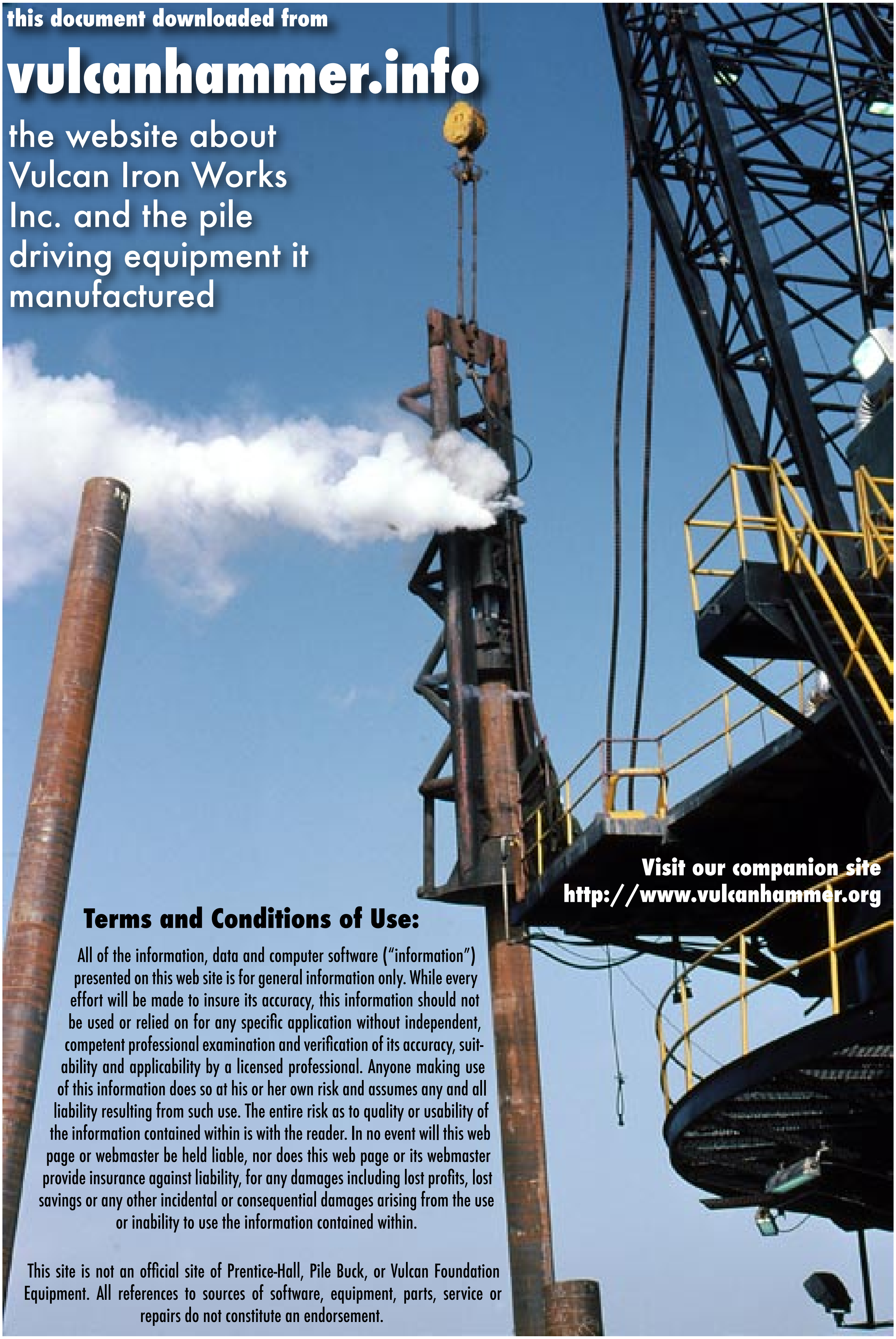

VIBRATORY AND IMPACT-VIBRATION PILE DRIVING EQUIPMENT[1]

Don C. Warrington, Vulcan Iron Works Inc.

Introduction

In terms of the history of technology and the speed of its advance, it has been a long time since D.D. Barkan's first vibratory pile driver turned its eccentrics in the field back in 1949. In the Soviet Union, where this took place, Joseph Stalin was still very much in charge, and the country was recovering from the horrible combination of the Purge and World War II. In the U.S., contractors were happily beating away at their piles with Vulcan, Raymond, and MKT steam impact hammers, and in Germany the Delmag organization was emerging from its own war reconstruction to begin the wordwide broadcasting of a large number of red diesel hammers.

Vibratory hammers have gone on to become an important tool in the installation of a large number of pile types, and yet there is a great deal that is not understood about how they work and what kind of results one can expect from them. What is the bearing capacity of a pile driven by vibration? What kind of response will various soils give when vibrated? And what happens when you add impacts to the system, as you do when using an impact-vibration hammer?

All of these questions and others are subjects of ongoing research in many countries; however, once this is all done, it needs to be disseminated, and here too there has been inadequate effort, whether for lack of resources or desire to keep trade secrets.

In late 1989 Mr. Chris Smoot of *Pile Buck* approached me about putting together such an article for the newspaper and an upcoming series of books he was publishing. In response to this, I put together both material I had already written and other materials to make up the article "Vibratory Pile Driving Equipment", which appeared in *Pile Buck* the following year.

As is the case with many projects, once the project itself is over one realizes that the work is ongoing. To begin with, there were many items in the original article that needed expansion and also some new topics needed covering; many of these were pointed out by readers. In addition to that, it became obvious that no comprehensive treatise on the subject of vibratory hammers was complete

[1]This article was originally published in 1989 in *Pile Buck*. It was subsequently revised in 1992 and published there again. A few revisions have been made for this internet edition. All of the information and data presented here is for general information only. While every effort will be made to insure its accuracy, this information should not be used or relied on for any specific application without independent, competent professional examination and verification of its accuracy, suitability and applicability by a licensed professional. Anyone making use of this information does so at his or her own risk and assumes any and all liability resulting from such use. The entire risk as to quality or usability of the information contained within is with the reader. In no event will this web page or webmaster be held liable, nor does this web page or its webmaster provide insurance against liability, for any damages including lost profits, lost savings or any other incidental or consequential damages arising from the use or inability to use the information contained within.

without the inclusion of material on impact-vibration hammers, a type of machine that is both very much like and very different from the vibratory pile driver. This became especially apparent when I co-authored the paper "Development and Improvement of Impact-Vibration Pile Driving Equipment in the USSR" with Mr. L.V. Erofeev of VNIIstroidormash, the construction equipment research institute in Moscow. Both of these issues are addressed in the current work.

Those who are familiar at all with my writings on this subject have noted the extensive coverage of Russian research and practice. The technology was first put to the field in what was then the Soviet Union, and there is quite a lot of written output on the subject in Russian, but as is the case with much Russian information it was a mystery to most Americans. Since I first set to work on this subject in 1988 (which coincided with my first visit to Russia), we have seen the end of the Soviet Union and the Cold War and the reemergence of Russia as a nation once again.

Once technical note that belongs right at the start is a distinction between vibratory equipment and impact-vibration equipment. For the purposes of this article, vibratory pile driving equipment refers to equipment whose forces are generated in an alternating sinusoidal force with no impact coming from the exciter, which impact-vibratory machines have both the sinusoidal force and impact within the exciter itself. These mechanisms will be explained in more detail later.

No work such as this can ever come to reality without the help of others. There are two special people whom the author would especially like to recognize. The first is Mr. Charles L. Guild of American Equipment and Fabricating. His contributions to the advancement of foundation installation in general and vibratory pile driving technology in particular are too numerous to list here; such an enumeration is a work unto itself. For this article he clarified many points concerning the resonant machine. More importantly, Charlie is a wonderful Christian and has been an inspiration to me and others who have had the privledge to know and work with him.

The second is Mr. Lev V. Erofeev of VNIIstroidormash, the Russian organization for Constructional Road-Building and Municipal Machinery. He was in reality the main author of the article on impact-vibration pile driving equipment, and his willingness to share information of this and other topics of Soviet and now Russian pile driving technology have helped to dispel the mystery surrounding these subjects and thus enable us to more greatly appreciate the accomplishments.

Others who have contributed to this article include Messrs. E.A. Narozhnitskii and M.L. Pevzner of the Leningrad Experimental Works of Construction Machinery; Ms. Sherrill Gardner of the Naval Civil Engineering Laboratory; Mr.

Richard Nelson of Pile Equipment, Inc.; Dr. David M. Rempe, consulting geotechnical engineer; Messrs. Bill Harrison and W. David Engle of Vulcan Iron Works Inc.; Dr. Michael O'Neill of the University to Houston; and Mr. Christopher Smoot of *Pile Buck* for enabling the publication of this and related works.

Finally this author would like to make an important "vibratory" acknowledgement by citing Haggai 2:6-7: "This is what the Lord Almighty says: `In a little while I will once more shake the heavens and the earth, the sea and the dry land. I will shake all nations, and the desired of all nations will come, and I will fill this house with glory,' says the Lord Almighty."

Chapter I
HISTORICAL DEVELOPMENT

§1 Development of Vibratory Equipment

The first vibratory pile driver used was in what was then the Soviet Union, a model BT-5 developed and first used under the direction of D.D. Barkan. This hammer had a dynamic force of 214 kN and the eccentrics rotated at 41.67 Hz, powered with a 28 kW electric motor. Used in the construction of the Gorki (now called once again Nizhni-Novgorod) hydroelectric development, the hammer drove 3700 sheet piles 9-12 m long in 2-3 minutes each.

The Soviets went on to develop a large variety of vibratory pile drivers and soil drilling equipment in the 1950's. They also first licensed their technology to the Japanese, who with several concerns have developed an extensive array of vibratory hammers. This technology has since spread worldwide, with such concerns as PTC and Tramac in France, Müeller, Tünkers and MGF in Germany, Tomen in Japan and ICE Europe in the Netherlands being well established in the field.

The first American made hydraulic vibratory was the MKT V-10, which they introduced in 1969, although both Vulcan and Foster had introduced Japanese and French vibratory pile drivers respectively in the early 1960's. A diagram of this machine is shown in Figure 1. This pioneering machine differs from most current vibratory pile drivng equipment in several respects. The first is the suspension; in common with the practice of the time, the V-10 used steel coil springs to provide dampening for the crane boom and hook, whereas now most machines use rubber springs. The second concerned the eccentrics; the V-10's eccentrics were long (a practice borrowed from vibratory screens and seperators) and mounted crossways on the machine. A motor was coupled to one of the eccentrics; gears transmitted the power to the rest. Most machines today mount the eccentrics from front to back of the case, and drive them either directly or through a speed changing pinion gear.

