Feature

While you may consider compaction an old-hat subject, there are many new and different approaches and products being used today. And there is a reason behind every one of them.

By Charles D. Bader

Let's face it. Soil compaction is an old-hat subject. After all, it has been practiced by man for thousands of years. And the fundamental need has remained year after year, millennium after millennium, and it still exists in the millennium just beginning. Today, compaction is being routinely used in virtually every construction project. After all, soil compaction increases load-bearing capability, prevents soil settling and frost damage, provides stability, and reduces water seepage, swelling, and contraction. What's more, building codes and inspectors demand it.

Now, as then, there are just two principal types of compaction force: static and vibratory. To quote from Multiquip's *Soil Compaction Handbook*:

"*Static force* is simply the deadweight of the machine, applying downward force on the soil surface, compressing the soil particles. The only way to change the effective compaction force is by adding or subtracting the weight of the machine. Static compaction is confined to the upper soil layers and is limited to any appreciable depth. Kneading and pressure are two examples of static compaction.

"Vibratory force uses a mechanism, usually engine-driven, to create a downward force in addition to the machine's static weight…. The compactors deliver a rapid sequence of blows (impacts) to the surface, thereby affecting the top layers as well as deeper layers. Vibration moves through the [soil], setting particles in motion and moving them closer together for the highest density possible."

While these are indeed the fundamentals of soil compaction, there are a variety of conditions and applications that dictate the design of the many different soil compaction products on the market. Therefore, it is useful to review these conditions and applications to gain an understanding of the design rationale of the products and what conditions dictate the use of each.

Soil Classification

Both the American Society for Testing and Materials and the American Association of State Highway and Transportation Officials classify soil as either granular or cohesive on the basis of a sieve analysis. Granular soil consists mainly of sands and gravels, whereas cohesive soil consists mainly of silts and clays. Jim Layton of the Wacker Corporation in Menomonee Falls, WI, explains the structural differences.

"In granular soil, the particles are held in position due to the frictional force that exists at the contact surfaces. In the dry state, granular soil particles can be easily separated and identified. In a moist state, a granular material such as sand may be formed to desired shapes but will crumble easily as soon as it is disturbed.

"Granular soils are best compacted by vibration. This is because the vibration action reduces the frictional forces at the contact surfaces, thus allowing the particles to fall freely of their own weight. At the same time, as soil particles are set in vibration, they become momentarily separated from each other, allowing them to twist and turn until they can assume a position that limits their movements. This settling action and repositioning of particles is compaction. All the air voids that were previously present in the soil mass are now replaced by solidly packed soil.

"In cohesive soil, the molecular attraction between soil particles is the force that holds the soil in place. As these particles are very small in size, high in number, and densely arranged, the cohesive force within the soil is very high. Cohesive soils are very hard in the dry state. When moist, they are plastic and can be molded or rolled into almost any shape.

"Cohesive soils are best compacted by impact force. Cohesive soils do not settle under vibration due to the natural binding forces between the tiny soil particles. These soils tend to lump, forming continuous laminations with air pockets in between…. Therefore, cohesive soils such as silt and clay are more effectively compacted using impact force because it produces a shearing effect that squeezes the air pockets and excess water to the surface and moves the particles closer together."

Of course, these are generalizations because there are many types of cohesive soils and granular soils. For example, the Unified Soil Classification System breaks down soil types into 15 types and indicates the quality of each as construction material. This and other classification systems take into account such factors as particle sizes, grain-size distribution, and the effect of moisture on the soil. Because of the wide variations among soils that might be encountered on a specific job site, soil testing is wise (and usually mandated).

Soil Testing

Prior to the start of excavation, samples of the soil on the site should be taken to a soil test lab for a Proctor Test to determine its density value. The Proctor Test will measure the density that can be attained for that soil and express it as a standard. It will also determine the effect of moisture on soil density. This is not a high-tech test. A standard weight is dropped 25 times on each soil sample from the job site. Each soil sample is weighed, oven-dried for 12 hours, and then reweighed. The procedure is repeated, adding different amounts of water to the soil with each repetition.

