Resonance Pile Driving with Zero Ground Vibration

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Abstract:

The Resonator RD 260 Resonant Pile Driver promises ground disturbance free, high production pile driving. The Resonator has recently been used on three production pile driving sites in the Netherlands and Melbourne, Australia to drive piles in sensitive areas where conventional pile drivers could not be used. Three case histories are provided. In the Netherlands the Resonator RD 260 was used at the Vopak Oil Storage facility in the Port of Rotterdam and the Oosterhaut Watermain replacement. Both sites required vibration free pile driving to create cofferdams adjacent to sensitive, highly valued assets. In each case access was an issue and schedule demands were stringent as shutdown windows were narrow. At each site the RD 260 provided ground disturbance free piling immediately adjacent to fragile structures. At Vopak the only site access was using a large crane positioned over 40 m from the location of pile driving. Driving was conducted amongst 900 mm dia pipes carrying heated crude oil.

In Melbourne the RD 260 was used to drive GU 18 sheet piling adjacent to light rail easements. The project was the first of many grade separations being constructed within Melbourne urban areas to lower the light rail and provide quieter rapid transit. The original trial used an RGT MR105 series vibrator but noise and vibration criteria were exceeded. The RD 260 was brought in for a trial and performed with high production and produced negligible ground vibration. Up to 17 sheet piles 14 m in length were driven in a 2.5 hour window during the trial.

Introduction

The Resonant Pile Driving method is gaining acceptance around the world as a new method to rapidly drive piles free of ground borne vibrations. The high frequency vibrator resonates the pile, essentially turning the pile into a spring, to excite the toe of the pile with high accelerations and low amplitude. High acceleration with low amplitude generates high penetration rates but the high frequency stress waves are quickly dissipated in the soil. Typically ground borne vibrations are measured at below 1 mm/sec within 1 to 5 m of the pile. The Resonant method can drive a pile next to a glass of wine, as has been demonstrated on numerous piling sites.

How Does Resonance Work?

The resonant method uses a hydraulic piston - cylinder geometry to generate high magnitude, high frequency oscillating force. This is a very different mechanism than the eccentric mass technology used in conventional sonic drills and vibrators.

A unique valve geometry achieves the high frequency flow switching necessary to oscillate the hydraulic piston at up to 180 Hz (10800 VPM). The valve rotation is controlled electronically for maximum accuracy of the desired frequency. The volume of hydraulic oil delivered through the valve (flow rate) determines the amplitude and the hydraulic pressure determines the peak force.
The main advantage of the Resonant piston-cylinder method is that it allows the vibration frequency to be tuned to the natural frequency of the pile, which excites the pile like a spring. Exciting the pile like an axial spring allows the storage (build up) and release of vast amounts of energy. In this way the pile is brought to a high acceleration state that penetrates through the soil. The challenge is to continuously tune the vibration frequency to the natural frequency of the pile as it is being driven into the ground. A computer algorithm has been developed for the Resonant Driver which automatically performs this tuning function. Through tuning the maximum driving efficiency and maximum force at the pile tip is achieved.

Vopak Oil Storage Facility Rotterdam

At the Vopak oil storage and transfer facility in Rotterdam, NL a pipe and valve gallery upgrade required the driving of a sheet pile cofferdam and new pipe bearing piles to expand and improve the facility. Typically pile driving, using either impact or vibratory methods, is not permitted due to the sensitive nature of the pipe valves and galleries. Poor access and difficult terrain generated by steep oil spill containment berms prevented the use of conventional or even small equipment from accessing and working at the site. The proven performance of the Resonator in similar soils allowed the owner to entertain use of the Resonator RD 260 Driver suspended from a 200 tonne crane situated on an access road over 35 m from the location of the sheet pile wall and pipe piles. AZ 18 x 700 sheet piles of 12 and 16 m in length and 323 mm od x 12.7 mm wall open ended pipe piles 24 and 28 m in length were to be driven.

