The installation of piles and casings is becoming increasingly difficult as restrictions on vibration become common in major urban areas. The use of high frequency, resonant excitation of a pile or casing permits ease of installation of sections to great depths with near imperceptible vibrations as close as 1 pile diameter.

The new Resonant Driver is able to excite a pile at its resonant frequency (up to 150 Hz or 9000 VPM) to produce elevated levels of acceleration, force and displacement in the pile. The combination of extremely high acceleration and controlled levels of displacement allow the pile to slice through varied soil with almost no vibration translated into the ground. In direct comparisons between conventional vibrators and impact hammers the Resonant Driver produces less than 1/50th the vibration. The Resonant Driver results in ground vibration of between 1/20 and 1/40 of common limit levels (1 cm/s or 0.5 in/sec) as close as 1 pile diameter. At a distance of 5 m (16 ft) from the pile or casing vibration levels approach imperceptible levels.

The Resonant Driver uses a proprietary algorithm to tune the drive vibration to the changing natural frequency of the pile as it is driven into the ground. By maintaining resonance the energy in the pile is built up like in a flywheel on an engine or a child on a swing. This build up of energy aids in driving and significantly reduces waste. Recent experience using the Resonant Driver is proving the technology can drive a variety of steel pile and casing sections through varied soils. Continued use of the Resonant Driver will create a data base of various pile and casing sections, soil types and achieved capacities.

**Introduction**

The installation of piles and casings is becoming increasingly difficult as crippling restrictions on vibration become common in major urban areas. Conventional impact and low frequency vibratory methods are no longer available to the contractor to advance piles and casings. High frequency conventional vibrators are able to reduce the measured ground vibration in many situations, however, they often cannot meet the restrictive limits imposed or may not be used immediately adjacent to sensitive structures. The use of super high frequency (up to 150 Hz or 9000 VPM), resonant excitation of a pile or casing permits ease of installation of sections to great depths with near imperceptible vibrations as close as 1 pile diameter.

The new Resonant Driver is able to excite a pile or casing at its resonant (or natural) frequency to produce elevated levels of acceleration, force and displacement. Combined high acceleration and controlled levels of displacement allow the pile to slice through varied soil strata with near imperceptible levels of vibration translated into the ground. Direct comparisons between conventional vibrators and impact hammers indicate the Resonant Driver produces less than 1/100 the vibration. The Resonant Driver results in ground vibration of between 1/20 and 1/50 of common limit levels (1 cm/s or 0.5 in/sec) as close as 1 pile diameter.

The Resonant Driver uses a piston - cylinder mechanism to deliver force to the pile through a specialized clamp. The high accelerations associated with resonance require non conventional clamping of the Driver to the pile. The Driver uses a proprietary algorithm to maintain constant tuning of the Driver frequency to the resonant frequency of the pile and ground. As the pile or casing penetrates the ground the natural or resonant frequency of the system changes. Without constant adjustment and tuning the Driver would apply the energy in contrast to the resonant frequency and thus at lower and lower efficiency with resulting stalling of the pile in the ground.

The concept of resonance is identical to pushing a child on a swing or shattering a wine glass with a tuning fork. The Resonant Driver
simply supplies power in tune with the natural frequency of the pile for maximum energy efficiency with no energy wasted in the 're-mobilisation' of the pile. The pile uses the energy to penetrate the soil at high acceleration and thus reduces energy loss to the ground. The increased efficiency of resonance results in:

- High production
- Small power sources, low energy costs and less pollution
- Low hammer weight, (200 Hp hammer weights 5000lbs)
- Virtually no vibration to the surrounding soil

Technology

The Resonant Driver is new technology offering high productivity, extremely low ground vibration and the potential for greater versatility than conventional piling equipment. Unlike existing impact or vibratory equipment that waste up to 70% of the energy shaking the ground, the Resonant Driver transfers higher amounts of energy directly to the point of work. When resonance is achieved energy is transferred into the pile in the most efficient possible way.