At a certain moisture, the soil reaches a maximum density when a specific amount of compaction energy is applied. The maximum density reached under these conditions is called 100% Proctor density, and this value is used as a basis for comparing the degree of compaction of the same type of soil on the job site. The compaction specification for the site may be expressed as a percentage of the maximum density (e.g., 85% Proctor).

This Standard Proctor Test, developed in the early 1930s by R.R. Proctor, a field engineer for the City of Los Angeles, has become universally accepted for most construction projects. For heavier structures such as nuclear power plants, a Modified Proctor Test was developed. The principles and procedures are the same, but it uses a heavier weight and a longer drop.

After compaction, the site must be tested to determine whether it meets the density specification determined in the laboratory tests. There are several tests used, says Steve Spence, compaction product manager for Multiquip Inc. of Carson, CA. "The two most widely used are the sand cone test and the nuclear density test.

"In the sand cone test, a 6- by 6-inch hole is dug in the compacted soil to be tested. The soil is removed and weighed, then dried and weighed again to determine its moisture content. The dry weight of the soil removed is divided by the volume of the sand needed to refill the hole. This gives us the density of the compacted soil in pounds per cubic foot. This density is [divided] by the maximum Proctor density obtained earlier (o determine whether the compaction meets the specified Proctor percentage).

"Nuclear density meters use a radioactive isotope source, Cesium 137, at the soil surface or from a probe placed into the soil. The isotope source gives off photons, usually Gamma rays, which radiate back to the meter's detectors on the bottom of the unit. Dense soil absorbs more radiation than loose soi, and the readings reflect overall density. A relative Proctor density is obtained after comparing maximum density with the compaction results from the test."

The cost of the sand cone test is quite low, but the process takes time, so equipment operation must be halted while the test results are derived. Conversely, the nuclear density test is much faster, but its cost is relatively high. Moreover, if the results of these field tests do not meet the compaction specification, the site will have to be recompacted and the field test repeated, thereby cutting into the productivity of the construction project.

At least two manufacturers have taken steps to resolve this dilemma. Both MBW Inc. of Slinger, WI, and Compaction America of Kewanee, IL, have developed soil compaction instrumentation that enables field crews to measure compaction in real time in lieu of laboratory testing.

"Our Soil Compaction Meter is independently tested and correlates with 95% Standard Proctor," says MBW's Brad Derosa. "To use it, a contractor places a disposable piezoelectric sensor at the bottom of his excavation before filling. As compaction begins, the sensor transmits voltage based on the pressure wave amplitude of the compaction process. Once the voltage signals a predetermined soil density, the system's hand-held meter flashes a stop light. Not only does this enable the contractor to measure compaction in real time without under- or overcompacting, but our Soil Compaction Supervisor unit permits a fast, easy transfer of compaction data to a computer, thereby providing evidence that the compaction specification was met."

Compaction America's Terrameter works somewhat differently, according to Manager of Marketing Services Steve Wilson. "It's mounted on the instrument panel of our Bomag roller compactors within easy reach of the operator," he says. "As the roller passes across the ground compacting the soil, the Terrameter monitors interaction between the acceleration of the roller's vibrating drum and the dynamic stiffness of the soil. Thus, the measuring system continually produces, stores, and displays a measurement of compaction quality called an Omega value. The higher the Omega value, the better the compaction. During each pass, the Terrameter calculates the average Omega value and compares it with previous passes.

