Sonic Pile Driving: The History and the Resurrection of Vibration Free Pile Driving

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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. High frequency conventional vibrators are able to reduce the measured ground vibration in many situations, however, they often cannot meet the restrictive limits imposed and may not be used immediately adjacent to sensitive structures. The use of super high frequency (up to 150 Hz or 9000 VPM) ‘sonic’ or ‘resonant’ pile drivers has proven in the past to permit ease of installation of sections to great depths with near imperceptible ground vibrations as close as 1 pile diameter. Early work in the United States with the Bodine-Guild sonic hammers and recent work with the Resonance Technology Intl resonant hammers has shown vibration free pile driving remains possible.

A Brief History

Sonic technology can be traced to England in 1913 when the Theory of Sonics, authored by Romanian George Constantinesco, was published by the British Admiralty. In the 1930s, fellow Romanian engineer Dr. Ion Basgan applied sonic vibrations to the drill pipe string of a conventional drilling rig. The result was improved drilling depth, speed and verticality without distortion, which was a challenge in those days with the methods available. Bore holes using the sonic method were drilled at the Moreni oil fields of Romania in 1938. Basgan filed patents on the technology in Romania and the USA. Success in Romania led to interest in developing sonic drilling in the USA during the 1940’s and 1950’s. Concurrent developments aimed at using vibrations to drill holes were conducted in Russia in the 1930’s and 1940’s. The initial goal was to speed up oil well drilling operations and most of the research was financed by the petroleum industry. In 1949 Russian Professor D.D. Barkan of the Scientific Research Institute for Footings and Foundations reported on research conducted on rotary-vibratory (sonic) drilling techniques. He proposed the use of sonic vibrations in sinking geological exploratory drill holes. At a meeting in 1957 at the Moscow drilling Institute, drilling rates of 3 to 20 times faster than conventional methods were reported.

The American program was initially conducted by Drilling Research Incorporated (DRI), which was in operation from 1948 to 1959. They developed a magnetostrictive-rotary-vibratory drilling system. This method was not successful but it demonstrated that vibrations could speed up rotary drilling rates substantially. During this early period, Dr. Al Bodine worked with Borg Warner on a down-hole vibrator, which he called a ‘sonic drill’. The machine operated using rotating eccentric masses driven by drilling fluid. Using eccentric masses produces force as a function of the square of the operating frequency. Thus, increasing frequency from 50 Hz to 100Hz results in a 4x increase in peak force and accelerations. The down hole drill operated with incredible production rates, unseen in the drilling industry to that time. However, it failed because excessive vibratory energy caused mechanical failure of the down-hole components. This occurred when resonance of the internal drill components caused runaway or ‘galloping’ amplitudes and accelerations. In the early 1960’s, Dr. Bodine developed a much larger top-hole
vibrator. The machine was intended to be used for oil well service work such as pulling stuck casing and rehabilitating oil wells. Mr. Bodine received many patents in the 1960’s for his work with ‘orboresonace’ drives.

In the 1960’s Bodine redirected efforts towards the development of a sonic pile driver. He engineered large vibrators with capacities between 500 and 1000 Hp but they suffered from poor reliability. Continued effort with the assistance of Charlie Guild of Guild Construction in Rhode Island and later with support of the Shell Oil Company improved both the performance of the equipment and understanding of its application. The larger vibrators worked successfully on many projects posting impressive production rates. These projects included the BART, Harvard University Museum Building and Merritt Island, Mass. At this time a young physics graduate from Cal Berkeley named Alan Bies, PhD joined the Bodine team. He witnessed the success of the equipment and understood the theory or resonance intimately. It became Dr Bies’s opinion that while the principle of using resonance was sound, the driving mechanism being applied (eccentric mass) was ill-suited to driving a resonant system in a controlled manner. Dr Bies later left the company and became a world renowned Professor of Acoustics in Australia.

Though the Bodine hammers called themselves ‘sonic’ they were in fact taking advantage of the concept of resonance. Resonance is achieved in many mechanical systems such as pushing a child on a swing or shattering a wine glass with a tuning fork. The vibrator simply supplies vibration power in tune with the natural frequency of the pile for maximum energy efficiency with no energy wasted in the ‘re-mobilization’ of the pile. The pile stores the energy elastically as a spring, expanding and contracting at its natural frequency. 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. To achieve resonance the push and pull cycle of the sonic vibrator must coincide with the input and reflected stress waves. The sonic vibrator must apply a downward compression force that creates a traveling stress pulse down the pile. When the pulse reflects upward to the pile top
as a tensile stress wave the sonic vibrator 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 the sonic vibrator is able to set up a standing wave pattern in the pile. Effectively the pile becomes a fly wheel into which the resonant energy is delivered. Within just a few cycles the pile develops substantial amplitude and acceleration. The trick is to maintain the natural frequency of the vibrator with the changing natural frequency of the pile as it is driven into the ground. Once resonating, the pile uses the built up energy to penetrate the soil at high acceleration and thus reduces energy loss to the ground. A common problem with resonance occurs when the stored energy builds up out of control. Larger and larger amplitudes of vibration and stresses within the pile cause failure, either of the pile or the mechanism attached to it.

