Bulk Liquids Berth 2 (Sydney): A case study in pile vibration monitoring and management

H. M. Barbour-Bourne[1], MSc BSc (Hons) and D P Jones[2], BSc (Hons) RPGeo

[1]GHD Pty Ltd, Locked Bag 2727 St Leonards NSW 1590 Australia; PH (+61) 02 9462 4700; email: Helen.Barbour-Bourne@ghd.com

[2]GHD Pty Ltd, Locked Bag 2727 St Leonards NSW 1590 Australia; PH (+61) 02 9462 4700; email: Daniel.Jones@ghd.com

ABSTRACT

Sydney Ports Corporation completed in 2013 the construction of the new Bulk Liquids Berth (BLB2) at Port Botany, NSW. (The BLB2 LP was transferred to NSW Ports on 1 June 2013 as part of the 99 year lease for Port Botany and Port Kembla). The berth construction included the installation of 136 large diameter driven piles adjacent to an underground Liquid Petroleum storage facility. The underground facility comprises four large caverns excavated into the Hawkesbury Sandstone bedrock 130 metres below surface level. To ensure the long term integrity of the storage cavern strict vibration limits were set as part of the conditions of approval for the BLB2 piling operations. Dynamic analysis using Plaxis 2D was undertaken, indicating that the proposed piling was feasible within vibration limits. A pile vibration management plan was developed in conjunction with all stakeholders, and a monitoring system installed. The piles were driven to target depths using both vibrating and impact hammer. Piling was staged with the furthest piles from the cavern being driven first, with works proceeding towards the cavern so that construction methodologies could be adjusted if the vibration limits were being approached. Vibration monitoring confirmed that the vibration limit criteria applied to the LP storage cavern were not exceeded by the piling, and that the vibration levels recorded were of the same order of magnitude as predicted in the analysis.

Keywords: LP, cavern, piling, vibration, seismic monitoring

1. INTRODUCTION

The original Bulk Liquids Berth (BLB1) has been in operations at Port Botany since 1979. This berth has been occupied on average between 50-60% of the time for the past ten years and more recently has experienced average berth occupancy levels in excess of 70%. The main products handled at the BLB are refined fuels, gases and chemicals / other bulk liquids. Planning approval to develop a second Bulk Liquids Berth (BLB2) at Port Botany was received from the Department of Planning in March 2008. On 31 May 2011, John Holland Pty Ltd was engaged to construct the BLB2. The berth became operational in December 2013. (NSW Ports, 2014)

Since the construction of the original BLB1 in 1979 a large underground liquid petroleum storage facility was built and after four years of construction, commissioned in 2000.The LP underground storage facility is owned and operated by Elgas Limited, and is adjacent to the supply terminal in Port Botany. The facility is notable in that it is the largest liquid petroleum gas storage facility in Australia and that it comprises large underground caverns excavated into bedrock. The facility consists of four largecaverns referred to as galleries in Hawkesbury Sandstone 130 metres below ground, with each gallery drilled and blasted to measure 230 m long, 11 m high and 14 m wide. The caverns containment of the LP product is based on the hydrodynamic containment principal in that a positive hydraulic gradient of water directed at each cavern will prevent the stored hydrocarbon products from migrating away (Goodall, Aberg, & Brekke, 1988) (King, 1999).

During design phases for the new BLB2 challenges regarding peak ground accelerations caused by construction activities, and primarily piling, were identified by Elgas.as being a potential risk to the existing caverns. Sydney Ports were advised by Elgas that the LP cavern and its operations were sensitive to ground vibrations, and that a maximum Peak Particle Velocity (PPV) limit of 1 mm/sec at the cavern level, with a “never to exceed” PPV of 3 mm/sec was set. Consequently dynamic modelling of pile driving vibrations to be expected by the construction of BLB2 were carried out, followed by the installation of a vibration monitoring system and live monitoring during construction.. Note the vibration limits were set by Elgas’ design advisors who are european based and are commensurate with the highest level (i.e. strictest guideline limit) per Table 1 in DIN 4150 (German Institute for Standardization, 1999).