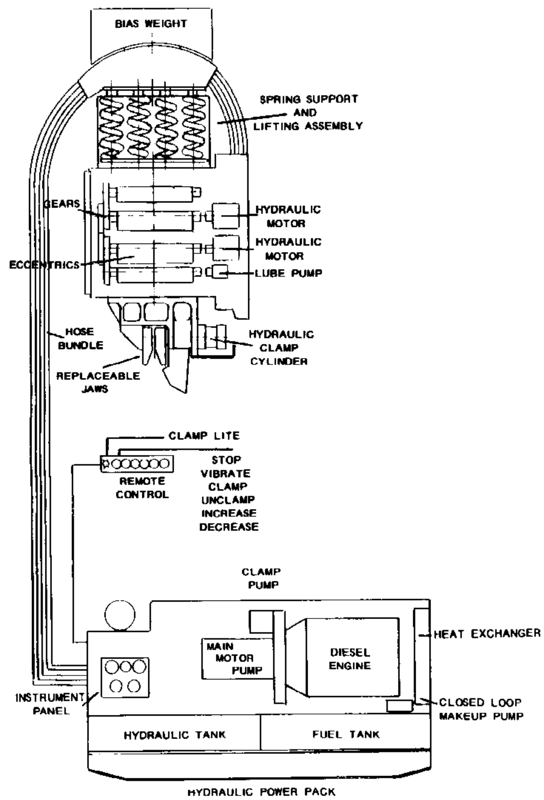

Figure 1 MKT V-10 Vibratory Hammer

From this beginning, the unique practices in the U.S. have lead to the evolution of a distinctive style of vibratory hammer in the U.S., and this has been followed elsewhere. Today it is embodied to a greater or lesser degree in the Vulcan, ICE (America and Europe), MKT, Foster, Casteel, and HPSI units that are on the market. In addition to the changes mentioned above, these characteristics include slim throat hammers for sheet pile driving, hydraulic drive, and high power motors, pumps, and engines.

Classifying vibratory pile driving equipment can be a complex business, but the most important division can be made on the basis of frequency, with the resultant relationships between dynamic force and eccentric moment. These quantities will be dealt with in more detail in §14. There are three basic divisions, which are as follows:

1)Low frequency machines: These are vibratory drivers with a vibrator frequency of 5-10 Hz, used primarily with piles with high mass and toe resistance, such as concrete and large steel pipe piles. They tend to have large eccentric moments to achieve their dynamic force, with high resultant amplitudes. An example of this type of machine is the Russian VPM-170, which is used by the Russian Ministry of Transportation and which is the largest made in the country. This machine produces a maximum dynamic force of 1,700 kN at its maximum frequency of 9.17 Hz and eccentric moment of 510 kg-m. This machine is designed primarily to drive caissons up to two (2) meters in diameter and is bolted to the pile rather than clamped. The Tomen organization in Japan has produced many machines of this type as well.

2) Medium frequency machines: These are drivers with a vibrator frequency of 10-30 Hz, used for piling such as sheet piles, small pipe piles, etc.. An example of this type is shown in Figure 2, a B-402 vibratory hammer actually driving Larssen type sheet pile on a tunnel construction job in St. Petersburg. This unit has a maximum dynamic force of 270 kN while operating at its rated oscillation frequency of 23.8 Hz and its maximum eccentric moment of 12 kg-m. These machines make up the majority of vibratory pile drivers in use today, as they combine the dynamic force necessary to excite the soil, the correct frequency to properly interact with most soils, and sufficient amplitude to get through the hard spots in the soil.

Figure 2 VNIIGS B-402 Vibratory Driver in St. Petersburg, Russia

3) High Frequency Machines: These consist of all machines which vibrate at frequencies of more than 30 Hz. They are of two basic types. The first are machines in the 30-40 Hz range which are designed primarily to minimize vibration of neighboring structures. These have been developed simultaneously both in Europe (ICE, Tünkers, PTC) and in the U.S. (Vulcan). The primary advantage of these machines is their lowered transmission of ground excitation to neighboring structures. These machines' frequencies are not high enough to improve driving and in some cases these machines have problems in overcoming toe resistance.

In a class by itself is a resonant pile driver, and the most significant machine of this type is the Bodine-Guild resonant driver, first introduced in the early 1960's. The central principle of the resonant driver is to induce resonant response in the pile, thus facilitating driving and extracting. The resonant driver operates at frequencies in the range of 90-120 Hz; in most cases the driving took place at the half wave frequency of the pile. The ability to achieve this response was dependent upon properly matching the frequency range of the machine to the length of the pile; in cases where this was not possible in a normal hammer-pile setup, a heavy wall follower connected the pile with the hammer. On the other hand, when the pile was exceptionally long, second and third overtones could be achieved; this was the case when a 273mm (10.75") O.D. wall pipe 115.8m (380') long was driven. Although in principle this concept has held great potential, the mechanical complexity of this machine has withheld it from extensive use.

§2 Development of Impact-Vibration Hammers

The term "impact-vibration hammer" refers to a type of vibratory pile driver that imparts both vibrations and impacts to the pile during operation. Based on theoretical work done during the Second World War by himself and others, S.A. Tsaplin prepared the first experimental impact-vibration hammer in the Soviet Union in 1949. The specifications of the hammer and test setup are shown in Table 1, and a drawing of this machine is shown in Figure 3. In field tests his impact-vibration hammer was welded to the top of metallic tube 110 mm in diameter, 8 mm wall thickness, 2.6 m long and with a mass of 200 kg. The hammer then drove the tube into a variety of sandy, sandy loam, and clay soils. A comparison was made here of the effect of driving by the impact-vibration mode versus the vibration mode, the latter of which was achieved by the complete blocking of the springs. The tests made it possible to establish that the efficiency of the impact-vibration driving is substantially higher with regard to both the maximum driving depth possible and the pile sinking velocity, and that the efficiency of the driving increases with increasing amplitude of the vibration exciter vibrations.

Table 1
Hammer and Test Setup for Tsaplin Impact-Vibration Hammer

Nominal rotational speed, Hz	48
Permissible frequency range w/generator, Hz	40-200
Power, kW	1.6
Exciter mass, kg	75
Overall mass, kg	95
Test Stand	
Material	Reinforced Concrete
Mounting	Rigidly Attached to Hammer
Mass, kg.	500
Generator	
Power Output, kW	50

The first broad practical application of the impact-vibration hammer took place in the construction of the Stalingrad (now Volgograd) power plant, where in the construction of the anti-filtration wall under the dam "Larssen-5" piles were driven to a depth of 13 m with the driving at the last site in sandstone of medium firmness. On this and other jobsites, the impact-vibration hammers were able to outdrive conventional vibratory hammers, air/steam and diesel hammers.

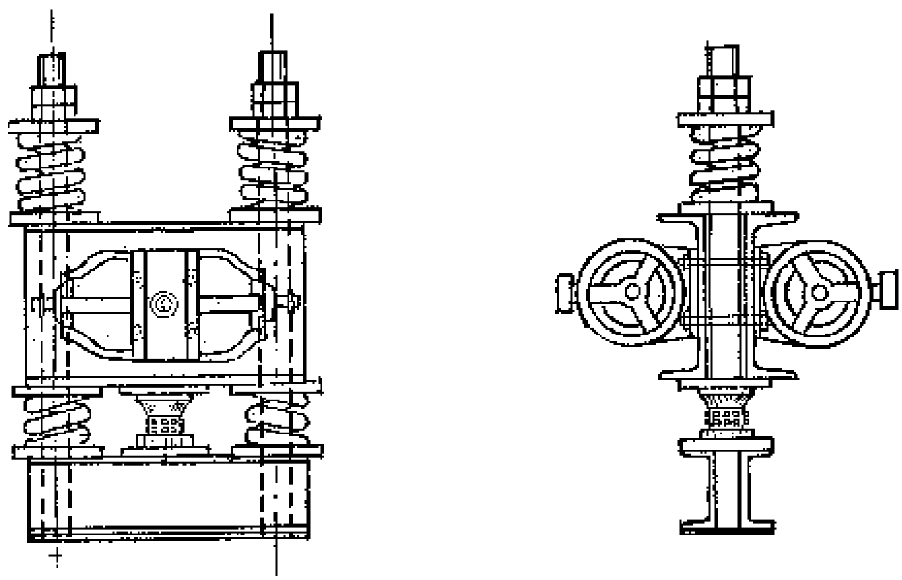

Figure 3 Tsaplin Impact-Vibration Hammer

The success of this and other jobsite and laboratory situations has led to the spread of the use of impact-vibration hammers, not only in Russia but also in other countries, especially those of the EC where manufacturers such as Menck and PTC have taken up the production of these units. There are no impact-vibration hammers manufactured in the U.S. at present.

Chapter II
CONSTRUCTION AND OPERATION OF EQUIPMENT

§3 Vibratory Hammer Exciters

Although there are many variations in design and construction, the vast majority of vibratory hammers are of the configuration shown in Figure 4. Briefly, there are two main components of the system: the exciter, which produces the actual vibrating force, and the power pack, which provides the usable energy for the motor(s) on the hammer to spin the eccentrics.

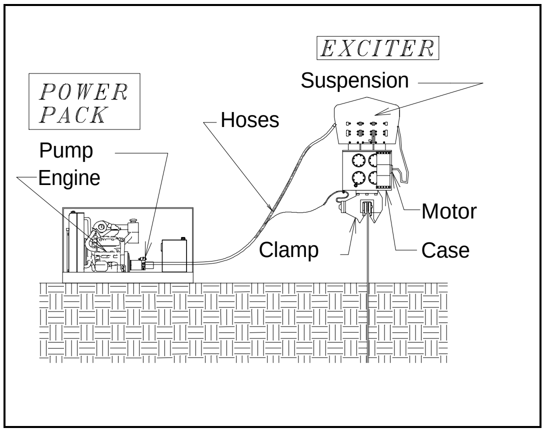

Figure 4 Basic Vibratory Hammer System

We first need to look at the exciter; it is divided into three parts:

1)Vibrator case: This contains the eccentric weights and does the actual vibration. The sinusoidal force is generated by the rotation of the eccentrics (see §14); thus, these eccentrics must be somehow both driven and synchronized.