In the early 1970’s. Mr. Bodine’s group had started to develop a smaller oscillator when his equipment was sold to Hawker Siddeley. At this time Hawker Siddeley, a well-known British aircraft manufacturer, founded the Sound Dynamics department to manufacture a line of vibratory equipment. The goal was to eventually market machinery based on vibratory technology for various applications such as civil construction. The original research was targeted at developing a large vibrator capable of developing resonance in a foundation pile. The thought was that such a machine could be used to drive the piling for the proposed Alyeska pipeline project (1975-77). Numerous attempts to produce large (750 to 1000 Hp) rigs failed due to reliability issues. Throughout the Hawker Siddeley years Charlie Guild continued to work with and develop the technology for production pile driving. Numerous test drives were conducted on sites and many successful projects were completed, though reliability issues continued to plague the eccentric drives. Data was gathered on the capacity of sonically driven piles and on ground vibrations during sonic driving. The results indicated that sonically driven piles met or exceeded the capacity of piles driven using conventional air steam hammers while taking only a fraction of the driving time. Comparative pile load tests were conducted at the Harvard Geochemistry Building and the Agassiz University Museum in Boston, Interstate Route 95, (Contract 6172), Providence RI and the NE Telegraph Co. Boston, Mass. The absence of ground borne vibration was documented at the Federal Building in NY City, Niagara Frontier Light Rail Rapid Transit in Buffalo NY and Dundas St Sewer Separation Contract in London, Ontario, Canada. These test programs established the sonic technique could drive piles to an equivalent capacity as driven piles, dramatically increase production rates and produce negligible ground vibrations which would not disturb neighboring structures.

Unfortunately the continued mechanical problems that plagued the larger sonic hammers led to their fall from favor in the piling industry. Their downfall lay in the bearing technology required to support both the vibrating shaft that housed the eccentric weights and the drive shaft. The extreme rotating speeds combined with very high loads were too much for bearing technology available even today.

As part of their research Hawker Siddeley developed smaller vibrators that could be used for drilling purposes. The machine proved successful in many oil, gas and gold exploration applications. A number of rigs were constructed and sold for these applications. The early rotary-vibratory drills, or ‘sonic drills’ as they were called, were not configured specifically as drill heads. They were basically oscillators that were modified for drilling and proved to be very unreliable and prone to frequent breakdowns. The earlier sonic drills used currently available
‘standard’ drill tooling which was not designed to take the high frequency vibratory loads imposed by the sonic drill. The result was frequent breakage of drill tools. Nonetheless, the rotary-vibratory technique demonstrated that it had great potential in the drilling industry. It was discovered during early experimentation that, in addition to being capable of drilling holes fast, the machine had an outstanding ability to take truly representative continuous cores of almost any overburden material. It was also able to core through boulders and into bedrock.

The severe recession of the early 1980’s discouraged Hawker Siddeley from continuing development work on sonic drill technology. However, one of the engineers from the Hawker Siddeley team, Mr. Ray Roussy continued to develop the technology specifically for small diameter drilling (<250 mm or 10”). He believed that sonic drilling would become the method of choice for most shallow earth drilling applications. For example, he had seen that one sonic drill could do as much drilling and sampling as three or four auger drills during the same time period. A number of companies began to use these specialty rigs and the equipment continued to develop and solve the mechanical problems.

In the early 1990’s, Boart Longyear, Salt Lake City UT, one of the world’s largest drilling contractors became interested in the potential of sonic drilling technology. Boart expanded into the Environmental Drilling sector with great success and became a leader in the environmental drilling business with their fleet of almost 180 sonic drill rigs worldwide. Sonic frequency technology has numerous advantages for environmental sampling. The high accelerations successfully cut the soils with minimal disturbance which provides clean un-smeared sampling from one layer to the next, a very important feature when sampling for trace amounts of contaminants. The method can create a hole with little to no introduction of water or air and thus low spoil, reducing the potential for top side wastes. Finally the method has proven success in all ground types with very high production. Roussy’s Sonic Drill Corp continues to develop this now reliable small scale technology and sell it throughout the world.