The design for BLB2 comprises a main wharf, mooring dolphins and various ancillary structures supported by 136 large diameter driven hollow steel tube piles. The contract levels for the piles were mainly in very dense sands, with some piles socketed into bedrock.

2. PILE VIBRATION ANALYSIS

2.1 Geological Model

A geological model of the site was developed using previously drilled deep, as well as new shallow investigation boreholes that had been undertaken as part of the ground investigations for the new BLB2 facility. The geology underlying the site can be characterised as boulder fill material, overlaying reclaimed land of dredged sands, over Botany Sand deposits comprising medium dense silty sand and stiff to very stiff sandy clay. These units unconformably overlie the bedrock, with weathered rock horizons either thin or absent above largely fresh, high strength Hawkesbury Sandstone. A 10 m thick shale bed is present within the sandstone at approximately 90 m depth, some 30 m above the cavern crown. Refer Figure 1 for conceptual arrangement of the piling relative to the cavern.

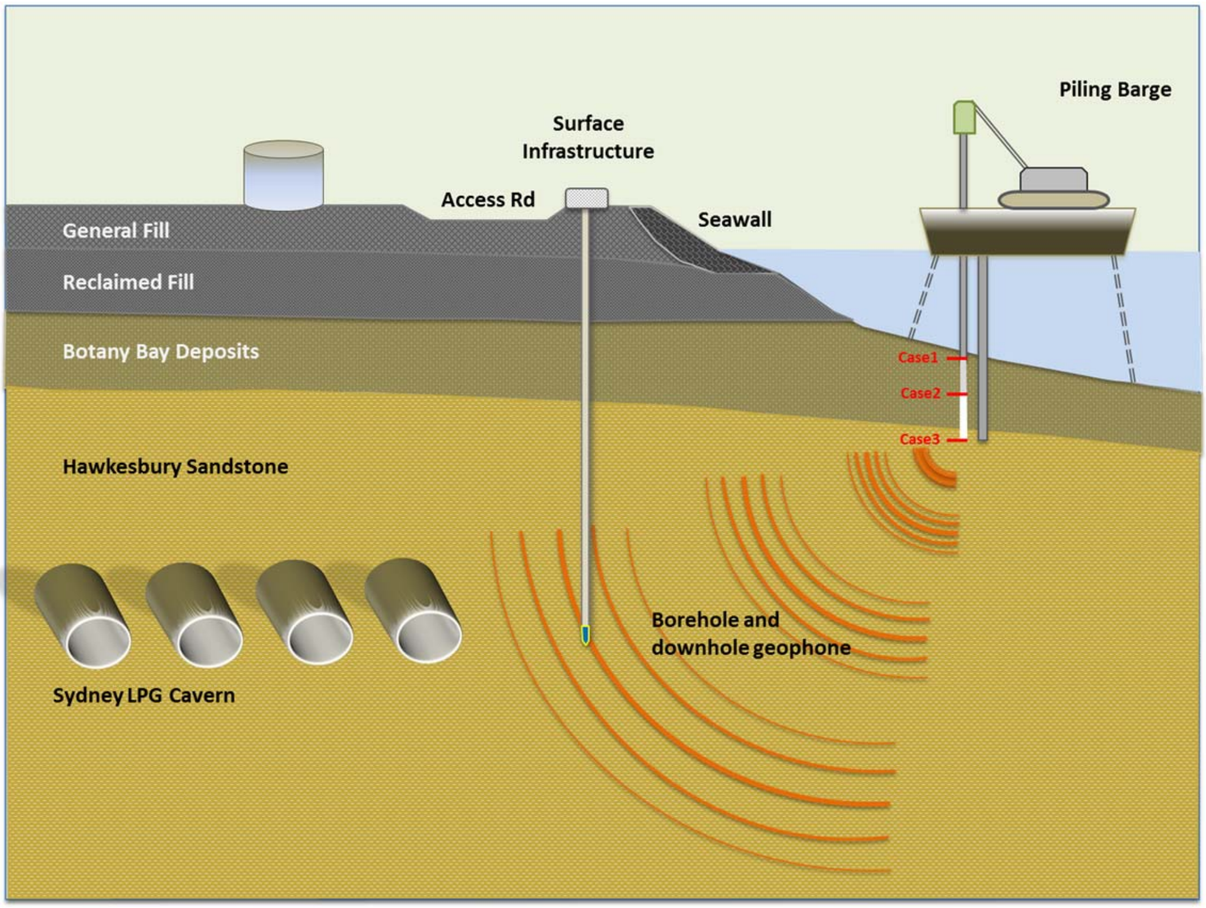

Figure 1. Schematic Cross Section showing geological setting, piling location proximity to Sydney LP cavern and the downhole geophone.

2.2 Plaxis Modelling

Associated analysis involved dynamic analysis of the piling to ascertain if it was feasible to install the piles using conventional techniques in the design locations, staying within the nominated vibration limits. A Plaxis model was adopted that employed an axially symmetric model with a single vertical pile situated at the axis of symmetry, details of the Plaxis input parameters and modelling undertaken are the subject of a companion paper (Kotze & Hull, 2015).

The maximum PPV calculated for the cavern point of interest is 0.2 mm/s using the hydraulic hammer HHK-16S. These results represent the expected increase in impact force with pile penetration approaching and contacting bedrock, whilst also negotiating the expected geological conditions. These results were considered to be the most representative of the proposed BLB2 pile driving.

3. PILE VIBRATION MANAGEMENT PLAN

Notwithstanding the results of the computer modelling, as a risk mitigation measure for the construction of BLB2, a Pile Vibration Management Plan (PVMP) was implemented. One of the principal requirements of the PVMP was to install and, during construction activities, maintain a Pile Vibration Monitoring System (PVMS) to allow nominated stakeholder representatives access to real time information for the timely reporting of data during piling activities. The piling contractor was also required to have provision for an alternative “minimum vibration” pile installation method in case of adverse monitoring results.