The most common way to accomplish this is through a gear system. The gears can actually function in various ways, depending upon how they are set up. Generally the eccentrics are mounted to the gear system, either partially or entirely; in either case the mounting is rigid. In some vibratory hammers, this rigidity is insured by making the gear a one piece eccentric. Several types of gears have been used in vibratory hammers, including spur, helical, and bevel. All types work best when the teeth are small but strong enough to transmit the power. Large teeth have been used extensively in vibratory hammers over the years, but small ones are quieter, more efficient, and more reliable.

Other schemes of synchronization are a)there are no gears, and most of the time the amplitude of the system synchronizes their rotation, each eccentric driven by its own motor (Tünkers), or b)the gears are synchronized by a chain and each eccentric is driven individually (H&M).

In any case, the dynamic force generated by the eccentrics is transmitted to the case by the use of antifriction bearings, which also facilitate rotation. These can be cylindrical, spherical ("screen" bearings), or ball, but to work properly they must be sufficiently large for the load and adequately lubricated, either by a pump system or a well designed splash system.

Geared eccentrics can be connected to the motor either by a pinion, or through belts or chain drives. For the latter two the motor is mounted on the static weight; a pinion drive requires that the motor be mounted directly to the vibrator case. Pinions are used as torque converters, which make optimum use of motors at their preferred operating speeds.

2)Clamp:This connects the vibrator case to the pile and thus transmits the vibrator's power from the vibrator case to the pile. Generally speaking, most clamps pinch the pile using a hydraulic cylinder and jaws, thus making a frictional connection. A few vibrators actually bolt or pin the pile to the vibrator case, as was done with the old Vulcan or MKT impact extractors. Some clamps (Foster) use some kind of leverage to enable the use of a small cylinder to generate a large force. For hydraulic clamps, both lever and direct cylinder clamps are shown in Figure 5.

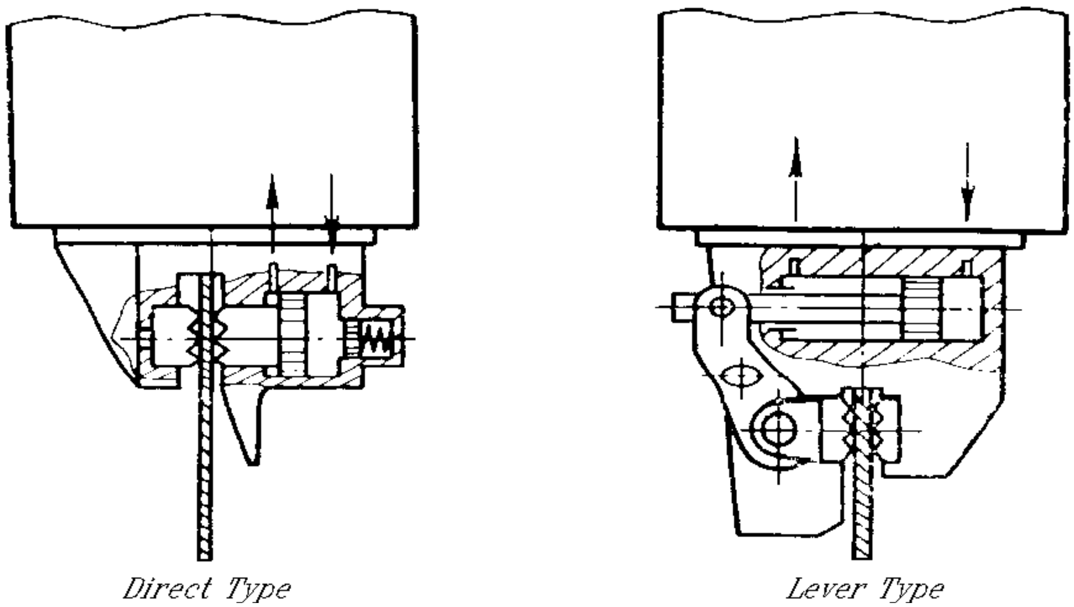

Figure 5 Hydraulic Clamps for Vibratory Hammers (after Tseitlin et.al. (1987))

3)Suspension: This is connected to the vibrator case by rubber or metal springs. In driving this provides additional weight to the system to force the pile into the ground without degrading the vibration of the system, although with most units additional bias weight can be attached to the suspension. In extraction the suspension system transmits static pull while dampening out vibration and thus protects the crane boom. For this to be effective the springs must be sufficiently soft and the bias weight sufficiently heavy to insure a suspension natural frequency that is much lower than the vibrator's operating frequency. Occasionally additional static weight is helpful during driving and the weights which accomplish this (called "bias weights") are attached to the suspension.

§4 Impact-Vibration Exciters

Although impact-vibration hammers share common constructional features with their vibratory relatives, there are important differences. Such variations can be seen in the machine shown in Figure 6. In common with more conventional vibratory hammers, it contains counterrotating eccentrics which impart vertical vibrations; however, these are contained in a head which is not rigidly connected to the pile but is free to some degree. This freedom enables the unit to impact the pile at a rate higher than conventional impact hammers. The alternating force of the eccentrics takes the place of the air, steam, diesel combustion or hydarulic fluid in moving the head up and down like a ram, with impact at either the top, bottom, or both ends of its "stroke". Although this can produce variations in the eccentric rotational speed of up to 40% (as opposed to the 5% or so normal for vibratory hammers), this variation generally does not impede the continuous, stable operation of the equipment.

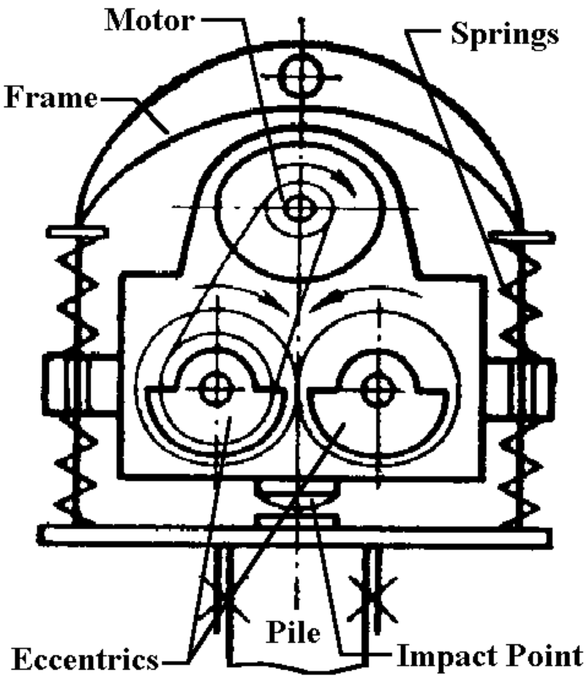

Figure 6 Basic Layout of Impact-Vibration Hammer

Some of the various parts of these hammers are discussed below:

Exciter/Head: The exciter of these machines is similar in general principle to strictly vibrating machines, with eccentrics driven by motors. With impact-vibration hammers, the exciter has a constant source of amplitude within the springs, and so the eccentrics are usually not synchronized with gears, each one driven by a motor. Bearing life with these machines is critical, and many of them must be used in the vibratory mode a good deal of their operation.

Frame and Springs: Frame design of these machines is critical since the frame provides both the regulation of the machine and its connection to the pile. The regulating springs are generally coil springs. The machine's vibration within the springs is regulated by both the spring rate and the pretensioning of the springs. The latter can be either fixed or regulated by hydraulic or electric means. Part of the machine's force on the pile is also transmitted by the springs if the frame is clamped to the pile.

Pile Connection: The most elementary of impact-vibration machines have no pile connection (or frame) at all and rest on the top like impact hammers. Although hydraulic clamps similar to ones used in vibratory hammers can be used, other schemes to keep the frame on the pile include simply making the frame heavier than the upward spring force or bolting the machine to the pile.

§5 Power Packs for Vibratory and Impact-Vibration Equipment

Turning to the power pack, a few vibrators, such as the Bodine-Guild resonant drivers, some of the early Soviet vibrodrilling machines, and some Japanese units, drive rotating eccentrics straight from diesel or gasoline engines by mechanical couplings. However, most vibratory or impact-vibration hammers transmit energy from the prime mover to the eccentrics through either electric or hydraulic systems. Since construction sites are usually remote, transportable power sources have been developed for vibratory hammers. These are referred to as power packs (for hydraulic units) or generator sets (for electric units). These units are similar for both vibratory and impact-vibration equipment.

Electric systems: These usually employ three-phase induction motors driven at a single frequency, which has encouraged the development of many systems to vary the eccentric moment and thus the driving force. In some cases electric vibratory hammers can be driven from a nearby three-phase mains, obviating the need for a generator set. The hammer thus only requires a switchbox to control it. A separate, small power pack, driven with an electric motor, is required to operate the hydraulic clamp, if there is one. This can either be on the ground or mounted on the static overweight. Electric systems are less and less popular because of maintenace and reliability considerations.

Hydraulic systems: For a variety of reasons hydraulic systems have become dominant, and the major manufacturers, such as Vulcan, ICE, and MKT, employ hydraulic drive almost exclusively. These systems use a diesel engine to drive a hydraulic pump, which in turn drives the motor on the exciter. A reservoir of varying size is used to store hydraulic fluid, to make up fluid in case of leakage, and to assist in the cooling of the fluid. A system of valves is used to control the fluid flow, both in starting and stopping the machine and during operation. Beyond these basics, there are specific differences between the various hydraulic power packs available; they are:

1) Pump Drive and/or Gearbox: The hydraulic pump is connected to the engine through a pump drive; sometimes this pump drive is a gearbox as well, acting as a speed changer to optimize the pump, while in others a direct drive is employed, eliminating gear losses.

2) Clamp Pumps: Some units have separate pumps for the hydraulic clamps and some integrate these into the main power source. Impact-vibration hammers that do not have a clamp on them do not need a clamp circuit.

3) Variation of Frequency and Force: Both of these can be varied either by using variable displacement pumps in the power pack or by simply varying the engine speed. Variable displacement pumps can have very sophisticated flow control mechanisms.