"A green indicator light indicates that the Bomag roller is compacting effectively. If the Omega value that meets the specification is achieved before the green light goes out, the operator may stop compacting. Alternatively, if the average Omega value increase between two passes is minimal, the green light will go out, signifying that maximum economic compaction has been attained. Thus, through the indication of Omega values, the Terrameter provides assurance of uniform compaction quality without the delay of laboratory testing. This leads to significantly increased compaction quality too. Because conventional test methods are applied only at sample points, they only provide partial compaction data. Conversely, the Terrameter assesses the entire area, thereby reducing the risk of under- and overcompacting throughout the compacted area."

Types of Compaction Equipment

Soil compaction equipment is available in a variety of different forms. The equipment can be self-propelled or it can be mounted on and use the hydraulic systems of earthmoving equipment. The self-propelled equipment falls into the following four major categories (although there are many different models and variations within each category):

1. forward vibratory plates
2. reversible vibratory plates
3. rollers
4. rammers

The primary factor that determines the selection of the optimum equipment for a given application is the type of soil to be compacted, although such complicating factors as confinement, trench depth and width, and cost can be important differentiators as well. Table 1 provides a rule-of-thumb guide to the effect of soil type on equipment selection.

Table1. Effect of Soil Type on Equipment selection

		Vibrating Sheepsfoot Rammer	Static Sheepsfoot Smooth Roller	Vibrating Plate Vibrating Roller

	Lift Thickness	*Impact*	*Pressure*	*Vibration*
Gravel	12 in.	Poor	No	Good
Sand	10 in.	Poor	No	Excellent
Silt	6 in.	Good	Good	Poor
Clay	6 in.	Excellent	Very Good	No

Forward Vibratory Plates

As indicated in Table 1, granular soils (sands and gravels) are best compacted by vibratory energy. Very small particles, such as sands, will respond best to very high frequencies, in the range of 10,000-15,000 vibrations per minute (vpm), whereas larger gravels will respond best to lower frequencies in the range of 2,000-4,000 vpm. Therefore, it is best to match the frequency of the vibration compactor to the most prevalent particles present in the soil to be compacted.

Forward vibratory plates are low-amplitude, high-frequency devices, Spence says. Gasoline or diesel engines drive an eccentric weight at a high speed to develop compaction force and vibrations that compact granular soils. (The engine and the handle are vibration-isolated from the vibrating plate.) The frequency range is usually from 2,500 vpm to 6,000 vpm to accommodate a range of granular soils.

The exciter design and the total static weight both play an important role in the efficiency and performance of the vibratory plate, Layton adds. "Exciter units operate on the principle of turning an unbalanced eccentric weight at high speed to produce centrifugal force. It is this centrifugal force, which varies with the square power of the exciter speed, that causes the machine to vibrate, move forward, and compact the soil.

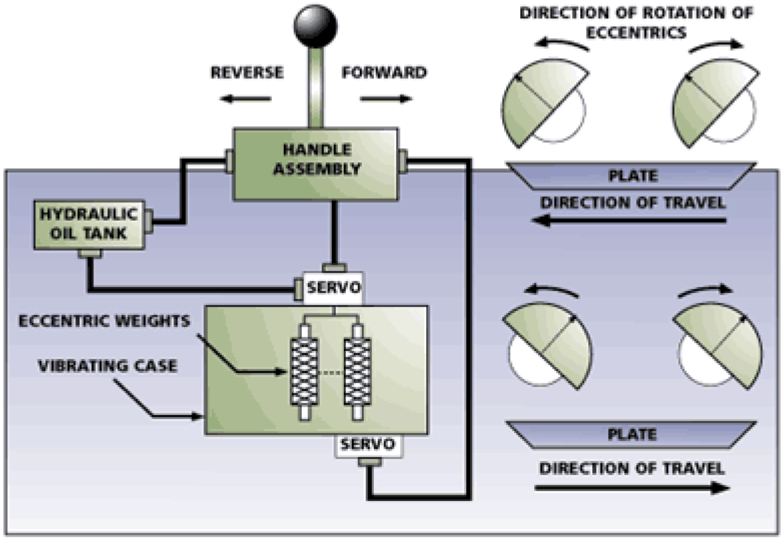
"The static weight of a small vibratory plate - 150- to 300-pound weight class - is usually negligible compared to the centrifugal force that is generated in the exciter. Here, the vibratory force is the dominant force that acts on soil particles during the compaction process. The heavier the plate, however, the more compaction force it generates. Therefore, for vibratory plates above 300 pounds, the static weight and the vibratory action have a combined effect on soil particles. The total effect is to vibrate and squeeze soil particles together to achieve compaction."