The reader is familiar with the propagation of a stress wave in a pile during impact driving. The impact impulse travels down the pile as a compression wave and reflects from the toe back to the surface as a tension wave. This wave reflection occurs over a time that is the natural period (frequency=1/period) of the pile. The Resonant Driver is able to time the push and pull cycle to coincide with the input and reflected stress waves. Thus the Resonant Driver applies a downward compression force that creates a travelling stress pulse down the pile. When the pulse reflects upward to the pile top as a tensile stress wave the Resonant Driver applies a tension or pull cycle, thus amplifying the existing stress and amplitude in the pile. By pushing and pulling at one end of the pile or casing the Resonant Driver is able to set up a standing wave pattern in the pile or casing. Effectively the pile or casing becomes a fly wheel into which the resonant energy is delivered. Within just a few resonant cycles the pile develops substantial amplitude and acceleration. An important aspect of the excitation is that at 120 to 150 Hz and amplitude of 5 mm, accelerations on the order of 150 to 225 g are produced. These levels of accelerations are equivalent to impacts which shed the soils efficiently and effortlessly in order to cut the pile through the soil and produce extremely low energy transfer and vibration into the soils. However, the high accelerations require non conventional clamping of the Resonant Driver to the pile.

The Resonant Driver uses a piston - cylinder mechanism to generate the excitation, unlike conventional vibratory hammers that use eccentric masses. The use of a piston cylinder arrangement, with a nimble valve geometry, allows for rapid tuning of the frequency independent of hydraulic fluid flow. In addition the Driver may started at any frequency, thus eliminating the ‘run up and run down’ through all frequencies with conventional equipment that can shake the base machine. The hydraulic fluid flow defines the amplitude of vibration and the pressure defines the force of vibration. The design is very simple and uses significantly fewer moving parts than conventional rotating shaft vibratory equipment. The only moving part subjected to high vibrational forces is the simple external casing. There are no bearings that experience high levels of vibration. In addition, the simple geometry of the mechanism allows for rotation of the pile or casing while vibrating (coincident drilling and vibration).

The equipment uses an algorithm to maintain constant tuning of the Driver frequency to the resonant frequency of the pile and ground. As the pile or casing penetrates the ground the resonant frequency of the system changes. Without constant adjustment and tuning the Driver would apply the energy in contrast to the resonant frequency and thus at lower and lower efficiency, with resulting stalling of the pile in the ground.

An important feature of the independent control over the force and amplitude of vibration is that it allows a large Driver to be used to drive even the smallest of piles. Typically large hammers can only operate on large piles that have sufficient mass and cross sectional area to prevent damaged. The large hammers cannot be ‘turned down’ to operate on smaller piles. A large Resonant Driver can accommodate even micro or pin piles because the flow rate can be easily reduced to limit amplitude and the pressures are a function of the resistance of the system. Thus a small pile with limited resistance
during installation will draw only enough pressure to advance the pile.

Increasing experience using the Resonant Driver is creating a data base of various pile and casing sections, soil types and achieved capacities. Early results indicate the Resonant Pile Driver may be used along side existing impact and vibratory equipment for many applications while eliminating ground vibration and maintaining site production.

**Demonstrations**

At recent test sites the 140 kW (200 Hp) Resonant Pile Driver has been used to drive 310 mm HP piles and pipe between 300 and 600 mm with masses of up to 176 kg / m. The HP piles drove well into soils of varying density due to the pile’s low cross sectional area. Smaller pipe piles also drove well, while the larger diameters had a tendency to form plugs and stall. In comparisons to conventional hammers, both impact and vibratory, the Resonant Pile Driver has performed generally very well. What remains significant is the absence of measured ground borne vibration during driving using the Resonant Driver.

**Test Site 1**

Piles were driven within the Fraser River Pile and Dredge Ltd yard located at 1830 River Road, New Westminster, British Columbia. The yard is located on the north bank of the North Arm of the Fraser River within the geography of the Fraser River Delta. The soils consist of dense alluvium over glacial tills. The Fraser River flows past a major terminal moraine (the New Westminster and Burnaby massif), which consists of highly variable, dense to very dense glacio alluvial soils. The Fraser River Pile and Dredge yard sits on the southern terminus of this moraine.