4) Control Type: These units can employ air, electric, or manual controls for the hydraulic circuitry. Manual controls are the simplest; however, they confine the operator of the unit to the power pack's location, which, depending upon visibility and other factors, may not be the most convenient place from whence to operate the machine. Remote controls allow more flexibility for the operator but are an added expense and source of trouble for the machine.

5) Enclosure: Some power packs have a sheet metal enclosure and some do not. The principal advantage of an enclosed power pack is protection from weather and criminal activity. Enclosures are also helpful if they provide sound deadening, although many do not. Open power packs are more economical and there is better access to the parts for service.

6) Open and Closed Loop Hydraulic Systems: Both appear on power packs in this application. Closed loop systems allow for better controlled starting, running, and stopping of the machines, but have traditionally been more complicated, and the power packs less adaptable to other applications.

In some cases, the crane hydraulic system can be employed to power the vibratory hammer. Although this eliminates the external power pack and diesel engine, all of the control and operational features of these integral power units are the same.

Chapter III
PILING DRIVEN BY VIBRATORY AND IMPACT-VIBRATION MACHINES

Vibratory pile drivers have been used to drive and extract virtually any type of piling used, although the specialty of vibratory and impact hammers is somewhat different. In the United States, the main application of vibratory hammers is the installation of steel, non-displacement piles where a definite bearing capacity is not required. This last condition is because of the state of the art of vibratory capacity prediction; this will be addressed later in the article. Vibratory hammers are also sometimes not as effective as impact ones in stiff, cohesive soils, or displacement piles that develop a good deal of toe resistance.

§6 Steel Piles

Sheet Piling: Figure 7 shows a hydraulic vibratory hammer installing sheet piling. The sheeting is set up according to normal American practice, namely to set the wall in place and then to drive the pile to the desired depth. This practice requires that the vibratory hammer be no wider at the throat than about 355mm, as the hammer must clear the adjacent piles. In driving sheeting in this way, it is also normal to drive the sheets two at a time, using a jaw with two sets of teeth and a recess between them large enough to accommodate the interlock.

Figure 7 Vibratory Hammer Installing Sheet Piling

Figure 2 shows an alternate method of driving sheeting with a vibratory hammer. Here the sheets are set as they are driven. As a rule, in this case the sheets are driven one at a time. No matter how sheet piling are driven, they should not be driven at penetration velocities of less than 5 mm/sec.

Impact-vibration hammers have been designed for and used with steel sheet piling in soils that produce high toe resistances and thus are not congenial to vibratory driving. Hammers that are used for both driving and extraction are able to impact both upwards and downwards. Impact-vibration hammers for sheet piles generally are equipped with clamps instead of an inertial frame.

H-Beams: Figure 8 shows a vibratory hammer driving an H-Beam. The conditions are similar to driving sheeting; however, when the pile's batter angle is critical, the vibratory hammer can be mounted in a set of leaders much as is done with an impact hammer. In addition to a bearing application (where the beam might be impacted to refusal), vibrated H-Beams are used for soldier beams and in slurry wall construction.

Figure 8 Vibratory Hammer Installing H-Beams

Figure 9 Vibratory Hammer Installing Caissons

Caissons and Pipe Pile: Figure 9 depicts a hammer driving a caisson. Caissons are a versatile item, extensively used with drilled shafts. To drive these, a special device called a caisson beam is employed. This is a horizontal slide with a set of two clamps attached to it. The clamps affix the pile to the hammer on opposite sides of the caisson. The clamps are locked to the slide during use but can be moved along the slide to enable a caisson beam setup to drive a variety of pile.

The equipment setup for caissons is duplicated with pipe pile. Generally it is best to vibrate pipes open ended, although some closed ended installation is done. An example application of driving pipe pile is the installation of pipe piles for offshore structures, such as petroleum production platforms. For some of these two caisson beams with two sets of clamps are used, the beams being configured in an "x" arrangement.

§7 Concrete Piles

Concrete pile installation with vibratory hammers is rare in the U.S. but more common abroad. It is done with both prismatic (square and octagonal) and cylinder pile. As concrete pile is always displacement pile, the vibratory hammer must develop some toe impact by raising and lowering the pile during the vibration cycle, thus allowing penetration. This is generally accomplished using low frequency vibrators with high amplitudes. Resonant machines have also been used to drive concrete piles, with a clamp which could tightly press against the pile. An alternative to this is to use an impact-vibration hammer, which can more effectively deal with high toe resistance than can a vibratory hammer; indeed, the need to drive concrete piles has been one of the most important factors in the development of these hammers (see Figure 10).

Figure 10 Impact-Vibration Hammer Installing Concrete Pile

§8 Wood Piles

As it is almost exclusively bearing pile, wood is rarely vibrated in the U.S. Extraction of wood pile, however, is common, and the vibratory hammer is an effective tool for this purpose. The wood pile can be extracted intact in this manner. Special wood clamps are used for this purpose.

Chapter IV
EQUIPMENT OPERATION

As we have seen, vibratory and impact-vibration hammers vary from manufacturer to manufacturer and model to model in their construction and operation; however, there are things which are common to all of this type of equipment. This section deals with some of these items. The guidelines below presuppose equipment with a remote power unit equipped with an engine. Equipment powered from an external mains will be similar except for the lack of an engine.

§9 Safety

Safety is basically common sense. There are standard safety rules, but each situation is different. Your common sense and experience will be your best guide to safety. Always be alert to problems and correct deficiencies promptly.

Since Russian machines have been described in detail, the following from the operation manual of the B-402 may prove of interest:

> Persons are allowed to operate the Vibratory Pile Driver who have reached eighteen (18) years, passed the

training and the knowledge check in the safety of building, handling, and piling works, and received the certificate for the right of operating the Vibratory Pile Driver, studied the present Technical Description and Operating Instructions, learned by practice the operation of the Vibratory Pile Driver, and have an experience in driving and removing piles.

Work supervisors must carry out a detailed briefing of the persons who are to operate the Vibratory Pile Driver on rules and safe techniques prior to the works. The persons who have not been present at the safety briefing are not allowed to work.

The one thing you must do FIRST

First, take time to take your operating manual, go to the exciter and power pack, and review all of the operating and safety features in the manual, and to likewise familiarize anyone else working on or with the equipment with these features.

Things you should NEVER do

Never allow unauthorized or unqualified people to either operate, maintain, or come within thirty (30) meters of the equipment.

Never allow anyone to stand directly under or within *at least* three (3) meters of the hammer or pile being driven during operation. Failure to do so could result in *injury or death* by being struck by falling parts, rocks, or dirt that the hammer has picked up by being laid on the ground.

Never operate the power pack's engine in a closed area. The breathing of the fumes can be fatal.

Never smoke or use open flame when servicing batteries. Proper ventilation is necessary when charging batteries. On units with a power pack enclosure, all of the doors of the unit must be open during battery charging.

Never smoke when filling fuel tank or hydraulic reservoir, or for that matter while anywhere near exciter, hoses, or power pack. Diesel fuel, gasoline, and hydraulic fluid are all very flammable.

Never adjust or repair the unit while it is in operation, except with the main motor and clamp controls provided for that purpose. If you need to make any other adjustments, shut the entire system down first.

Never attempt to operate the engine with the governor linkage disconnected.

Never store flammable liquids near the engine.

Never unclamp the exciter from the pile when there is any line pull on the suspension or when the hammer is still vibrating.

Things you should ALWAYS do

Always store oily rags in containers. If these get into an hydraulic system, you will have a mess.

Always remove all tools from unit before starting.

Always be sure that, with hydraulic systems, all pressure is out of the system and that all pressure gauges read zero before you start working on the hydraulics of the system. The high pressure fluid in hydraulic lines can be very dangerous if it escapes, such as in a hose break or loosening of a fitting or component. Even when you think the system pressure is zero, you should proceed with extreme caution, assuming all the while that all of the lines are still fully pressurized. This means primarily that you should open all fittings and connections slowly until you see that there is no pressure on that particular connection. Keep your face and body away from the potential line of fire of any fluid while you are working with hydraulic connections.

Always make sure that you make any hose fittings or connections very tight when you reassemble them. Failure to do so can result in the hoses coming loose, resulting in hoses flying around, hydraulic fluid spraying everywhere, and people being injured or killed by all of this. This also applies to any bolted or otherwise fastened connection on either the exciter or power pack.

Always make sure that electrical systems are properly grounded during operation. Also, make sure that they are not connected to any power source in any way and that there is no voltage of any kind in the system before servicing same.

Always make sure that electrical connections and wiring are tight and completely insulated to prevent shock if accidentally touched. This is especially important in waterfront or marine situations; uninsulated wire can result in widespread electrocution of wild and human life. Any electrical fuse, breaker, or control boxes must be *closed* before any kind of operation.

Always be sure to wear gloves and other protective clothing while working on any part of the system, or even better to wait until the system has cooled down. Hydraulic components, electrical wiring and switchgear, and the engine get very hot during operation.

Always make sure that the pile is firmly gripped by the jaws when clamping.

§10 Basic Operation

Rigging: To permit lifting of the hammer, a wire rope must be secured from the crane line to the lifting hole or pin on the suspension. In choosing the wire rope for any unit, a generous safety factor should be used. Wire rope which is worn or frayed must be discarded. Several turns of a smaller diameter cable will usually last longer than one turn of a large diameter cable. Make sure that the wire rope assembly you use has at least double the capacity of the suspension. For hammers that use a lifting shackle, make sure there are no loose bolts, nuts, or pins in the shackle.

Engine Start-Up: Read the engine start-up procedure in the manufacturers operation manual. Follow any applicable instructions.

Do not start the power pack if the temperature of the hydraulic oil is below -18° C.. The case oil and/or fluid temperature should be at least 0° C. before starting the exciter at a slow speed. After starting engine, let it run slowly for at least five minutes.

In Use: Complete all applicable preparation for operation as described in the hammer's operating manual. Perform any required periodic maintenance before operation. The user should also be thoroughly familiar with the inner workings and control operation of the power pack/generator and exciter before operation. An understanding of how the unit works will give the operator a feel for what is happening and will also be invaluable in troubleshooting the unit should a problem arise.

Do not operate the exciter at full speed if the temperature of the hydraulic fluid and/or case oil is below 15° C.. If the temperature of the hydraulic fluid or case oil is below that level, set the engine at a moderate speed and start the hammer. Allow the exciter to run until the fluid and/or oil reaches the required temperature. Full speed operation is now permissible.