![Figure 1. Vopak Facility Site plan](image_url)

The site is adjacent to the Maas River in the Port of Rotterdam. The soils consist of alluvial deposits typical of mature deltaic structures. A typical CPT plot is provided in Figure 3 which shows sands and sandy silts with interbeds of clayey silts and silts. The soils are generally weak with Qc values generally between 10 to 20 MPa with peaks of 25 to 30 MPa. Friction values range between 100 kPa to 250 kPa with Rf % of 1 to 2 % and highs of 3 to 4%.
Figure 2 Site plan showing Pipe Gallery and Cofferdam location

Figure 3. Typical CPT at the Vopak site, Port of Rotterdam.
Sheet piling operations began in January of 2016 with de Koning BV foundation contractors, NL. Sheet piles varying in length between 12 and 16 m were driven immediately adjacent to live pipes and valves that continued to carry heated crude and refined oils. Ground and pipe/valve monitoring was conducted throughout driving and established ground vibrations of less than 1.5 mm/sec and structure vibrations of less than 1 mm/sec. The owner specified vibrations were not to exceed 5 mm/sec.

The AZ 18 x 700 sheet piles drove easily in the 12 m lengths. Threading, plumbing, driving and completion of sheets were straightforward with driving times of less than 5 minutes common. However, the same sheet, and often immediately adjacent to easily driven 12 m sheet piles proved to drive easily or with great difficulty. Some sheets required up to 45 minutes to drive due to what appeared to be clutch friction or difficulty in controlling the spreading of the sheet pile tips (when driven in pairs). Single sheets often proved to be no easier to drive. The clamping system used a single clamp situated over the clutch of the sheet pile pair and thus drives the sheet off of the central axis and centre of mass. When driving single sheets the clamp was placed on the centre of the sheet web and thus would be at or close to the centre of stiffness and centre of mass of the sheet.

It was determined that the cause of the difficulty in advancing the sheet is related to the off axis resonance modes of the sheet piles, either in bending or in torsion. In the bending mode the sheet had a tendency to both flex and form traveling or standing waves or suffer from high amplitude ‘flange flapping’ where the flanges of the sheet would move laterally at high frequency and amplitude. These motions robbed energy from the driving process, increases clutch friction and increased soil damping during the driving process.

The 323 mm dia pipe piles were driven open end to working capacities of 700 to 900 kN. The pipes were driven to depths of 24 m and 28 m. The Resonator required 20 to 28 minutes to drive the pipe. Ground vibration monitoring proved peak particle velocities of about 1 mm/sec at 3 to 5 m.

This proved to be the first time the Vopak site permitted any form of pile driving within the active facility which proved to be a huge success for both the owner and the contractor as great savings were realized through the use of large, remotely based equipment that could reach into the pipe gallery and suspend the driver. Similar upgrades are planned for the facility in the future.

**Oosterhaut Watermain**

The Oosterhaut watermain project proved to be an emergency repair of a leaking, high capacity, high priority watermain in south Central Holland. The municipality required a cofferdam in order to exhume the problem watermain and conduct a repair. The saturated soil proved to be soft and at high risk of settlements or disturbance due to vibration, which could cause movements of the watermain and further damage. The Rd 260 Resonator was selected as it ensured minimal ground disturbance during placement of AZ 26 by 14 m long sheet piles to form the cofferdam.
The cofferdam drove very well in the alluvial soils. A typical CPT plot is provided in Figure 4 above showing dense sands and sandy silts. The water table was at a depth of about 2 m. The soils are generally dense with Qc values generally between 10 to 20 MPa with peaks of 25 MPa. Friction values range between 50 kPa to 125 kPa with Rf % of 1 to 1.5%.

The cofferdam was completed with little difficulty in terms of clutch friction or off axis bending. Though the soils are slightly less dense at the Oosterhaut site the main reason appears to have been the heavier sheet sections drove better with less off axis motion. Overall the driving experiences indicate that a combination of axial and off axial resonant modes may coincide or be close enough in frequency to cause multiple vibration modes during driving of certain sheet sections and lengths. Typically a lighter sheet section will be more susceptible to off axis movement and lower off axis resonant modes with more multiples within the range of driving frequency. Should off axis resonance occur it can hamper the driving process with increased resistance (due to clutch friction and off axis vibration amplitude) and a loss of driving energy as the undesired, off axis modes and flange flapping modes absorb energy. The diagrams below in Figure 5 render a typical sheet pile in axial and off axial resonance.
Melbourne is undergoing a major grade separation as part of a cross town light rail upgrade. The current at surface light rail commuter service is to be dropped below ground in excavated trenches to improve noise and traffic congestion through removal of over one hundred level crossings. A test program was conducted using a standard Bauer RGT rig with an MR105V high frequency vibratory driver. The ground at Bentleigh is very hard dry clays and clayey sands and thus pre-boring was required to achieve penetration. Various pre-boring geometries and depths were used for the test program and the sheets were successfully driven to depth (14 to 16 m), however, noise and vibration restrictions were exceeded using the RGT system. Following the test...
program a change was proposed to drilled methods of shoring construction which was much more expensive and time consuming. An additional test program was conducted using the RD 260 Resonator technology. Similar pre-boring was conducted and the sheets were driven to grade in less time using the RD 260 than the MR 105V and with a fraction of the ground vibration. Noise was less with the RD 260 as well and met the required specification.