Reversible Vibratory Plates

Inherent to the design of the forward vibratory plate compactor is the fact that it can only move in one direction, a situation that limits its maneuverability, particularly in confined areas. Conversely, a reversible vibratory plate compactor can move in both directions because it has an exciter system with two eccentric weights that revolve in opposite directions. These weights are arranged such that the plate will move in the opposite direction every time the relative position of one eccentric is changed 180º with respect to the other.

This is accomplished in different ways depending on the manufacturer's design. In the Mikasa MVH hydraulic system shown in Figure 1, forward and reverse are changed by switching pressurized oil between the servo pistons located on the eccentric case. The servo positions change the position of the eccentric weights. In the Weber system, one of the weights is keyed solid with constant pitch while the other weight is allowed to move 180º in pitch. The reversibility comes from simply varying the pitch of the movable weight. The Wacker mechanism uses a sleeve gear in the exciter. The lever the operator holds controls a hydraulically actuated piston that connects to this sleeve gear. As the piston moves in and out, the sleeve gear rotates, changing the relationship between the two eccentric weights thereby determining the direction of travel.

Figure 1. Hydraulic Reversing Process



Whatever the mechanism, as Ron McCannell, vice president of operations for Weber Machines USA points out, the fact that there are two weights moving in the exciter case creates twice as much force as a comparably powered forward vibratory plate compactor. What's more, changing the direction of a reversing plate occurs instantaneously at full shaft speed, without the necessity of stopping the machine. In fact, the eccentrics can be changed in infinite increments from full forward to full reverse, thereby achieving maximum maneuverability. The plate can even be held in place with no forward or reverse motion so that the full centrifugal force can be applied for spot compaction.

"Reversibles do cost more than forward plates," McCannell concedes. "A 200-pound reversing plate lists at $3,700 as compared to $2,500 for a forward-plate machine - all other things being equal. That's a very small cost difference considering the far greater productivity inherent to the reversible. A contractor can easily justify the added cost based on first-year labor savings alone."

In material provided by spokesperson Kathy Reissig, Stone Construction Equipment points out that there's good reason for the added cost of a reversible plate compactor. "Reversible plates pound the ground harder than forward plates with as much as three-plus times the impact force - from 5,200 pounds to 12,880 pounds. Also, reversible plates are very versatile. They can be equipped with a remote control capability that lets an operator compact a trench without ever actually getting into one. While some forward plates are designed for trench work, they still require someone to walk behind them to keep them under control."

Steve Stone questions the maneuverability of other reversibles in trenches or other confined areas. "Most designs only allow a remote-controlled reversible plate to steer forward, 90º to the right or left, or go reverse," he points out. "Only recently have we developed ‘stepless steering,' a configuration that features one large eccentric assembly with a weight arrangement that allows a 180º freedom forward and a 130º freedom of rear motion. Therefore, wherever you point the joystick on the remote, that's where the machine will go."

Stepless steering would seem to be icing on a cake that has already earned the enthusiasm of contractors and manufacturers alike. Stone sums it up succinctly, saying, "Dollar for dollar, a reversible is possibly the best compaction buy you can find."

Rollers

There are four general types of rollers: static, vibratory, sheepsfoot, and pneumatic tire. However, the use of static rollers for soil compaction has been steadily declining since the introduction of vibratory rollers because static rollers must be very heavy to handle even moderate soil lifts. By the same token, the use of pneumatic tire rollers is primarily limited to surface compaction with effective compaction depths of no more than 6 in.