Make sure the exciter is positioned parallel to the pile and that the full length of the jaw will make contact with the pile when clamped. Engage the "clamp close" control. The clamp will close in a couple of seconds. The operator should make sure that the pile is firmly gripped by the jaws.

Once adequate clamping pressure has been reached, the hammer is ready to vibrate. Engage the "start" control. The exciter case and pile will begin vibrating.

If driving, the combined weight of the hammer and pile will force the pile into the ground. As the driving resistance increases, the drive pressure or amperage will increase until it reaches the maximum power output of the power pack. Any increased resistance may cause the hammer to slow down somewhat. The hammer may be operated in this condition for short periods of time; however, extended periods will cause the unit to overheat, causing possible damage to the vibrator components. Also, if conditions warrant, the frequency of hydraulic units can be varied by adjusting the engine speed.

If extracting, the crane must exert a net pull on the hammer-pile system. This will cause the pile to move upward. When extracting, in general the best procedure is to start the exciter without crane pull, allowing it to come up to speed, loosen the soil and to drive a little. Once this loosening has taken place, extraction is easier. It is *very important* that the crane not exert an upward pull greater than the rated capacity of the exciter's suspension.

Shutdown: Once driving or extracting is complete, engage the "stop" control. The exciter will stop in a couple of seconds. Make sure there is no net crane pull on the hammer, and the exciter has stopped vibrating. Engage the "clamp open" control, and remove the hammer from the pile. When you're ready to stop for a longer time, also allow the engine to idle for five (5) minutes to cool, reduce engine speed to idle, and turn engine start switch to off.

Chapter V
MECHANISMS OF DRIVING BY VIBRATION AND IMPACT-VIBRATION

§11 Classical Theories of Soil Response to Pile Vibration

As the name implies, vibratory hammers apply a vibratory, i.e., an alternating and rapidly repetitive force, to drive piles. Now, when driving piles by impact, it is necessary for the hammer to generate high forces to move the pile blow by blow; on the other hand, vibratory hammers impart energy to the pile-soil system continuously rather than incrementally. Impact drivers also impart their motive force in one direction, namely down, which is where one wants the pile to go. Vibrators, however, are inherently bidirectional in their force generation, so either during driving or extraction half of the force is going the wrong way. Yet vibrators can be effective for both operations. How can this be?

The key to solving this problem lies in the soil response to vibration. There are three basic explanations that have been tendered to explain the mechanism of vibratory driving; these are summarized as follows:

Thixotropy: Gumenskii and Komarov (1959) explain this process as follows: "By thixotropy (from the Greek "thixis" -- shaking -- and "trope" -- change) of dispersed systems in general, or of soils in particular, we mean their liquefaction during jarring by some mechanical action (shaking, stirring, etc.). Under such circumstances, at a constant temperature, there occurs a transition from a gel to a sol, which, after a certain time, is again converted to a gel. Thixotropy should thus be considered to involve two aspects: liquefaction and solidification. These constitute a reversible process, since it is repeated many times."

With this theory, when the soil is excited by vibration, the resistance is reduced so that the system can either drop by its own weight or come out of the ground from the pull of the crane. The pile is not actually forced into the ground by the vibrating force but by the net applied static force on the system. For driving, gravity acts to push the pile downward into the soil; however, if the crane were to exert a net upward force on the system, the pile moves upward. This enables a vibratory hammer to act as an extractor, which is important in many applications. Important variables for this theory are frequency, power, acceleration or dynamic force, and velocity

Implicit in this explanation of soil response is the need for energy input. What we are dealing with here is a chemical phenomenon; like others, it needs energy input to make it work. With vibratory hammers this is generally expressed as energy over time, or power. Inadequate power will result in incomplete soil transformation and increased apparent soil resistance.

System Amplitude: This concept is most succinctly stated by Erofeev et.al. (1985): "Centrifugal force created by the vibration exciter with the turning of the shafts with unbalanced loads, or eccentrics, attached to them cause the pile to vibrate. The characteristics of these vibrations depend on the static moment of the eccentrics, the frequency of the vibrations as determined by the angular velocity (ω or θ), the weight of the vibratory pile driver-pile system, and the properties of the soil. The amplitude of the system's vibrations is decisive for the insertion of the pile. At a low vibrational amplitude, displacement of the soil with respect to the side surface of the element being inserted does not exceed the limit of its elastic deformation and the pile is not sunk into the ground. As the amplitude of the vibrations increases, residual deformation of the soil occurs and the pile begins to slip relative to the soil, i.e., it is sunk into the ground." This principle, of course, is also applied to wave equation analysis of impact driving, as no set of the pile is possible without exceeding the elastic limit, or quake, of the soil. Important variables for this theory are frequency and amplitude.

Dynamic Force: This concept is based on the hypothesis that the force generated by the rotating eccentrics breaks the bond between the pile and the soil, thus making vibratory driving (or extraction) possible. A general adjunct to this hypothesis is the modeling of the soil resistance as being dry frictional or Coulombic in nature. Starting with a version of Equation (4) modified to include Coulombic soil resistance, Tseitlin et. al. (1987) describe a mathematical model to compute vibratory penetration. In this discussion, having made the preceding assumptions, they go on as follows: "Experimental research has established that the amplitude of the vibrations A_g of the ground surrounding the pile is comparable to the amplitude of the pile being sunk only during the initial stage in which the pile vibrates together with the ground. As breakthrough progresses, the ground vibrations diminish, while those of the pile increase; in the final stage of breakthrough, the ratio of the amplitude of the pile's vibrations to that of the ground vibrations reaches two to three orders of magnitude, which also permits us to consider the ground surrounding the pile immobile during the sinking process...Experimental data attesting that the elastic component of lateral ground resistance is two orders of magnitude less than the plastic component exemplify the fact that the elastic component of lateral ground resistance is negligible during vibrational sinking at high speeds. As far as the viscous component of ground resistance during vibrational sinking is concerned, it is nonlinear in nature (i.e., it has a soft characteristic)...and it changes little with increases in speed even at low vibration speeds (5-10 cm/sec)." Important variables for this theory are frequency and acceleration or dynamic force.

§12 Summation and Synthesis of Vibratory Driving Mechanisms

With these three models (and any other that might be proposed), it would seem that the mechanism for vibratory pile driving is well understood, but the reality is different. Without making a rigorous analysis of these methods, some attempt to make sense of it all must be made and so a few observations are in order.

The whole object of vibratory pile driving is to sink or extract piling into soil, and so the response of the soil to the vibration is the critical factor. However, when we consider "soil response", it is easy to overlook the fact that piles interface the soil in two ways, namely in shear (shaft friction) and compression (toe bearing). Soils are not bound to respond to either static or dynamic loading in the same way and in fact do not.

Vibratory hammers that are used for non-displacement piles generally have low to moderate amplitudes and operating frequencies above 20 Hz. In the U.S. at least, these machines make up the vast majority of the vibratory hammers. When displacement piles (such as concrete piles) are driven with vibratory hammers, frequencies around 10 Hz are more common along with much higher amplitudes. This type of variation indicates that all three theories of vibratory driving have application depending upon the type of pile and of course of soil.

In addition to the variation of drivers with piles, as a general rule vibratory drivers are found to be most effective in cohesionless soils. This is probably true because these soils are more likely to undergo thixotropic change. Since low displacement piles have by definition less toe resistance, it seems that the combination of low toe resistance and cohesionless soils is the ideal situation for vibratory driving, and in these cases the thixtropic model (and perhaps the dynamic force model) applies, although Gumenskii and Komarov (1959) showed thixotropy to take place in clays routinely.

When soils become more cohesive, vibratory driving becomes less effective, but it is also found that increasing the amplitude will aid the pile sinking considerably. The reason for this probably relates to the toe resistance, whether it is with low or high displacement piles. It is unlikely that the sucessive compression of the toe produces much thixotropy, especially in cohesive soils, and so when toe resistance is elevated -- whether by a large toe area or with stiff, especially cohesive soils, or both -- the vibrator must resort to a different mode of operation, in this case by picking up the entire system and forcing it down onto the toe by the vibratory cycle (frequently referred to as a "chopping" mode). This in effect makes the entire pile an impact ram, and in this case system amplitude becomes very important, as is stroke with an impact hammer. High system amplitudes allow more easily high velocities which make the impact more effective.

Finally, one factor that does not appear in any of these models is that of frequency, although it has been shown that soil response does vary with frequency. (O'Neill, 1988)

We can see from these considerations that the differing explanations of vibratory driving stem in reality from that fact that different piles and soils demand to be driven differently. It is also likely that our understanding of the mechanisms of vibratory driving and extraction and their application will improve as research continues.

§13 Driving Mechanism of Impact-Vibration Machines

Impact-vibration hammers do not drive piling exactly like either impact or vibratory hammers but in reality are a mixture of the two. The best way to consider this is to look at in relation to pure vibratory driving.

As we have said above, vibratory driving is least effective when the toe resistance is high. Impact-vibration hammers are more effective in these situations because they can generate high peak forces to drive through these, much as a high amplitude high velocity vibratory hammer can do. It is for this reason that impact-vibration hammers are used extensively for concrete piles. They are capable of delivering the driving forces necessary to overcome the high toe resistance.

With relation to impact hammers, these hammers deliver a lower impact energy per blow with more blows than a vibratory hammer can. In soils where elastic compression is not a major problem, this should produce comparable results.

Impact vibration hammers produce some forces through the springs. In general, these are not a major factor in impact-vibration driving, especially where the frame is loaded down with deadweight to keep it on the pile. In such a case, there is no transfer of alternating force to the pile. Bi-directional force with impact-vibration machines is possible if the exciter is allowed to impact at both the top and the bottom of its travel, and this can be helpful in both driving and extraction.

Chapter VI
MATHEMATICAL DESCRIPTION OF VIBRATORY AND IMPACT-VIBRATION MECHANICS AND DRIVING PERFORMANCE

§14 Basics of Vibratory Mechanics

A vibratory pile driver is a machine that installs piling into the ground by applying a rapidly alternating force to the pile. This is generally accomplished by rotating eccentric weights about shafts. Each rotating eccentric produces a force acting in a single plane and directed toward the centerline of the shaft. Figure 11 shows the basic setup for the rotating eccentric weights used in most current vibratory pile driving/extracting equipment. The weights are set off center of the axis of rotation by the eccentric arm.