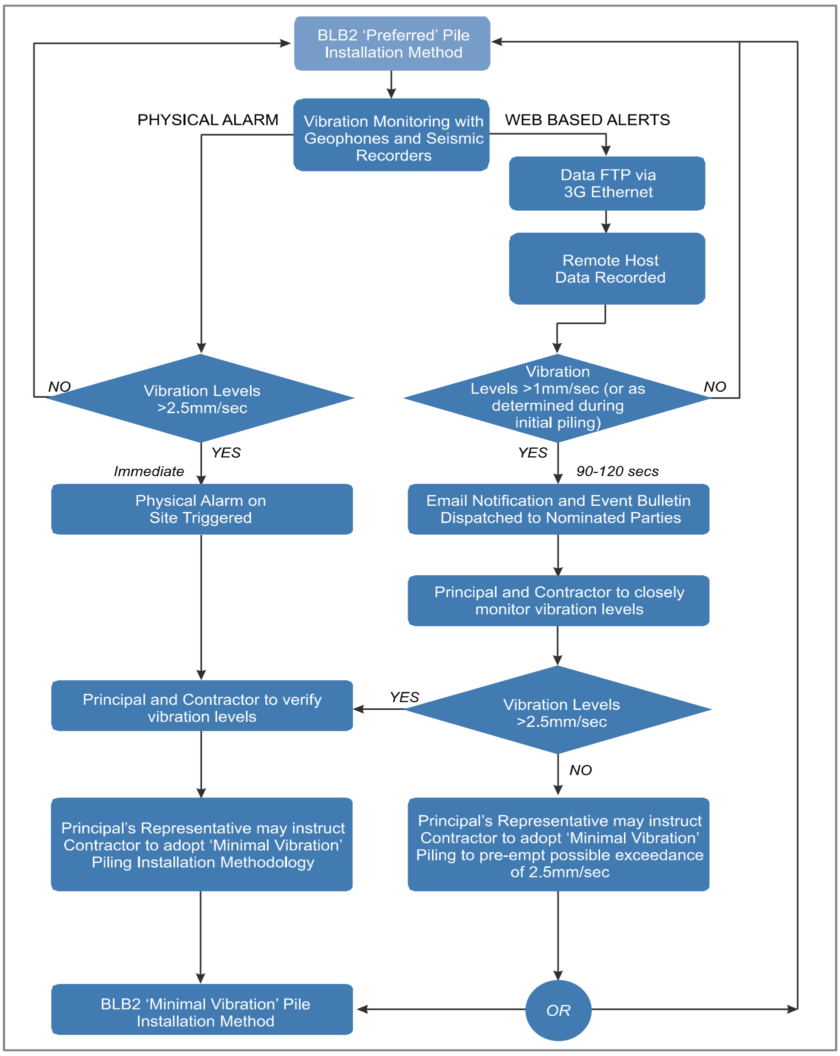

Figure 2. Pile Vibration Management Plan detailing, actions and outcomes to manage vibration limits during construction piling.

The PVMP set out guidelines to be used to direct the pile installation method at each pile location; defined peak particle velocity threshold limits; and nominated outcomes should these values be reached. The nominated limiting values were an “attenuation limit” of 1 mm/sec at the cavern level, and a “never to exceed” value of 3 mm/sec. In summary the PVMP set out the following requirements:

- In the event that monitoring of the piling demonstrated that vibration threshold limits are not exceeded then pile installation proceeded using the preferred piling installation procedure subject to continuing acceptable PPV readings;
- If the attenuation limit of 1 mm/sec were exceeded in an isolated reading that should not be interpreted as a signal to change the installation method;

- If vibrations detected exceeded the attenuation level of 1 mm/sec but did not exceed 2.5 mm/sec, the pile installation continued and any direction by the Principals Representative to change the installation method depended upon the distribution of the recorded readings above the attenuation level;
- In the event that vibration levels exceeded 2.5 mm/sec all pile installations would have ceased immediately, and the direction to change piling methodology to the minimum vibration method would follow.

The magnitude of transmitted vibration is considered to be inversely proportional to the square of the distance therefore it was anticipated that piling within areas of broadly similar distance would result in the transmission of similar vibration levels. As such the site was divided into pile installation zones based upon the distance of the pile from the nearest point on the cavern.

The initial piling set up location was nominated to be at the furthest point from the cavern with the piling contractor to employ their nominated preferred method for installation. Depending on the monitored PPV readings of the transmitted vibration the pile was to be installed to its full design depth. Following the successful completion of the first pile, a pile at a median distance to the cavern was nominated for installation. Once these two piles were successfully completed the contractor could undertake the piling in their preferred order. During piling closest to the cavern it was required to have a designated person on-site actively monitoring the PVMS and correlating the timing of the piling activities and the vibrations recorded to ensure no breaches of the PVMP.

4. PILE VIBRATION MONITORIN**G**

The Pile Vibration Monitoring System (PVMS) was developed to measure the vibrations at locations between the cavern and the pile by the use of geophones. Given the LP facility is continuously filled with gas and is not accessible at any time, no new geophones can be installed within the caverns. Geophones installed at the ground surface or seabed would not be representative of the vibrations occurring between the piling located offshore in Botany Bay some 30m below sea level, and the cavern at around 130m depth. Geophones were needed to be installed between the piling tip and the cavern as described.

Four locations were chosen on the seaward side of the caverns to install geophones in boreholes at 130m depth below sea level. A fifth geophone was installed on the opposite side of the cavern to observe attenuation across the caverns. The distance horizontally between the closest pile and the sidewall of the cavern was 72m. Since geophones would not be located at the cavern itself, two of the seaward geophones were installed in locations that were at cavern level (i.e. at 130m depth) and were exactly 72m from the nearest pile location. These two geophones, when piling at the closest point, would record the equivalent level of vibration as that experienced at the cavern.