A vibratory roller has exciter weights in at least one of its drums to generate vibratory action in addition to the effect of its static weight. The vibratory impulses break up the frictional force between the soil particles. Since this allows deeper layers of soil to vibrate and settle, vibratory rollers can accommodate larger lifts and provide quicker and more effective compaction than static rollers.

As Wacker's *Contractor's Update* points out, however, walk-behind vibratory rollers are not as cost-effective as reversible vibratory plates. To quote that report directly, "Most reversible plates cost less than walk-behind rollers but have a much larger cubic-yard capacity. The larger contact area of the baseplate transmits more vibration to the surface producing (deeper soil lifts and) more effective compaction. This greater compaction capability gives the contractor a more productive, less costly means of compaction (than is possible with rollers)." See Figure 2.

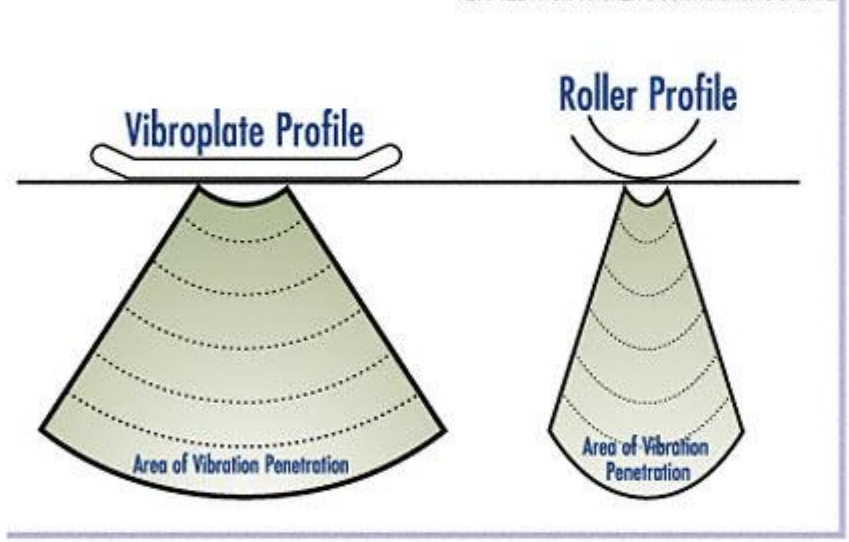


Figure 2. The Plate Advantage

ADAPTED FROM WACKER'S CONTRACTOR'S UPDATE

The sheepsfoot roller is one of the most recognizable compaction devices and is used throughout the world. These rollers have drums with many protruding studs, each similar to a sheepsfoot, that provide a kneading action. It works on a wide range of materials but is most effective for compaction of plastic soils like clay or silt. When used on more granular materials, sheepsfoot rollers tend to shove rather than compact such soils.

According to information supplied by Steve Wilson, "The sheepsfoot compacts from the bottom of each lift to the top. High contact pressures cause the feet to penetrate through the loose material and actually compact the soil directly beneath the foot tip. Towed sheepsfoot rollers can only work at speeds from 4 to 6 miles per hour, which prevents any benefit being received from the forces of impact or vibration. A high number of coverage passes are required with sheepsfoot rollers because of the small contact area compacted by each foot.

"Self-propelled sheepsfoot rollers equipped with fill spreading blades…are capable of higher productivity than towed sheepsfoot rollers. They are more expensive to own and operate than towed sheepsfoot rollers, however.

"The tamping foot roller incorporates the advantages of the sheepsfoot and steel wheel into a high-speed compaction tool. Like the sheepsfoot roller, it compacts from the bottom to the top of the lift for uniform density. And like the steel wheel, it also compacts from the top of the lift. The tamping foot roller is capable of high rolling speeds without throwing material because of the design profile of the tamping foot. [Unlike the sheepsfoot roller], it leaves a relatively smooth, sealed surface so that haul units are able to maintain good speeds when traveling over the fill. In some cases, the added productivity from this advantage can offset the cost of compaction."