![Figure 1. The 140 kW (200Hp) Resonant Driver mounted on a 600 mm diameter pipe pile.](image-url)
Geotechnical Parameters

The site consists of 3 m. of coarse granular materials that contain many inclusions of timbers, steel, cobbles and boulders over native glacio alluvial soils. The native soils are typically dense to very dense sands and gravels with cobble sizes. The water table varies with the tidal influence of the Fraser River at about 3 to 5 m in depth below the surface.

Geotechnical investigation was conducted via exploratory drilling at the proposed location of the test piling. The first bore hole was conducted using hollow stem augers. The SPT counts within the upper 3 m were obfuscated by the presence of timbers and cobble sizes but were generally in the 10 to 20 range per 300 mm. Below 4 m the hollow stem auger plugged and jammed due to sands infiltrating the hollow core of the augers. A second borehole was conducted within the proposed test area using solid stem augers to a total depth of 14.2 m. SPT counts were difficult to obtain due to caving of the solid stem auger hole at the 4 – 5 m depth upon retraction of the augers. This region experienced wet running coarse sands and gravels. Below a depth of 5 – 6 m the drilling was very difficult with high torque pressures and high downward pressures required to advance the augers. The augers encountered significant resistance to turning and penetration throughout the drilling between 6 m and 14 m depth in dense to very dense coarse sands and gravels. At 14 m very dense silt glacial till was encountered. SPT blow counts are estimated to be in the range of 50 to 80 blows per 300 mm between 5.4 and 14 m. Within the very dense glacial tills the blow counts are estimated to be on the order of >100.

Pile Driving

Two piles were selected for driving using the Resonant Driver. The first pile was a 19.8 m long HP 310 x 74 kg HP (HP 12 x 53) section with a mass of 1480 kg. The second pile was a 17.8 m long 300 mm diameter pipe pile with a 22 mm wall and a total mass of 2668 kg. The pipe pile tip was treated with a weldment to increase the outside diameter by approximately 10 mm.

The HP pile was driven to a depth of 12.5 m (41 ft), over a period of approximately 19 minutes. The pipe pile was driven to a penetration of over 9 m over a period of approximately 14 minutes. Each pile was monitored for vibration using conventional Blastmates (SSU 2000DK Seismograph and noise monitoring station by Geosonics) and high precision vibration monitoring sensors.

In comparison, using conventional technology, an 18 m long HP 310 x 74 pile was driven to a depth of 6.3 m using a 1640 kg (3600 lbs) drop hammer with varying height. Drop heights were increased to 3 m, or 48kNm (36000 ft*lbs), from 2.5 through 6.3 m penetration at end of driving. Blows varied from 5 to 20 / 300 mm in the upper 2.5 m and increased from 35 to 60 bl / 300 with depth to 6.3 m penetration. The time required to drive the pile was approximately 1 hr 08 minutes.

An ICE 216 (133 kWatt or 180 Hp) conventional vibrator was used to drive an 11.9 m (39 ft) long HP 310 x 74 (HP 12 x 53) pile. The pile was driven to a maximum depth of approximately 2.5 – 3.0 m at 4 locations but was unable to penetrate the dense gravels and cobbles at a depth of 2.5- 3.0 m despite driving times in excess of 10 to 15 minutes. At a later date an MKT - V17, 250 kWatt (335 Hp) conventional vibrator was used to drive a pile in direct comparison to the Resonant Driver. The MKT hammer drove an 11.9 m (39 ft) long HP 310 x 74 (HP 12 x 53) pile to refusal at a depth of 11.3 m. The total driving time for the pile was on the order of 10 to 11 minutes. During the driving of the pile a large depression 1.2 m (4 ft) across was formed around the pile at the stabbing point. Very high vibrations were noticed up to 3 or 4 metres from the pile.