4.1 Installation of pile vibration monitoring system

In May 2011 five boreholes advanced through reclaimed-land fill, Botany Bay deposits and into Hawkesbury Sandstone. Due to the proximity of the borehole to the Elgas LP gas storage facility drilling was undertaken by specialist gas well accredited drillers utilising appropriate safety equipment, including a Blow Out Preventer (BOP) comprising a valve and flare line at the surface and steel casing grouted into competent bedrock.

Downhole survey of all the boreholes was undertaken using a digital gyro survey system to ensure that the boreholes did not deviate towards the cavern and that the geophones were installed at the nominated location. Inclinometer casing was installed to the base of each of the boreholes with a survey of the inclinometer twist undertaken. In each borehole a geophone (and a backup) was installed on guides made to fit the grooves of the inclinometer casing. With the downhole survey and the inclinometer twist survey a true location and orientation of the geophone was provided.

Once the geophone was at full depth down the hole and had been tested, it was grouted into place via a tremmie tube, with the grout allowed to flow into the annulus around the inclinometer case through large perforations that had been predrilled though the inclinometer casing. Near the collar of each borehole, surface infrastructure for the geophone was established, comprising a footing with a weatherproof housing containing a seismic recorder and a 3G wireless modem powered by rechargeable batteries and solar panels.

The installed system continuously records data locally, but in order to manage and review important data a trigger system was implemented. Email alerts were sent out when predetermined threshold values or ratios of Short Term Average over Long Term Average (STA/LTA) were reached. Figure 3 details Pile Vibration Monitoring, interface between the installed downhole geophones, seismic recorders, software interface and stakeholders.

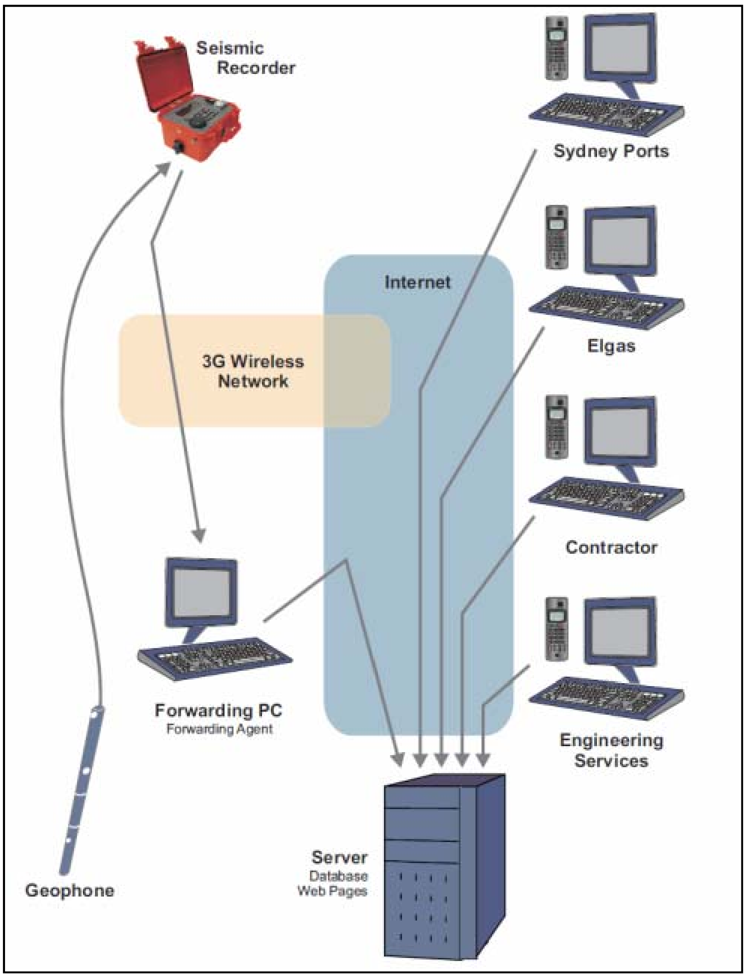

Figure 3. Pile Vibration Monitoring System: showing the interface between installed equipment, software and the various stakeholder parties.