The Bentleigh site soils are represented by the borehole below in Figure 6. Soils consist of very dense sands and very dense clayey sands with SPT blow counts exceeding 60 bl/300 mm and typically in the 100 to 125 range. The formations were very dry with ground water emerging only during the wet season at depths of 8 to 10 m.

The grade separations consisted of bringing the trains 6 to 8 m below ground at stations and major crossings. Long stretches of track where the trains run at high speeds were left at grade. Thus the trenches consisted of gradual slopes into and out of the rail stations and crossing depressions. Sheet pile walls were constructed to permit excavation and placement of base slabs and wall slabs supported by cast in place struts. The working easements were restricted and ran adjacent to heavily

![Figure 6. Bentleigh Road typical Borehole](image)
travelled train and road corridors. Residential communities surrounded the construction with houses typically as little as 12 – 15 m from the piling work. Noise and vibration mitigation were mandatory. A program of pre-drilling followed by sheet pile driving was conducted on several sites simultaneously. Noise and vibration monitoring was conducted throughout the work.

The contractor purchased a total of 3 RD 260 units which were mounted on Eurostyle base machines from Liebherr, ABI and Bauer. A total of over 8 months of piling was required to complete the work. GU 18 and PU32 sheet piles were driven in lengths varying from 6 m through to 18.5 m. Driving times varied as soils conditions changed across the site with some regions experiencing very hard soils (>150 bl/300mm) which required additional pre-boring. Productions as high as 28 to 34 sheet piles per day were recorded.

Noise
Noise monitoring was conducted for both the RGT and the Resonant sheet pile driving at the Bentleigh site in similar soils and under similar driving conditions (sheet type, length and driving time). Figure 7 indicates the measured results for noise and a regression analysis predicting noise closer to and further away from the source for each of the RGT and the Resonator. The data shows the Resonator (red dots) is on the order of 6 to 8 dBA lower than the RGT MR 105V hammer. The measured sound pressure indicates the Resonator achieved noise levels of 80 dBA at a distance of 12 m. This is in keeping with measurements made in Canada and Europe under similar conditions. Pipe and HP piles are significantly quieter as the sheet piles are very flexible and become loud speakers. Concrete piles are typically very quiet and will easily pass residential noise requirements.

Vibration
Vibration monitoring was conducted throughout the Bentleigh and McKinnon Road grade separation projects. Measured ground vibration for the RD 260 during the pile test program and throughout production driving was a maximum of 1 mm / sec. Spectral density analysis indicated the majority of the ground borne energy is at the
driving frequency, which, with the Resonator is typically higher than 100 Hz. Thus the motion is at a high frequency and as a result the actual ground displacement amplitudes are very low. Ground motion within a range of 1 to 5 m of the pile remains at just 1 to 1.5 mm/sec. During the RGT test program measurements indicated ground vibrations as high as 30 mm/sec at 10 m from the pile. Thus the RD 260 Resonator produces on the order of 1/30 the vibration of a conventional vibrator and is essentially un-noticed by a human.

![Figure 8. Measured ground vibration for RD 260 and MR105V](image)

**Conclusion**

Resonant Pile driving has proven to provide rapid pile installation with negligible ground borne vibrations and negligible settlement of nearby soils or structures. High frequency vibrations cause near pile liquefaction of the soil and high pile accelerations cut cleanly, leaving the soil undisturbed. Vibration and optical survey monitoring during Resonant driving of piles indicates little to no disturbance occurs. Noise levels are typically less than that of conventional pile driving but may be affected by off axis vibration modes and are noisier for lighter sheet piles. Pile drivability is high for heavier Z sheet or U section sheet piles where higher stiffness and driving closer to the centre of stiffness and mass reduce off axis vibration modes. Sheet, pipe and HP piles have been successfully driven to high capacities in a variety of soils.