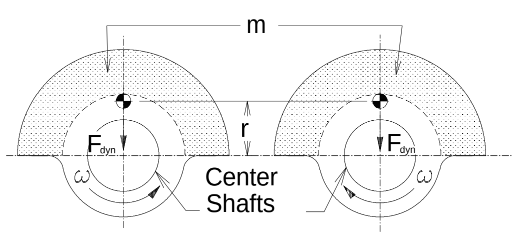

Figure 11 Vibratory Eccentric Configuration

Generally speaking, many of the traditionally measured quantities for vibratory hammers such as amplitude, acceleration ratio, etc., are computed for the "free-hanging" case, i.e., with only the mass of the system taken into account and no soil resistance. For most conventional vibratory hammers, one can consider the entire system a rigid mass. This is because the relatively low frequency vibrations of most vibratory hammers do not bring the distributed mass and elasticity of the system into play. By definition, with the sonic pile drivers the resonant properties of the system become significant, and the analysis becomes more complicated.

As the figure shows, the weights rotate about the center shaft with an angular velocity w, given by the equation

$$\omega = 2 \cdot \pi \cdot \theta \qquad (1)$$

where ω = angular velocity of rotation, rad/sec

θ = frequency of vibrations, Hz = (Eccentric RPM)/60

For a rotating body, the force exerted on the center shaft is given by the equation

$F_{dyn} = m\, r\, \omega^2/1000$ . . . . (2)

where F_{dyn} = dynamic force of eccentrics, kN
m = eccentric mass, kg
r = eccentric moment arm, m

If we define

$K = m \cdot r$ . . . . (3)

where K = eccentric moment, kg-m

we can substitute to

$F_{dyn} = K \cdot \omega^2/1000$ . . . . (4)

If only one eccentric is used, in one revolution a force will be exerted in all directions, giving the system a good deal of lateral whip. To avoid this problem, the eccentrics are paired so the lateral forces cancel each other, leaving us with only axial force for the pile. Machines can also have several pairs of smaller, identical eccentrics synchronized and obtain the same effect as with one larger pair. Thus, the "m" term means the sum of all the eccentric weights, the eccentric arm length for all being equal.

Without considering the effects of gravity, the equation of motion is

$x'' = 1000 \cdot F_{dyn} \cdot \sin(\omega \cdot t)/M$ . . . . (5)

where x'' = instantaneous acceleration of system, m/sec^2

The solution of this equation is

$x = K \cdot \sin(\omega t)/M$ . . . . (6)

where x = system displacement, m

In the process of integrating Equation (5), we can derive three very important quantities. The first is the ratio of accelerations, or the peak acceleration during a vibratory cycle; it is

$n = F_{dyn}/W_{dyn}$ . . . . (7)

where n, n_1, n_2 = ratio of maximum acceleration of system to acceleration due to gravity, g's
W_{dyn} = vibrating weight of system, kN = $g \cdot M/1000$
g = acceleration of gravity = 9.8 m/sec^2

The second is the peak velocity, which is

$v_{dyn} = gn/\omega$ . . . . (8)

where v_{dyn} = peak dynamic velocity during the cycle, m/sec

These quantities are important because the power transmitted to the soil must be done in an efficient manner from a high energy source through the pile-soil interface to a low one in the soil. As the vibratory excitation is dynamic, it must be done through these quantities. Minimum values for n have been established from 1.5 to 9, but there is no consensus on this.

Finally, the maximum displacement is

$x_{max} = K/M$ . . . . (9)

where x_{max} = maximum displacement of system (zero to peak), m

Since the acceleration, velocity, and displacement of the system solved from Equation (5) are all sinusoidal with respect to time, these quantities are measured from the zero line of the sine wave. Customarily, the maximum cycle displacement of the vibrator, called the amplitude, is measured from peak to peak and is expressed as

$A = 2x_{max}$ . . . . (10)

where A = amplitude of system (peak to peak), m

The instantaneous torque driving the eccentrics is

$T_{inst} = (F_{dyn/\omega})^2 \cdot \sin(2\omega t)/(2 \cdot M)$ . . . . (11)

where T, T_{inst}, T_{max}, T_{rms} = motor torque, kJ

The maximum instantaneous torque is

$T_{max} = (F_{dyn}/\omega)^2/(2 \cdot M)$ . . . . (12)

Looking forward to the power requirements, normally one would use an root mean square (rms) value to match an application to a motor, so

$T_{rms} = T_{max}/\sqrt{2}$ . . . . (13)

From the torque the power is simple to compute, given by

$N = \omega \cdot T_{rms}$ . . . . (14)

where N = motor power, kW

Adequate power is *essential* for successful vibratory driving because, among other reasons, maintenance of the vibratory frequency is impossible without it. An underpowered machine will slow down and thus reduce its own driving capability. Excess power, on the other hand, is pointless as the system will not take any more power than it needs. This is one of the hardest things to understand about vibratory systems; the problem is most succinctly stated by Goncharevich and Frolov (1985):

> The power which is required to operate the vibratory machine in the given regime and the power which can be transmitted by a vibrator of a specific type are determined by a whole complex of factors: vibrator parameters, machine characteristics, and the acting loads in the machine. It is not possible to impart additional power to the vibratory machine by simply increasing motor output. Each vibratory machine consumes strictly determined power, whose value is dependent on a whole set of factors acting in the vibratory machine-vibration exciter-load system.

The one thing over which the machine operator has most control that can influence power requirements is the static force applied to the system, whether with bias weight or downcrowding in driving or additional crane force in pulling.

§15 Basics of Drivability and Capacity Prediction For Vibratory Hammers

The ability of vibratory machines to drive piling is well demonstrated; however, one major obstacle to the expanded use of these machines is the lack of an accepted method to relate the driving performance of a hammer/pile/soil system to either the resistance of the soil to driving or the static capacity of the pile. This section will discuss some of the methods developed in the past to determine the drivability of vibratory hammers and ultimately the bearing capacity of the piles driven.

The methods presented below date from the very earliest application of vibratory technology to pile driving to the present; they take a wide variety of approaches and will give a wide variety of results. For convenience, we will break down these methods into four groups:

1)Parametric methods: Certain characteristics are tested against some kind of standard to determine drivability.

2)Energy methods: Drivability is determined based on the energy flow through the system, along with other considerations.

3)Methods from Laboratory and Model Tests: These methods are derived from correlations gathered from tests in a laboratory setting, usually driving a pile through a soil tank.

4)Time Dependent Nonlinear Methods: These seek to apply numerical integration techniques to the direct solution of the equation(s) of motion of the vibrating system. These include the wave equation techniques popular with impact hammers.

One important observation at this point is that, in general, vibrated piles have lower bearing capacity than impact driven ones. This is because impact driving produces soil compacting at the toe that vibrating does not.

Most of the formulae below are reproduced from their sources; however, when necessary they have been altered into a uniform units (SI) and notation system.

§16 Parametric Methods

Tünkers Dynamic Force Method: Basically, this method employs the formula

$F_{dyn} \geq s \cdot A_s$ . . . . (15)

where s = Unit Soil Shaft Resistance, kPa
A_s = Shaft Area of soil, m^2

Values for the factor r are given in Table 2. The formula is only applicable when $x_{max} \geq 2.38$mm. To compute the shaft area for sheet piling, this method employs the following computation:

$A_s = 2.8 \cdot l \cdot d_{inter}$ . . . . (16)

where l = Pile Length, m
d_{inter} = Width of Sheet piling, m (from interlock to interlock).

Table 2
Values of σ for Tünkers Method

SPT Value, blows/30cm		Soil Resistance, kPa
Cohesionless Soil	Cohesive Soil	σ
0-5	0-2	9.86
5-10	2-5	11.87
10-20	5-10	12.83
20-30	10-20	14.84
30-40	20-30	15.80
40+	30+	16.76

Beta Method: A given vibratory hammer is suitable for driving a given pile when

$$F_{dyn} + W_{dyn} + W_{st} \geq \beta_o \cdot R_{so} + \beta_i \cdot R_{si} + \beta_t \cdot R_t \quad (17)$$

where W_{st} = Non-Vibrating Weight of System, kN
β = Beta Factor for Soil Resistance (general)
β_i = Beta Factor for Soil Resistance (outside shaft)
β_o = Beta Factor for Soil Resistance (inside shaft)
β_t = Beta Factor for Soil Resistance (toe)
R_{si} = Inside Pile Shaft Soil Resistance,kN
R_{so} = Outside Pile Shaft Soil Resistance, kN
R_t = Pile Toe Soil Resistance, kN.

Suggested values for β are given in Table 3. For extraction, this formula is altered to read

$$F_{dyn} + F_{ext} - W_{dyn} - W_{st} \geq \beta_o \cdot R_{so} + \beta_i \cdot R_{si} + \beta_t \cdot R_t \quad (18)$$

where F_{ext} = Extraction Force of Crane, kN.

Table 3
Values of β_n for Beta Method

Type of Soil	β
Round Coarse Sand	0.10
Soft Loam/Marl, Soft Loess, Stiff Cliff	0.12
Round Medium Sand, Round Gravel	0.15
Fine Angular Gravel, Angular Loam, Angular Loess	0.18
Round Fine Sand	0.20
Angular Sand, Coarse Gravel	0.25
Angular/Dry Fine Sand	0.35
Marl, Stiff/Very Stiff Clay	0.40

where n = i, o, or t depending upon relative position of pile and soil in question.

Table 4
Values of Pile Toe Weight Pressure p_o for Savinov and Luskin Method (For Saturated Sandy and Loose-Clayey Soils)

Type of Pile	Pressure, kPa
Small Diameter Steel Pipe and other Piles w/A_t<150 cm²	150-300
Closed End Pipe Piles, A_t<800 cm²	400-500
Square and Rectangular Reinforced Concrete Piles, A_t<2000 cm²	600-800

Savinov and Luskin Method: This method was developed in Russia by two of the pioneers in the development of vibratory pile driving equipment. Presented below is a reformulated version, done for simplicity and clarity. The steps are as follows:

1)Computation of the required minimum dynamic weight: To insure sufficient weight for pile sinking, the minimum dynamic weight of the system is computed by the formula

$$W_{dyn} \geq p_o \cdot A_t \quad (19)$$

where A_t = Toe Area of Pile, m^2
p_o = Toe Pressure of System, kPa (as given in Table 4)

Although the method calls for the weight computed above to be dynamic, there is also the possibility of having part of this weight to be static.