4.2 Background monitoring phase

Following the commissioning of the PVMS and prior to commencement of piling approximately four months of background data was monitored. This period was intended to provide data on the background “noise” at the site and ensure no false positives occured during the actual piling installation. The general ambient background vibrations were between 0.0001 to 0.0006 mm/sec, punctuated by events that were attributed to surface events, geoseismicity or vibrations associated with adjoining site activities.

Of interest was that the system could often detect the berthing of ships at BLB1 as well as the jostling of vessels on the BLB1 moorings when there were strong prevailing northwesterly winds. A minor geoseismic event was recorded on 8 August 2011 at around 22.34 EST with the epicentre located approximately 1 km west of Port Botany, and an earthquake magnitude (ML) of around 1.3. This was also confirmed by an external third party seismic network. The maximum PPV recorded for the geosiesmic event was 0.011 mm/sec. At the commencement of site activities, but prior to piling, some jet grouting was undertaken for some temporary works. The geophone in the vicinity of the contractor facilities recorded events in the order 0.008 to 0.012 mm/sec, with 0.012 mm/sec being the maximum vibration recorded prior to piling commencement.

4.3 Pile installation and Construction monitoring phase

Pile driving commenced at BLB2 in November 2011. Piling was undertaken from a flexi float barge positioned in the water using anchors. Pile driving was managed using a 250 tonne crane with a 56 m boom. The crane was used to position the pile into the piling leader after which the gates of the leader closed around the pile. The crane then lifted a 14 tonne ICE (International Construction Equiment) vibrating hammer onto the top of the pile and engaged the jaws of the hammer on to the top of the pile with the crane taking the load of both the hammer and pile. The pile was initially driven using the vibratory hammer until first refusal of the pile. Piling was then completed using a Juntan 9 tonne impact hammer to drive the pile to the required contract level. See Figure 4 for a typical piling set up at the BLB2 site.

Figure 4. Poseidon flexi-float barge and 250 tonne crane, with pile in the leader using the 14 tonne ICE vibrating hammer to drive a raked pile.

In accordance with the PVMP, early in the project an “Intensive Pile Vibration Monitoring” period applied to certain key locations. These areas were subject to piling sequentially and were used to develop an understanding of what piling activities were taking place and the associated PPVs. In particular correlation of time, type of piling equipment, toe RL at start and end of piling, pile blow counts, range and maximum PPV’s recorded and which geophone recorded the maximum ppv were required to make an assessment of the data. All remaining production piling locations, not nominated for “Intensive Pile Vibration Monitoring”, were monitored remotely. Monitoring reports were provided weekly to the nominated stakeholders.

4.4 Observations during piling

In most cases the drop or impact hammer recorded higher PPV’s than the vibrating hammer for the same pile. During piling for each piling episode when the hammer drop height was increased it was possible to see an increase in the value of the PPV. When the hammer drops there is the initial impact of the pile followed by a secondary bounce. This “hammer bouncing” trace could also be observed in the recorded PPV’s. See Figure 5 for characteristic wave forms for the Juntan 9 tonne impact hammer and Figure 6 for 14 tonne ICE vibrating hammer.