Rammers

Figure 3. Rammer Cutaway

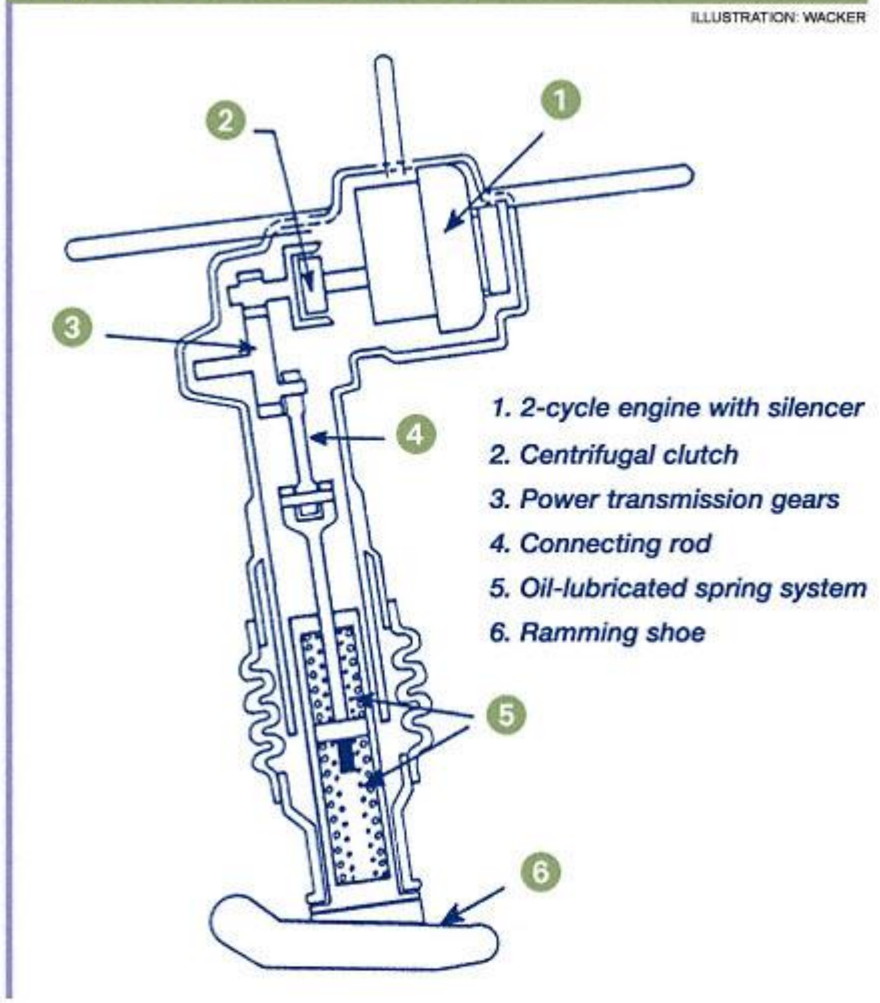


ILLUSTRATION: WACKER

Rammers (see Figure 3) are hand-operated impact devices that deliver high-impact force through a rectangular shoe plate roughly 1 ft.^{2} in size. Capable of delivering up to 4,500 lb. of impact per blow and up to 800 blows per minute, rammers are an excellent choice for cohesive and semicohesive soils. The compaction force is generated by a small gasoline or diesel engine powering a large piston set with two sets of springs. The hand-operated rammer, which can weigh in excess of 200 lb., is inclined at a forward angle to allow forward travel as the machine jumps. As a result, rammers can travel at more than 50 ft./min. and therefore compact more than 3,000 $ft.^2$/hr. (Stone markets a rammer with a forward travel speed of up to 90 ft./min., boasting a productivity of 4,950 $ft.^2$/hr.)