2)Determination of the soil resistance: For vibration purposes, the soil resistance is determined by the following formula:

$$F_{cr} = \int Z \cdot \sum_{i=1}^{i=k} s_i \cdot l_i \quad \text{(Piling in general -- 20a)}$$

$$F_{cr} = \int \sum_{i=1}^{i=k} s_i \cdot l_i \quad \text{(Sheet Piling -- 20b)}$$

where F_{cr} = Critical Force for Driving, kN
Z = Pile Perimeter, m
s_i = Soil Element Shaft Resistance, kPa or kN/m
l_i = Pile Element Length, m

The length of the pile is first divided into segments of length l_i, then the soil resistance s for each segment is taken from Table 5, depending upon the type of soil in the given segment.

Table 5
Soil Resistance for Savinov and Luskin Method

Type of Soil and Pile	σ	
	For Piles, kPa	For Sheets, kN/m
1)Saturated Sandy and Visco-Plastic Clay Soils		
Steel Tubes	6	
Reinforced Concrete Piles	7	
Open-Ended Pipe Piles	5	
Sheet Piles, Light (Heavy) Sections		12 (14)
2)The same as (1), but with Interlayers of Compact Clay or Gravelly Soils		
Steel Tubes	8	
Reinforced Concrete Piles	10	
Open-Ended Pipe Piles	7	
Sheet Piles, Light (Heavy) Sections		17 (20)
3)Stiff Plastic Clay Soils		
Steel Tubes	15	
Reinforced Concrete Piles	18	
Open-Ended Pipe Piles	10	
Sheet Piles, Light (Heavy) Sections		20 (25)
4)Semi-Hard and Hard Clay Soils		
Steel Tubes	25	
Reinforced Concrete Piles	30	
Open-Ended Pipe Piles	20	
Sheet Piles, Light (Heavy) Sections		40 (50)

3)Computation of the dynamic force of the eccentrics: The dynamic force is first computed to meet the following two criterion:

a)Soil resistance factor: The dynamic force should be greater should be greater than the soil resistance, as expressed by the formula

$$F_{dyn} \geq \aleph \cdot F_{cr} \div \psi \qquad (21)$$

where ψ = Pile Factor (0.8 for concrete piling and 1 for all other piling.)
$\aleph$ = Soil Resilience Coefficient (should be between 0.6 and 0.8 for vibration frequencies between 5 and 10 Hz and 1 for all other frequencies.)

b)System acceleration factor: The peak cycle acceleration should fall within values such as

$$n_1 \leq F_{dyn} \div W_{dyn} \leq n_2 \quad (22)$$

Values for n_1 and n_2 are given in Table 6. The method seems to favor Equation (22) over (21) in case of conflict.

Table 6
Values for Ratio of Accelerations "n" for Savinov and Luskin Method

Type of Pile	Minimum Ratio of Accelerations n1	Maximum Ratio of Accelerations n2
Steel Sheet Piling	2.00	6.67
Light Piles	1.67	3.33
Heavy and Pipe Piles	1.00	2.50

4)Compute the necessary frequency to insure a minimum peak vibration velocity by the equation

$$\omega = 1000 \cdot F_{dyn}/(v_{dyn} \cdot M) \quad (23)$$

Velocity v_{dyn} should fall between 0.5 and 0.8 m/sec.

5)Compute the eccentric moment using rigid body vibratory mechanics by the equation

$$K = 1000 \cdot F_{dyn}/\omega^2 \quad (24)$$

6)Check for adequate amplitude against the recommended values for x_{max} as shown in Table 7. Amplitude is computed using the equation

$$x_{max} = 1000 \cdot K \cdot \psi/M \quad (25)$$

Table 7
Amplitude Requirements for Savinov and Luskin Method

Frequency, Hz	5-12 Hz	13-17 Hz	18-25 Hz
Type of Pile and Soil	Half Amplitude, mm		
Steel Sheet Piling, Open Ended Pipe Piles, and Other Piles with At < 150 cm²			
Sandy Soils		8-10	4-6
Clayey Soil		10-12	6-8
Closed End Steel Pipe Piles, At < 800 cm²			
Sandy Soil		10-12	6-8
Clayey Soil		12-15	8-10
Reinforced Concrete Piles, Square or Rectangular Section, At < 2000 cm²			
Sandy Soil	12-15		
Clayey Soil	15-20		
Reinforced Concrete Cylinder Piles of Large Diameter, Driven with Soil Plug Removed			
Sandy Soil	6-10	4-6	
Clayey Soil	8-12	6-10	

7)Compute the power of the driving motors: This is done using the formula

$$N = K\theta^3(3.2\times10^{-6}D + .079K/M) \quad (26)$$

where D = Diameter of Bearing Race, mm

Equation (26) was developed with the following assumptions:

a)Efficiency of the power transfer from motor to vibration exciter is 90%.
b)Coefficient of rolling friction in the bearings is 0.1%.
c)Of the power actually sent into the soil, 15% of it is lost in the soil mass.

The Savinov and Luskin method is unique in that it uses parameters of empirical and theoretical derivation (ratio of accelerations, dynamic velocity, soil resistance, soil and pile material factors, and pile toe pressure) and combines their use using standard, free-hanging, rigid-body vibratory mechanics. The result is a hammer that is optimized for the pile to be driven. This method is iterative; it may require several cycles to get the resulting hammer to fit the parameters to the best extent possible.

Evaluation: The main advantage of the parametric methods is their relative simplicity of formulation and computation. The parametric methods make integrating experience-developed factors into the calculation very simple as well.

There are two main disadvantages of parametric methods. The first one is that none of the methods either adequately take into account all of the variables present in the vibratory installation of piles or account for the interaction between these variables. For instance, except for the Savinov and Luskin method, none of the methods take into account either the effect of power availability and input into the system or of frequency. Also none can be considered really valid at frequencies higher than 25-30 Hz. The second shortcoming of parametric methods is the lack of any consideration of installation velocity either as an input variable or as a result. This is important for two reasons; first, computing velocities for a number of system combinations is the only comprehensive way to compare different systems; second, any scheme to use vibratory drivers with bearing piles will probably use installation velocity as an acceptance criterion, much as the blows per meter (foot) are used now with impact hammers.

§17 Energy Methods

Energy methods to compute drivability are based on the assumption that, during most vibratory driving, the power put into the system by the vibrator equals the power taken out by the soil resistance. Thus energy methods are steady state methods, and do not take into account transient effects. There are two energy and power sources of a system: 1)the driving motor of the vibrator, 2)the potential energy of the system falling through the gravity field. The sink or destination for this energy is the resistance of the pile acting against the sinking pile. Mathematically, this energy and power flow is expressed by the formula

$$R_u \cdot V_{sys} = N + (W_{dyn} + W_{st}) \cdot V_{sys} \quad (27)$$

This equation can be reformulated in two ways; first, to compute penetration velocity,

$$V_{sys} = N,(R_u - W_{dyn} - W_{st}) \quad (28)$$

and for bearing capacity of the pile,

$$R_u = W_{dyn} + W_{st} + N,V_{sys} \quad (29)$$

where R_u = Soil Resistance, kN
V_{sys} = Pile Penetration Velocity, m/sec

These are ideal equations; in practice, these methods add factors to account for actual conditions.

Davisson Method: This formula was proposed to predict the bearing capacity of piles driven with the Bodine BRD-1000 resonant vibratory pile driver. Making an analogy with the dynamic formulae, in the place of impact a full cycle of the eccentrics is considered as the time of energy transfer from hammer system to soil; thus, the loss factor is based on a per cycle basis. Generalizing, the formula is

$$R_u = (N+(W_{dyn}+W_{st})\cdot V_{sys})/(V_{sys}+\theta\cdot S_l/1000) \quad (30)$$

where S_l = Soil Loss Factor, mm/cycle

and for penetration velocity, we can rearrange it to read

$$V_{sys} = (N-R_u\cdot\theta\cdot S_l/1000)/(R_u-W_{dyn}-W_{st}) \quad (31)$$

Values for S_l are given in Table 8. The formula is mainly intended for field use, and so all of the variables are taken from actual data.

Table 8
Loss Factors for Davisson Method

Soil @ Pile Tip	Loss Factor Sl, mm/cycle*	
	Closed-End Pipe Pile	H-Beam
Loose Silt, Sand, or Gravel	0.24	-0.21
Medium Dense Sand, or Sand and Gravel	0.76	0.76
Dense Sand or Sand and Gravel	2.44	2.13

*Values developed for Bodine BRD-1000 Resonant Driver. Formula not applicable in rock.

Snip/Soviet Methods: These are placed with the energy methods because of their format and their involvement of horsepower, deadweight, and (indirectly) penetration velocity. They were developed for precast concrete cylinder pile. They are

$$R_u = (\lambda-30000\cdot V_{sys}/(A_o\theta))\cdot(245\cdot N/(A_o\theta)+W_{dyn}+W_{st})/F \quad (32a)$$

and

$$R_u = (245\cdot\lambda\cdot N/(A_o\cdot\theta)+W_{dyn}+W_{st})/F \quad (32b)$$

where λ = Soil Coefficient
F = factor of safety (generally F=2)

Equation (32a) is for penetration velocities of 0.5-1.67 mm/sec, and (32b) for 0.05-0.5 mm/sec. Values for l vary with soil conditions and are given in Table 9.

Table 9
Soil Coefficient for Snip/Soviet Formula

Soil Type	k
Saturated Sand	4.0-7.5
Moist Sand	3.0-4.5
Dry Sand	2.5-4.0
Sand Clay	2.5-5.0
Silty Clay	2.2-4.5
Clay	2.0-4.5

Evaluation: Energy methods have three main advantages. They are inherently simple. They are able to incorporate many factors into the analysis. They give as a result a penetration velocity (or conversely a bearing capacity), which allows meaningful comparison of different systems with each other.

The main disadvantage of energy methods lies in one of their advantages, namely their simplicity. They may not take into account all of the necessary factors in a meaningful way. This is in part due to their lack of broad field correlation. The Davisson method has extensive field documentation, but it is only been done for the Bodine hammer, which operates at frequencies well above most any other vibratory pile driving machine. Conversely, the Snip/Soviet method is well tested for penetration velocities that would be considered low in the U.S. These methods need more field development under a wide variety of conditions if they are to reach their full potential.