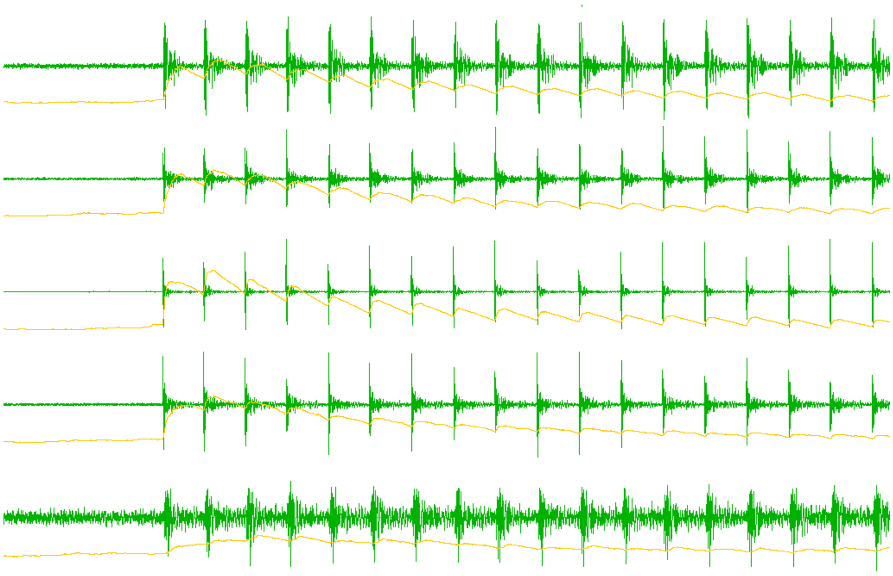

Figure 5. Characteristic wave form for Juntan 9 tonne impact hammer, which clearly shows impulses generated by the primary impact of the hammer and a secondary “hammer bouncing” trace (the X axis time and Y axis PPV value).

The recorded pile vibrations were consistent with what was expected across the site with no apparent variation or amplification caused by an unidentified potential geological feature. For example the attenuation over distance was well demonstrated by the piling for the road bridge structure. Piling for this long linear structure moved progressively past the monitoring points, with the maximum vibrations progressively moving down the line of geophones.