Rammer specialists such as Stone and Multiquip have as many as 10 different models in their lines to accommodate different field needs. Multiquip's Mikasa MTR-35HS, for example, weighs just 90 lb., making it easier to use in the field but at the cost of delivering an impact of just 1,212 lb. per blow, less than half that of any other rammer in its line. Shoe size is another variable. Whereas 10 to 11 in. x 13 in. is the popular shoe size of all manufacturers, that same MTR-35HS has a shoe size with a width of less than 6 in. Why? Lower weight was just one of the reasons, Steve Spence explains. A standard-width chain trencher creates a 6-in. trench, so a 5.9-in. shoe is ideal for this application.

Engine type is another differentiator, Spence says. Contractors who operate all their equipment with diesel fuel or contractors who do work on job sites where gasoline-powered equipment is restricted [such as a petrochemical plant or an oil refinery] have little choice. They must use diesel-powered rammers. And two-cycle gasoline engines on rammers are changing now. Today, modern two-cycle rammer engines are oil-injected, with a separate tank for the gasoline and a separate tank for the oil. That way, only gasoline runs through the carburetor; the oil is mixed with the fuel in the engine cylinder. Finally, EPA air-quality restrictions threaten to ban conventional two-cycle engines. The solution? A four-cycle engine running at a little lower RPM. Not only does it generate lower emissions, there is also less harsh noise and a 27% increase in fuel efficiency. A four-cycle engine costs about 2% more and delivers about 15% less impact, so there are tradeoffs for a contractor to consider."

Carrier-Mounted Equipment

While self-propelled compactors are widely used in the construction industry, they are by no means the only entry in the field. Compactors as attachments to earthmoving equipment represent an alternative that many contractors are using, and suppliers of these attachments have attractive product lines. For example, Allied Construction Products of Cleveland, OH, markets a line of vibratory compactor/drivers that attach to and operate off the hydraulic systems of skid-steers, backhoes, loaders, and excavators and are in the attachment catalogs of most original equipment manufacturers.

Allied, which claims to have pioneered the concept of hydraulically operated vibratory compactor drivers, currently markets five models of these Ho-Pac machines, ranging from a model designed for attachment to skid-steers up to a powerful model designed to attach to excavators of at least 45,000 lb.

"Attached to the carrier's boom, the Ho-Pacs use an eccentric, rotating weight that creates vibration and impulse energy," says Manager of Sales and Marketing Steve Sabo. "Specially designed rubber mounts direct the energy to the Ho-Pac's compaction plate, not the carrier's boom. The compactor operates off the carrier's hydraulic system and reaches out to work anywhere the carrier's boom can reach. Static downpressure and high-impulse vibration forces produced by the compactor are ideal for compacting granular soils. The vibrations generate stress waves that bring the soil's air to the surface. As a result, the soil particles are rearranged, compressed, and compacted."

This carrier-mounted compactor configuration can generate powerful compaction forces. Allied's Model 9801, for example, operates off a 45,000-lb.-class excavator and can generate 20,000 lb. of impulse force at 2,000 cycles per minute.

Depending on job conditions, the company says, it can compact in 4- to 6-ft. lifts to densities in excess of 95% Proctor with a production of 160 yd.^{3} or more per hour. And, Sabo points out, each Ho-Pac model can function as a driver as well as a contractor, thereby adding versatility to a contractor's fleet.

Pack Wheel of Madison, TN, also markets a carrier-mounted compactor. Called the Pack Wheel, this static wheel compactor is designed for use on virtually all excavating equipment, owner Jim Thilmony says. "It uses the power of the machine to achieve compaction levels equal to or greater than standard construction specifications. Each Pack Wheel uses eight compaction feet on each 32- or 18-inch-diameter wheel. The openness of the Pack Wheel allows penetration through the backfill, packing from the bottom upward. The spacing between the wheels, combined with the slotted rims, enables it to penetrate from 18 to 24 inches into the fill. It rolls back and forth, mixing and packing as it goes, rather than riding over the top as a conventional hydraulic packer does. What's more, the open-wheel design allows almost continual backfilling. Therefore, fewer lifts are necessary, and that further reduces backfill and packing time on the job."