Today

Based upon the early success of sonic drill technology and the proof of concept successes in pile driving Dr David Bies continued to ‘tinker’ with ideas and concepts that would meet the needs of the application. Recent progress with an entirely new mechanism has lead to a new round of success in the driving of piles with high frequency vibration. The new Resonant Driver is novel in a number of ways. The mechanism does not use eccentric masses, but instead a piston and cylinder arrangement with a unique valve. Thus the downfall of the Bodine hammers; the vibrating shaft bearings, are eliminated. The new technology is able to excite a pile at its resonant (or natural) frequency to produce elevated levels of acceleration and force. However, the mechanism inherently limits peak displacement and will not suffer from runaway acceleration and force. 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 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 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.

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 be started at any frequency, thus eliminating the ‘run up and run down’ through all frequencies with conventional equipment that can shake the base machine or surrounding buildings. The hydraulic fluid flow rate 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 cylinder. There are no bearings that experience high levels of vibration. In addition, the simple geometry of the mechanism allows for rotation of the pile while vibrating.

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 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 140 kW (200 Hp) and 260 kW (351 Hp) Resonant Pile Drivers have used to drive 310 mm HP piles and pipe between 300 and 800 mm with mass of up to 276 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 at depths of up to 15 m. In comparisons to conventional hammers, both impact and vibratory, the Resonant Pile Driver has performed well. What remains significant is the absence of measured ground borne vibration during driving using the Resonant Driver.

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 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
The 140 kW (200Hp) Resonant Driver mounted on a 600 mm diameter pipe pile.

Geotechnical investigation was conducted via exploratory drilling at the proposed location of the test piling. 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 SPT blow counts are estimated to be in the range of 50 to 80 blows per 300 mm to depth of 14 m. Within the very dense glacial tills below 14 m the blow counts are estimated to be >100 per 300 mm.

Two piles were selected for driving using the Resonant Driver; a 19.8 m long HP 310 x 74 kg HP (HP 12 x 53) section with a mass of 1480 kg and a 17.8 m long 300 mm diameter pipe pile with a 22 mm wall and a total mass of 2668 kg. 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 Blast-mates (SSU 2000DK Seismograph and noise monitoring station by Geosonics) and high precision vibration monitoring sensors. 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 did not produce enough ground vibration to trigger the devices so they were manually triggered for each event by tapping the triaxial meter by hand. The recorded velocity waveforms indicate the maximum ground velocity when driving into dense soils is on the order of 0.5 mm/second at a distance of 5m 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.

In comparison 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. Drop heights ranged between 2.5 m to 3 m, or 48kNm (36000 ft*lbs) at the 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 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 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 and ground vibration of 1.5 to 2 cm/s were documented 3 metres from the pile.

At a nearby production site 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 to very dense sands and silts with depth. The site is typical of a deltaic environment with deep deposits of layered silts and sands. The area has been filled within the upper 1 m with wood chip materials to provide a working platform. The native soils below are typically loose to compact silts and sands increasing to compact 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. The water table varies with the tidal influence of the Fraser River at about 2.5 to 5 m in depth below the surface.

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 kN/m peak energy was used to drive open ended 500 mm and closed ended 600 mm diameter x 12 mm wall pipe piles. The Resonant Pile Driver was used to drive two pile sizes at the site: an HP 310 x 74 section 19.8 m in length and a 400 mm dia x 12 mm wall pipe pile 23.85 m in length. The HP pile was driven to full depth of approximately 19 m and the 400 mm diameter pipe pile to a depth of 10.4 m. The HP pile drove to full depth in 12 minutes at a maximum flow rate of 4.5 l/s and an operated pressure 14 MPa for total driving power of 52 kW (70Hp). The 400 mm dia pipe pile plug was measured to be 5.47 m from ground level. 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). 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 (1 V/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 driving of the 750 mm diameter open ended pipe pile using the APE 200 and a 500 mm diameter closed end pipe pile using a drop hammer 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 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.
In late 2008 a 260 kW Resonant Driver was used to drive pipe piles and HP section into dense sands and silts. The hammer drove piles up to 600 mm in dia to depths of 14 to 15 m into very dense (>100 bl / 300 mm) sands. Driving times ranges between 8 and 15 minutes for the Resonant Driver. Ground vibrations were measured and recorded at less than 1/10 of allowable levels at a distance of 7.5 m. The same piles were driven by a 480 Hp high frequency vibratory hammer to similar depths in similar times. The ground vibrations during driving with the conventional hammer exceeded allowable levels by a factor of 1.5.

**Conclusion**

The precedence set by the Bodine Sonic Drivers in the early 1960’s for rapid production with minimal ground disturbance is being relived today with new high frequency technology. The new Resonant Driver based upon a piston and cylinder mechanism is able to resonate a pile and advance it rapidly into the ground while causing near negligible ground vibrations and thus will be safely drive piles adjacent to sensitive structures. More work is needed and access to production pile driving sites is required to improve the data base of pile and soil types that are appropriate for the use of the resonant pile driving method.