Noise monitoring was conducted using a Bruel and Kjaer type 2250 sound meter. The acoustical data provides a time history of the sound level in dBA at 5, 10 and 30 m for intervals that include background noise and Resonant Pile Driver operation. The noise levels are typically 85 dBA for background (including the revving power pack), 100 dBA at 5m, 94 dBA at 10m and 92 dBA at 30 m. The equivalent noise / sound pressure levels were determined over a reference time interval of 3 minutes during operation of the Resonant Pile Driver. Each 3 minute interval corresponds, approximately, to the penetration of the pile by a distance of 1.5 m.

Figure 2 provides the background measured noise level for the site while the power pack was
operating at full revs. The data indicates the background noise for the site is on the order of 80 to 85 dBA. The 5 and 10 m measurement points indicate the distance from the pile, however, the power pack was positioned off to the side, approximately 7 m from the 5 and 10 m monitoring points. The 31 m monitoring point was about 20 m from the power pack.

Figure 2. Background noise level.

Figure 3 provides the noise levels recorded during the driving of the HP 310 x 74 pile. The measured noise is plotted with depth of penetration of the pile. The noise generally reduces with depth of penetration, however at the end of driving the noise level rises due to an increase in the flow rate of hydraulics supplied to the pile. The noise levels recorded during the driving of the 300 mm diameter pipe pile show similar results.

Figure 3. Noise levels with depth of penetration for the HP 310x74 pile

Vibration monitoring was conducted using the industry standard Blastmate, SSU 2000DK Seismograph by Geosonics. Triaxial velocity sensors
are used to monitor vibration for up to 10 seconds per event. The sensitivity of the equipment is set for peak velocities that exceed 50 to 60 cm/s with a minimum trigger threshold of 0.5 mm/s. The Resonant Driver could not trigger the devices so they were manually triggered for each event by tapping the triaxial meter by hand. A typical monitoring event is shown in Figure 4, indicating the physical trigger event (two peaks) at the beginning of the event.

![Graph](image-url)

**Figure 4.** Longitudinal velocity history, 5 m from 300 mm pile, 3 m penetration.

The recorded velocity waveforms indicate the maximum ground velocity when driving into dense soils using the Resonant Pile Driver is on the order of 0.5 mm/second at a distance of 5 m from the pile. This represents 1/20th of the acceptable ground vibration levels for work in urban areas in North America. The data further indicates the vertical component of the ground velocity is less than the transverse and longitudinal components.

**Location 2**

The piles were driven at a production piling site within the Fraser River Delta on Richmond Island in Vancouver, BC. Piles of 500 mm, 600 mm and 750 mm diameter were being driven as part of an environmental control structure. The site is within the outer region of the Fraser River Delta with soils consisting of loose to compact sands and silts increasing to dense at 6 m and increasingly dense with depth. Soil SPT counts increase with depth ranging from 2 - 10 bl / 300mm at the surface, 18-30 bl at 6 m depth and 50 - 60 bl at 18 m depth. SPT’s were taken using a mechanical hammer in holes developed to a depth of approximately 6 m using a solid stem auger. CPT holes were developed to a depth of 18 m immediately parallel to the solid stem auger holes. The water table varies with the tidal influence of the Fraser River at about 2.5 to 5 m in depth below the surface.

**Pile Driving**

At this site production pipe piles 750 mm dia x 16 mm wall were driven using an APE 200 470 kW (630 Hp) conventional vibratory hammer to a penetration depth of 7.5 m. A 3200 kg drop hammer with 47-113 kNm peak energy was used to drive open ended 500 mm and closed ended 600 mm diameter x 12 mm wall pipe piles. The open ended 500 mm dia pipe piles drove with significantly less resistance than the closed end piles, did not take up as abruptly and...
reached a maximum driving resistance of 17 blows per 300 mm for a design working load of 80 to 100 tonnes (160 – 200 tonnes ultimate) as estimated using dynamic formula.