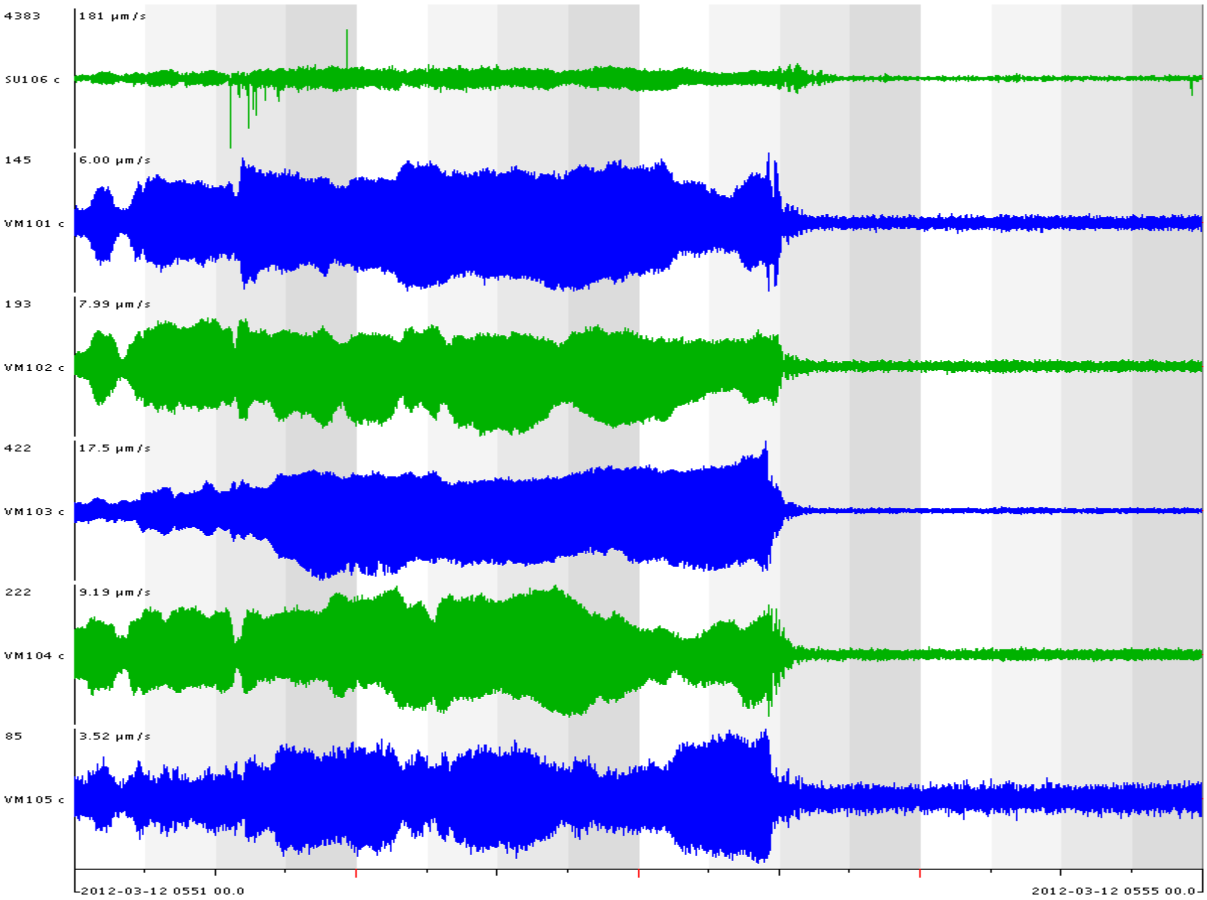

Figure 6. Characteristic wave form for the 14 tonne ICE vibrating hammer, (the X axis time and Y axis PPV value).

A total of 136 piles were driven for the construction of the BLB2 project between 29 November 2011 and 26 April 2012. The vibrations at cavern level were recorded by the PVMS for each pile driven, and a maximum PPV for that pile reported. The highest PPV recorded during piling was 0.124 mm/sec whilst using the Juntan 9 tonne impact hammer to drive the pile to contract level for the mooring dolphin closest to the cavern.

During the construction and phase there were no verified incidences of an exceedance of the vibration limits. There were occasional spikes which did trigger the alerts system, however following an assessment of the wave forms it was quickly determined that these were not vibration waveforms but electrical interference. As no vibration limits were exceeded the piling contractor was able to install all piles with its preferred piling methodology and there were no resultant delays in the piling program.

5. CONCLUSION

The associated Plaxis 2D analysis modelling predicted the piling would generate a maximum PPV of 0.2 mm/sec during hard driving at the closest point to the cavern (Kotze & Hull, 2015). The rigorous monitoring system and processes put in place on this project saw a maximum observed PPV during construction piling of 0.124 mm/sec whilst pile driving at the closest location to the cavern. The prediction and the observations are very similar and demonstrate that with the development of an accurate geological model, appropriate input parameters and sensible modelling it was possible, in this case, to closely predict what occurred in reality.