MBW also manufactures a carrier-mounted machine: its EXA vibratory roller attachment for backhoes and excavators up to 60,000 lb. The boom-mounted EXA essentially combines the features of a static wheel and a vibratory plate, combining the static rolling process with an intense vibration. "The EXA's small footprint is important," says MBW's Brad Derosa. "Because of it, the pounds per square inch that the EXA supplies is approximately three to four times the intensity of the same carrier using a boom-mounted vibratory plate. The vibratory force is also 50% to 100% greater on a per-square-inch basis, which enhances the placement of granular materials, particularly larger particles like crushed rock or pit-run gravel."

Self-Propelled or Machine-Mounted Compactors?

There is considerable controversy as to whether carrier-mounted compaction is cost-effective in the long run. Sabo believes that machine-mounted compactors are more productive than self-propelled models. After all, he contends, the range and the static weight of the carrier are inherent advantages. Of course, Sabo represents a company that makes only machine-mounted compactors, but both Derosa and Thilmony agree with his contention, and their companies make self-powered models as well as machine-mounted ones. Derosa asserts that a machine-mounted compactor is "five to six times more productive than a walk-behind, even one equipped with a remote control." Thilmony laconically adds that "contractors usually have *some* unit standing around that they can mount a compactor on."

Both Spencer and McCannell believe this line of reasoning is misleading. Spencer dismisses it out of hand, saying, "An excavator is an awfully expensive compactor." McCannell elaborates on this point: "If a contractor owns one of those big machines and he's using it to tamp dirt, it's just a waste of money. Most machines can only deliver 11,000 to 12,000 pounds of force for compaction, and it will cost them about $10,000 for the attachment plus the cost of hooking it up each time. I can sell him a self-propelled vibratory plate compactor listing at $15,000 that will deliver that much power, and he won't have to tie up a $160,000 machine. It's the money per yard that a contractor makes moving dirt that keeps him in business, not a little compacting."

Durability

Everyone seems to agree on one basic point: Compactors are one item that you shouldn't buy on the cheap. McCannell states the issue most forcefully. "This is equipment designed to beat itself to death while it pounds the ground. Because of the constant vibration and the working environment created as a soil compactor operates on a daily basis, logically it becomes necessary to accept the fact that eventually there will be a limit to the productive life of these machines.

Therefore, it just makes sense that when a machine is being designed, consideration should be given to the fact that at some point in time, it will need to be repaired and even rebuilt. With this thought in mind, Weber has been building forward and reversible compactors that are completely rebuildable at a reasonable cost. For example, all Weber models have a sealed vibrator housing with oil-bath lubrication for the bearings. And all bearings, seals, and belts are available over the counter locally. Also, the vibrators are detachable from the base plate to facilitate repair or rebuilding. I could go on and on. As an industry, we owe it to our customers to extend the life of our products as long as possible."

Wilson of Compaction America agrees that manufacturers should plan for rebuilding, adding that "except for the drum surface, you can recondition a wheel-type compactor indefinitely. The engine can be rebuilt, and all the hydraulic components, the drive components, the differential, and the transmission can be replaced." And Wacker publishes specific maintenance and trouble-shooting features to extend compactor life. The company points out with considerable pride that rammers and plates it built 40 years ago are still being used by contractors today.

That sounds like the age-old solutions to the age-old needs weren't all that bad. Innovations since have just made things better - in terms of durability, in terms of performance, and in terms of value.

Charles D. Bader is with Dateline II Communications in Los Angeles, CA.

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