§18 Methods from Laboratory and Model Tests

The use of laboratory and model testing to establish the drivability of vibrated piling represents an attempt to establish a reliable correlation based on an actual physical situation but in a controlled environment. Generally it involves setting up a tank full of soil and driving the piling through the tank, either horizontally or vertically. The various parameters of the system can then be varied to produce data for correlation purposes.

Bernhard's Method: To compute the static bearing capacity, the method employs the following formula:

$$R_u = f \cdot N \cdot l / (V_{sys} \cdot l_{soil}) \quad (33)$$

where l_{soil} = Length of Soil Penetration by Pile, m
f = Soil Loss factor (suggested value is 0.1)

The tests that established the formula were run in a frequency range of 50-5250 Hz.

Schmid and Hill's Formula: They propose from statistical data reduction that the penetration velocity of the pile can be estimated by the formula

$$V_{sys} = 0.417 \cdot g \cdot n^{0.75} \cdot ((W_{st} + W_{dyn}), R_u + 0.0036 \cdot n - 0.018)/\theta \quad (34)$$

The test pile was driven through sand exclusively. The test setup limited the frequency to a maximum of 30 Hz. Schmid went on to develop another method, his Toe Impulse Formula, which is

$$R_u = \alpha \cdot (W_{dyn} + W_{st})/(\theta \bullet \sqrt{(2 \cdot V_{sys},(\theta \cdot n' \cdot g))}) \quad (35)$$

where a = a coefficient, taken to be 0.67
n' = acceleration in excess of the minimum acceleration to effect driving, g's

O'Neill's Formula: This formula came from tests run on a vibrator driving a miniature pile in a sand tank. It is

$$R_u = 0.050 \cdot N'/(V_{sys} \cdot (\sigma'_h/92.8-0.486) \cdot (1.96 \cdot D_r-1.11) \cdot (1.228-0.19 \cdot d_{10})) \quad (36)$$

where s'_h = horizontal effective stress, kPa
D_r = relative density
d_{10} = grain size, mm
N' = power actually delivered to the pile top, kW

The theoretical power the vibrator generates can be computed by the equation

$$N = \theta \cdot (4000 \cdot W_{st} + 2 \cdot K \cdot \omega^2 \cdot (1 + \theta^2/(\theta^2 + \theta_n^2))) \cdot (K \cdot \theta^2/(1000 \cdot M \cdot (\theta^2 + \theta_n^2))) \quad (37)$$

where θ_n = natural frequency of suspension with respect to the vibrator mass, Hz

and this is related to the power actually delivered to the pile top by the formula

$$N' = (0.25 + 0.063 \cdot n) \cdot N \quad (38)$$

The peak acceleration can be computed by the formula

$$n = (3.54-2.186 \cdot D_r) \cdot (8.99 + 2.76 \cdot d_{10}) \cdot ((39.37 \cdot V_{sys})^{(1.71-s'_h/85.1)}) \quad (39)$$

Evaluation: The advantage of laboratory and model test formulas are that the results they give have their root data taken from a controlled physical environment. The various parameters of the system can thus be taken into account in a physically realistic and truly interactive fashion.

The main weakness of these laboratory derived formulae is that the conditions produced in the laboratory may not include all that is actually experienced in actual vibratory pile driving. They should be used only when the original conditions under which they were derived are present in the field. Also, none of the formulae above is comprehensive in its parameter inclusion. Nevertheless, because of their virtues, laboratory and model tests remain an important constituent of vibratory pile driving research.

§19 Time Dependent Nonlinear Methods

The newest method to be applied to vibratory installation of piling is that of time dependent nonlinear methods. These methods seek to actually solve the equations of motion of the vibratory system through numerical integration. These methods divide themselves into two categories: 1)methods which consider the distributed mass and elasticity of the system (wave equation techniques), and 2)those which don't (rigid body techniques).

VIBEWAVE Method: This involves using a modified version of the TTI program. This model uses a finite difference mass-spring-dashpot model which is solved using a modified version of Euler's Method.

TNOWAVE Method: This again involves the modification of a wave equation analyzer for use with vibratory hammers. TNOWAVE uses the method of characteristics to solve the wave equation.

Piecewise Integration Techniques: These are rigid body techniques which are applied to the system. The pieces are determined by changes in the variables, especially the reversal of the soil frictional force. Since the equations for these techniques can be formulated dimensionlessly, parametric studies can be performed using these techniques. In addition to solving longitudinal vibratory motion, these have been applied for longitudinal-rotational and impact-vibrational type drivers.

VIBDRIVE Method: This was developed by the author for the VIBDRIVE analysis program. It is a rigid body technique that uses a variation of Euler's technique (different from TTI) to solve the equations of motion. A Coulombic soil model is used for the shaft resistance and a constant resistance plug model is used for the toe.

Evaluation: Assuming that they are properly set up, time dependent non-linear methods are the most complete method available to analyze the vibratory installation and extraction of piles. They can take into account all system variables through their thorough modeling of the system. This is especially important with the wave equation methods at higher frequencies, as both distributed mass and elasticity in the system become more important.

The main weakness of these methods is the accuracy of the constituent components of the model. These must be both thoroughly understood and accurately simulated for meaningful results. These conditions have not been met yet; the popular Smith model for soil response cannot be applied without modification to vibratory soil excitation.

§20 Methods for Impact-Vibration Hammers

Because of their construction and operation, impact-vibration hammers are by their nature more complex to analyze than their vibratory conterparts, and so create more analytical problems. Most of the information given below is taken fron Tseitlin et. al. (1987). Before we get into the actual calculations, we need to define a few important, dimensionsless quantities.

The first thing to note -- and in reality it is one of the first things that anyone noted about these machines -- is that the exciter does not impact the anvil with every blow. Tsaplin (1953) first observed this, and defined the ratio of the frequency of rotations to the frequency of impacts. This is mathematically stated as

$$i = \theta/\theta_i \qquad (40)$$

where i = ratio of imacts to exciter frequency
θ_i = number of impacts per second
θ = frequency of vibrations, Hz

With most impact-vibration machines, the exciter is mounted in the frame with springs, and so we can define define the ratio of the natural frequency of the head/spring system to the impact frequency, which is

$$\xi_1 = \theta_n/\theta \qquad (41)$$

where ξ_1 = ratio of natural frequency of exciter to frequency of impacts
θ_n = natural frequency of the exciter, Hz

We also need to define two force ratios; they are

$$f = F/F_{dyn} \qquad (42)$$

and

$$\gamma = R/F_{dyn} \qquad (43)$$

where f = ratio of shaft soil resistance to dynamic force of exciter
F = shaft soil resistance, kN
γ = ratio of toe soil resistance to dynamic force of exciter
R = toe soil resistance, kN

Finally, we need to set the angular operational parameter a'; generally, it should range from 17½° to 30°.

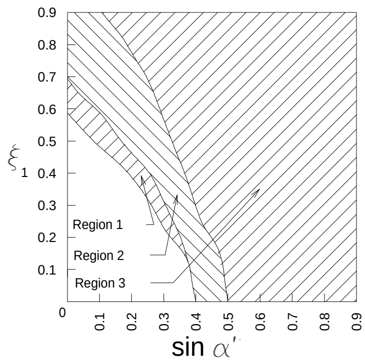

Figure 12 Regions of Impact-Vibration Driving (after Tseitlin et. al. (1987))

Having set all of these parameters, we need to first determine if we are in a region where impact-vibrational action is taking place. Looking at Figure 12, we see three regions where impact-vibrational action is possible. Taking the values for α' and ξ_1, we determine which region we are actually in. Impact-vibrational action is possible if the sum of f and γ is greater than 8 for Region 1, greater than 4 for Region 2, and greater than 2 for Region 3.

This having been determined, a dimensionless velocity for the exciter can be defined by the equation

$$y'_1 = 1.204 + 6.841x_1 - 6.161x_1^2 + (4.357 - 21.215x_1 + 16.203x_1^2)\cdot\sin\alpha' - (6.188 - 15.434x_1 + 10.616x_1^2)\cdot\sin^2\alpha' \quad (44)$$

where y'_1 = dimensionless velocity

The actual impact velocity can be computed by the equation

$$v_{impact} = \omega\cdot K/(m_1\cdot y'_1) \quad (45)$$

where v_{impact} = impact velocity, m/sec

m_1 = mass of exciter, kg

The dimensionless impact displacement (pile set) is given by the equation

$$y_n = (0.137 - 0.02\cdot(f+\gamma) - 0.0009\cdot(f+\gamma)^2)\cdot y'_1 \quad (46)$$

where y_n = dimensionless displacement

and the actual set is determined by the equation

$$x_{pl} = K/(m_1\cdot y_n) \quad (47)$$

where x_{pl} = pile set, m.

In order for the pile to be moving, the pile must meet minimum a minimum displacement criterion given by the equation

$$D_l < 1000\cdot x_{pl} \quad (48)$$

where D_l = Perkov-Shaevich Criterion, given in Table 10, mm.

Table 10
Perkov-Shaevich Criteria for Impact-Vibration Hammers

Soil Type	Minimum Value, mm
Oversaturated Sands of Medium Corseness and Compactness	1.6
Saturated Sands of Medium Corseness and Compactness	2.2
Macroporous Sandy Loams of a hard constituency	2.8
Loams of stiff-plastic constituency	3.2
Undersaturated Sands of Medium Corseness and Compactness	4.6

The power consumed by the machine is given by the equation

$$N = K\theta\cdot(8\cdot(2.808 - 3.04\cdot\sin\alpha' - 0.0125\cdot(f+\gamma))\cdot(0.5/\xi_1)^{0.12}\cdot(d/4)^{0.752} + 3.22\cdot10^{-4}\cdot\theta^2\cdot D)/100 \qquad (49)$$

This formula assumes that the transmission efficiency of the motor to the vibrator is 90% and that the coefficient of friction of the bearings is 0.1%.

CONCLUSION

Vibratory and impact-vibration hammers have proven themselves a versatile tool to install and extract many kinds of piling. The former are limited principally by very stiff soil conditions where impact is required and a lack of an accepted method of determining the drivability and bearing capacity of the piles they drive. The latter are limited mainly by mechanical design considerations. These will be addressed as the technology progresses and the versatility of this equipment will continue to be enhanced.

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