or ‘set’ becomes small. Under these latter conditions, the impact force at the pile head could well approach in the order of 3 to 4 times the design working load of the pile. For this work both a medium range pile force of some 3,800kN (about 1000kN for the axisymmetric model) as well as a ‘hard driving’ case where a maximum force at the top of the pile is some 9200kN were used.

## 6 PILE VIBRATION ANALYSES AND RESULTS

The earlier work provided a good starting point for assessing the problem of the effect of different pile installation methods on vibrations in the Cavern but the following were required to be addressed -

- lack of information of adopted parameters; in particular damping (which is considered to have an important influence on results)
- the inability to explain the perceived anomaly in the results for driving at small pile penetrations
- the stability of the initial solution before commencing pile impact was not demonstrated
- more than 5 cycles of vibrating hammer might be needed to develop a steady state response in the ground
- more than one point of interest was needed in the Cavern and particularly in the water curtain
- the use of a simplified ground model
- no consideration of hard driving conditions.

The work carried out addressed these issues by -

- a presumed worst case of no material damping for the analyses
- recognising that at small pile penetrations the adopted hammer operational characteristics will need adjustment, i.e., ‘soft’ driving will be associated with lower impact force
- computationally expensive calculations with 1.5 second settling time, deemed necessary to ensure the solution was not influenced by initial conditions in the FE analysis (see Figure 4)
- multiple cycles of the vibrating hammer were deemed necessary and suggested that a steady state response did not arise but that resonance may indeed be possible (see Figure 5)
- up to 10 points of interest were reported including three points along the water curtain
- adopting ground parameters based on in-house knowledge and a reinterpretation of the data
- discussions with industry and implementation of modified hard driving analysis.

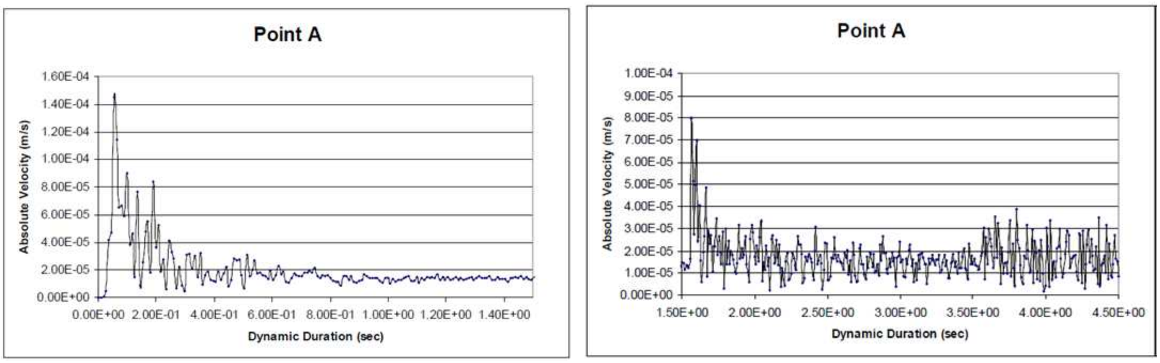


*Figure 4. Results from Plaxis dynamic analyses showing a) 1.5 seconds was required to reduce background vibrations set up during initial stage of modelling; b) the subsequent response to driving.*

The above ensured that the quality and reliability of the results was enhanced. The results are presented in summary form in Table 1 and the results for the 1200mm diameter pile of Analysis 6 with hard driving at near full depth are considered to be the most appropriate.

*Table 1: Maximum Predicted peak particle velocity (mm/s) at points of interest for different piles, hammers and toe depths.*