Whilst the vibration limit set was low, the project with normal piling procedures was deemed feasible based on the modelled predictions. The project was completed with all stakeholders satisfied that the nominated vibration limits had not been breached by the piling activities at any time. The PVMS was not only effective in detecting construction phase vibration it was also clearly able to distinguish between hammer types, and even detect local seismic events.

6. ACKNOWLEDGEMENTS

We would like to acknowledge ES&S, NSW Ports, Smithbridge Group and Elgas Limited.

REFERENCES

German Institute for Standardization. (1999). DIN 4150-3 (1999-02) Structural vibration - Effects of vibration on structures. Berlin, Germany: DIN.

Goodall, D. C., Aberg, B., & Brekke, T. L. (1988). Fundamentals of gas containment in unlined rock caverns. *Rock Mechanics and Rock Engineering, 21*, 235-258.

Kotze & Hull (2015) *Vibration assessments for the Sydney LPG cavern from construction piling for the adjoining Bulk Liquids Berth 2, Port Botan, Australia.* ANZ 2015

King, J. (1999). *Hydrocarbon storage in mined caverns, a guide for state regulators.* Oklahoma: Interstate Oil and Gas Compact Commission, Oklahoma City.

NSW Ports. (2014, 09 21). Projects and Planning - Bulk Liquids Berth 2. Port Botany, NSW, Australia. Retrieved from http://www.nswportsbotany.com.au/projects-and-planning/bulk-liquids-berth-2/