The Resonant Pile Driver was used to drive three pile sizes at the site: an HP 310 x 74 section 19.8 m in length, a 400 mm dia x 12 mm wall pipe pile 23.85 m in length and a 600 mm dia 12 mm wall pipe pile 18.9 m (driven again at 17.4 m) in length. The HP pile was driven to full depth of approximately 19 m, the 400 mm diameter pipe pile to a depth of 10.4 m and the 600 mm diameter pipe pile to depth of 6.1 m. The 400 mm dia pipe pile plug was measured to be 5.47 m from ground level. Similarly the 600 mm dia pipe pile was plugged at a depth of approximately 2.5 m. The HP pile drove to full depth in about 12 minutes at a flow rate of 3 l/s increasing to 4.5 l/s at depths beyond 14.5 m. The power pack operated at a pressure of 13 to 14 MPa for total driving power of 31.5 kW increasing to 52 kW (70Hp) with depth. The 400 mm dia pipe pile was driven at a maximum of 17 MPa at 5.0 l/s for a peak driving power of 72 kW (95Hp). The 600 mm dia pipe pile was driven at a maximum of 5 l/s and a pressure of 17.9 MPa for a total driving power of 85 kW (110 Hp). In each case the piles were driven using the automated electronic frequency tuning system, which optimized the driving frequency at the resonant frequency of the pile-soil system.

Vibration monitoring was conducted using three Dytran Instruments single axis accelerometers including two model 3191A1 (10 V/g) and one model 3192A (1V/g). The data acquisition system used included a 1 MHz A/D board integrated with a Toshiba PC. This permitted readings of ground acceleration on each channel at a rate of 1000 Hz. Measurements were made during conventional driving of the 750 mm diameter open ended pipe pile driven using the APE 200 and a 500 mm diameter closed end pipe pile during impact driving with up to 113 kNm of impact energy. The data indicates that the vertical ground vibration levels are over 1.75 m/s² at a 10 m distance for the vibratory driven pile and well above 8 m/s² at a 10 m distance for the impact driven pile. At 30 m from the source the vertical ground accelerations are on the order of 0.4 m/s² for the vibratory driven pile and 1 m/s² for the impact driven pile.

Vibration monitoring during Resonant driving indicated the magnitude of the ground acceleration is higher than would be expected for the HP section in softer soils at the remote location. Typical accelerations at 10 m are on the order of 0.25 to 0.3 m/s². The acceleration histories appear to show little change in the ground motion with pile penetration at the 10 and 30 m locations. For the 600 mm pipe pile the vibration levels were on the order of 0.4 m/s² during penetration of the crust and dropped to 0.25 m/s² for the remainder of driving.

**Conclusion**

Five test piles were successfully driven into compact to very dense layered silty sand and gravel at two sites adjacent to the Fraser River in Greater Vancouver, BC, Canada using the 140 kW Resonant Driver. Two HP 310 x 74 sections, pipe piles of 300 mm dia x 22 mm wall, 400 mm dia x 12 mm wall and a 600 mm dia 12 mm wall pipe pile all over 18.0 m in length were driven. The ground vibrations monitored during driving indicate the ground disturbance to be nearly imperceptible. Typical vertical ground accelerations at 5 m, 10 m and 30 m from the pile were on the order of 0.8 – 1.3 m/s², 0.4 – 0.5 m/s² and 0.1-0.15 m/s² respectively. Ground vibration monitoring indicated levels on the order of 3 mm/s during crust penetration and dropped to 1 mm /s at deeper penetration levels. Corresponding conventional equipment driving similar piles monitored at the site produced 10 to 40 times the ground excitation. The noise monitoring indicates the Resonant Driver is slightly to somewhat louder than a conventional vibratory pile driving hammer and less noisy than a conventional impact hammer. The noise levels are typically (including the revving power pack), 97-100 dBA at 5m, 94-98 dBA at 10m and 90-92 dBA at 30 m. The noise levels do not appear to dissipate with pile penetration.