| **Analysis** | **Pile** | **Hammer** | **Points of Interest** | | **(mm/sec)** | | |
|---|---|---|---|---|---|---|---|
| | | | | **Case** | **I** | **II** | **III** |
| **1** | 800x20mm | IHCS-150 | A | Storage Gallery A | 0.1 | 0.1 | <0.1 |
| | 1200x20mm | HHK16S | A | Storage Gallery A | 0.2 | 0.2 | 0.2 |
| **2** | 1200x20mm | HHK16S | A | Storage Gallery A | 0.25 | - | - |
| | | | B | Storage Gallery A | 0.36 | - | - |
| (Extended | | | C | Top of pile | 3400 | - | - |
| Points of Interest) | | | D | Along pile | 3.3 | - | - |
| | | | E | Along pile | 4 | - | - |
| | | | F | Along pile | 2.5 | - | - |
| | | | G | Bedrock sample point | 1.2 | - | - |
| | | | H | Bedrock sample point | 0.9 | - | - |
| | | | I | Bedrock sample point | 0.45 | - | - |
| | | | J | Bedrock sample point | 0.45 | - | - |
| **3** | 1200x20mm | HHK16S | A | Crown of Storage Gallery A | 0.4 | 0.33 | 0.34 |
| | | | B | Water Curtain Gallery | 0.22 | 0.22 | 0.21 |
| (Refined Geotech | | | C | Mid length water curtain BH | 0.39 | 0.36 | 0.38 |
| Model) | | | D | Base water curtain BH | 0.68 | 0.68 | 0.68 |
| | | | E | Directly beneath pile | 5.44 | 4.59 | 4.92 |
| | | | F | Directly beneath pile | 4.97 | 5.15 | 5 |
| | | | G | Directly beneath pile | 3.17 | 3.17 | 3.17 |
| | | | H | Bedrock (close to pile) | 1.5 | 1.5 | 1.5 |
| **4** | 1200x20mm | ICE416L | A | Crown of Storage Gallery A | 0.17 | - | - |
| | | | B | Water Curtain Gallery | 0.19 | - | - |
| (Vibratory | | | C | Mid length water curtain BH | 0.12 | - | - |
| Hammer | | | D | Base water curtain BH | 0.12 | - | - |
| Settling | | | E | Directly beneath pile | 1.65 | - | - |
| Time) | | | F | Directly beneath pile | 0.71 | - | - |
| | | | G | Directly beneath pile | 1.11 | - | - |
| | | | H | Directly beneath pile | 0.69 | - | - |
| | | | I | Bedrock (close to pile) | 0.33 | - | - |
| | | | J | Bedrock (off-set from pile) | 0.21 | - | - |
| **5** | 1200x20mm | HHK16S | A | Crown of Storage Gallery A | 0.1 | <0.10 | <0.10 |
| | | | B | Water Curtain Gallery | 0.1 | <0.10 | <0.10 |
| (Hydraulic | | | C | Mid length water curtain BH | 0.1 | <0.10 | <0.10 |
| Hammer | | | D | Base water curtain BH | 0.1 | <0.10 | <0.10 |
| Settling | | | E | Bedrock below pile | 0.25 | 0.17 | 0.16 |
| Time) | | | F | Bedrock (off-set from pile) | 0.18 | 0.1 | 0.14 |
| | | | G | Bedrock sample point | 0.1 | 0.1 | 0.1 |
| | | | H | Bedrock (shallow) | 0.33 | 0.21 | 0.19 |
| | | | I | Bedrock sample point | 0.15 | 0.1 | 0.12 |
| | | | J | Top of pile | 2605 | 465 | 448 |
| **6** | 1200x20mm | HHK16S | A | Crown of Storage Gallery A | - | - | 0.2 |
| | | | B | Water Curtain Gallery | - | - | 0.1 |
| ("Hard | | | C | Mid length water curtain BH | - | - | 0.2 |
| Driving") | | | D | Base water curtain BH | - | - | 0.2 |
| | | | E | Bedrock below pile | - | - | 0.5 |
| | | | F | Bedrock (off-set from pile) | - | - | 0.4 |
| | | | G | Bedrock sample point | - | - | 0.2 |
| | | | H | Bedrock (shallow) | - | - | 0.7 |
| | | | I | Bedrock sample point | - | - | 0.4 |
| | | | J | Top of pile | - | - | 2352 |

For locations of points of interest for Analyses 5 and 6 see Figure 3; other Analyses had similar points, as noted.

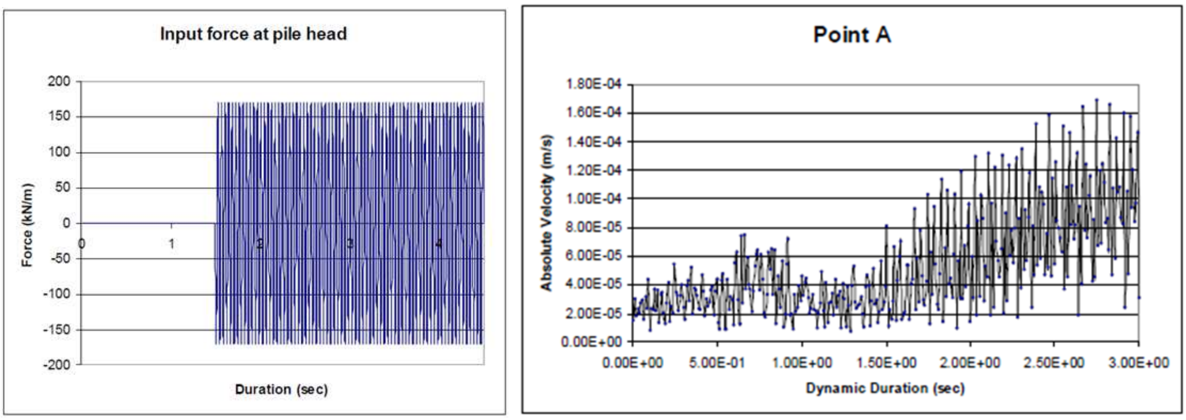


*Figure 5. Results from Plaxis dynamic analyses of vibratory hammer showing a) 1.5 seconds settling time followed by multiple cycles; b) the subsequent non-convergent response to driving.*

Figures 4 and 5 when compared with the pile responses measured and presented in the companion paper by Barbour-Bourne and Jones (2015), show broad agreement.

## 7 CONCLUSIONS

The identification of sensitive structures in the proximity of proposed piling operations is essential, as are estimates of potential adverse pile vibration impacts.

With the preparation of suitably accurate geological and geotechnical models, it has been possible to utilise FE program Plaxis 2D axisymmetric dynamic feature to accurately model piling vibrations from the construction of BLB2.

In the absence of precedents for deep unlined LPG storage caverns in Hawkesbury Sandstone the nomination by Elgas of a maximum peak particle velocity (ppv) attenuation limit of 1mm/sec at Cavern level was stringent. This limitation was deemed acceptable however, given the criticality of maintaining the integrity of cementitous grout in the rock mass fractures around the Cavern, for both gas containment and seepage inflow criteria. Our FE modelling predicted a maximum ppv at Cavern level during BLB2 piling of 0.2mm/sec, which was considered to confirm the feasibility of the BLB2 piling design and construction proposal.

Piling at BLB2 subsequently proceeded as proposed and, through the design and implementation of a project-specific pile vibration monitoring system and pile vibration management plan, see companion paper Barbour-Bourne and Jones (2015), the highest ppv recorded at Cavern level during BLB2 piling was 0.124mm/sec.

It was concluded by all stakeholders that the BLB2 piling operation was appropriately and successfully reviewed, modelled, conducted, monitored and managed, in very close proximity to the Elgas undergroung LPG storage facility.

## 8 ACKNOWLEDGEMENTS

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