A WORD TO THE WISE ABOUT LIGHT COMPACTION EQUIPMENT

SPECIFICATIONS

In the early 1980s, MBW was an active member of the LIGHT EQUIPMENT MANUFACTURER'S BUREAU (LEMB) of the CONSTRUCTION INDUSTRY MANUFACTURER'S ASSOCIATION (CIMA) that produced LEMB Standard # 1 for "Vibratory Rammers" and LEMB Standard # 2 for "Vibratory Plates". In the period 2005 to the present, MBW has taken part in meetings of light compaction equipment manufacturers brought together in an international effort to develop new standards. While all of the participants working to arrive at consensus on a number of technical issues are to be commended, we worry that this latest effort may suffer similar dilutions of fact and relevance that plagued LEMB twenty-five years ago. This industry should know, in part as a result of LEMB Standards # 1 and # 2, that poorly conceived standards confuse and mislead the public. We take this opportunity to express our concerns.

Compaction equipment users have always wanted to know how hard a rammer or vibratory plate "hits". To answer this question, interested parties look to manufacturer's published information. Unfortunately, IMPACT FORCE, CENTRIFUGAL FORCE, TOTAL APPLIED FORCE, AMPLITUDE and STROKE, AREA OF COMPACTION, DEPTH OF COMPACTION, WEIGHT, and TRAVEL SPEED provide interested parties with information of far less value than generally assumed. Relevance is at issue. Promotion of unrealistic performance expectations is a problem. Some information is presented in a fashion that encourages the public to mistake data for something it does not represent.

Impact Force, as the term is used in LEMB Std # 1, quantifies the energy required to produce impact impressions when a rammer is run over a steel plate. Manufacturers freely note that LEMB # 1 has been disappointing in terms of repeatable test results. In the 1980s, MBW tested all of its own and a number of competitor's rammers. Results varied from test to test with some results as much as 50% below published Impact Force values.

Beyond the repeatability issue, it is noteworthy that LEMB # 1 allows for some interesting arithmetic manipulation. Values expressed in "foot pounds/blow" are converted into "pounds/blow" via a questionably applied soil stiffness normalization factor. The converted result is intended to be divided by the surface area of a rammer's shoe to arrive at "specific soil pressure", the end result of LEMB # 1. No manufacturer publishes specific soil pressure data, although all manufacturers convert foot pounds/blow into pounds/blow. It's more impressive to claim that a rammer hits with 3000 pounds of force/blow than 64 foot pounds/blow or provide the specific soil pressure of 0.45 foot pounds/square inch/blow.

Some other issues deserve consideration in regards to LEMB # 1. The stiffness of a steel plate is constant and many times greater than stiffness values associated with soil. A plate of steel is solid. Soil is particulate in nature. Not only do particulates and solids react differently to energy inputs, but the operating dynamic of a rammer is observably different when operated over steel. The assumption that LEMB # 1 correlates to real world soil applications is a reach. Finally, the energy of the rammer producing impressions in steel (LEMB # 1) is concentrated not on the full surface area of the rammer shoe, but on a very, very small surface area, essentially a hardened steel ball.

A person schooled in soil mechanics might reasonably inquire as to the relevance of IMPACT FORCE derived from LEMB # 1. The compaction of steel, after all, is a topic of marginal interest. We are interested in using rammers to compact soil - particulate soil, soil influenced by variable moisture, and soil possessing stiffness levels that are intentionally altered during the compaction process. When we use a rammer on soil its energy is distributed over the entire surface area of its shoe. More importantly, it is well known that conditions of compaction, i.e., soil type, gradation, moisture content and lift depth, have greater bearing on achieving compaction goals than the size or "impact force" of the compactor. Indeed, favorable conditions of compaction facilitate achieving acceptable results with a range of compactors. Conversely, adverse conditions of compaction predispose compaction activity, employing even the largest and "hardest hitting" compactors, to failure. In spite of LEMB # 1 and manufacturer's technical data that imply otherwise, the relevance of IMPACT FORCE is at issue.

UPDATE 2/1/2009 – *Effective this date MBW will no longer publish IMPACT FORCE or COMPACTION FORCE data in connection with its range of rammers. LEMB Standard # 1 was abandoned in a recent international (ISO) standardization effort. No alternative method for determining IMPACT FORCE was agreed upon. A number of rammer manufacturers concurred that IMPACT FORCE is a moving target, variable with conditions of operation/compaction, and misleading when applied for comparative and/or fitness-for-use analysis. Literature updates as reprinted.*

Centrifugal Force (**CF**) impels a compactor's effective vibratory mass outwardly from the centerline of a rotating eccentric shaft (LEMB # 2) and is one of several factors used in the calculation of amplitude. Unfortunately, CF has become one of the compaction industry's most misleading specifications. CF generated by a vibratory compactor's rotating eccentric(s) should never be misconstrued as a measure of how hard the compactor "hits". CF tells nothing of value about a vibratory compactor's appropriateness for a particular compaction application. Comparing one plate's CF to that of another reveals nothing about comparative performance, amplitude, or hitting power. Indeed, CF has no practical value when presented as a stand alone specification. Relevance is at issue, a point clearly made by Lars Forssblad in VIBRATORY SOIL AND ROCK FILL COMPACTION, Copyright Dynapac Maskin AB, Solna, Sweden, 1981, "It has been shown that no relationship exists between centrifugal force and the vibrating force transmitted to the ground … the real vibrating force is mainly dependent on amplitude".

Compaction equipment manufacturers have long known that CF is regularly mistaken for "how hard" a vibratory compactor "hits". Manufacturers have done little to correct the public's confusion and continue to present data with the expectation that CF will be mistaken for something it does not represent.

UPDATE 2/1/2009 – *Despite the fact that Centrifugal Force is of no practical value to users of vibratory plates, Centrifugal Force was retained as a specification in the recently published ISO standard for vibratory plate compactors. As of 2/1/2009 MBW will footnote its vibratory plate specifications as follows …**"Centrifugal force is not an expression of compaction effectiveness or force".** Literature updates as reprinted.*

Total Applied Force is the sum of CF and OPERATING WEIGHT and is of no value whatsoever to buyer/users of light compaction equipment. As noted above, CF should never be confused with compaction force delivered to the soil. Operating Weight, as we will see shortly, grossly overstates mass set in motion to perform compaction work.

Amplitude and Stroke are terms used to quantify the motion of a mass subject to energy inputs. "Amplitude" is usually associated with higher frequency compactors. Motion generated is small, often .1 or less of an inch. "Stroke" also describes mass motion and is usually associated with lower frequency (1000 or less cycles/min) compactors producing motion in the 2 to 5 inch range.

UPDATE 2/1/2009 – *As of this date MBW declines to publish STROKE data for it range of rammers. Rammer stroke is highly variable and misleading for purposes of comparative and/or fitness-for-use* *analysis. Side-by-side comparison of rammers coupled with soil testing is the only reliable means of developing fitness-for-use analysis.*

"Amplitude" is one of the meaningful pieces of information that could be provided. Unfortunately, committees charged with developing standards for light compaction equipment have avoided amplitude, although amplitude data has been provided in connection with vibratory rollers for decades. This formula (heavy roller amplitude) is expressed as:

$$Amplitude = \frac{768 * CentrifugalForce}{\left(\pi * \frac{frequency}{30}\right)^2 * OperatingWeight}$$

where centrifugal force is measured in lbs, frequency is measured in VPM and operating weight is measured in lbs. When applied to comparatively smaller vibratory plates, some fine tuning of the formula is necessary in regards to the definition of "Operating Weight".

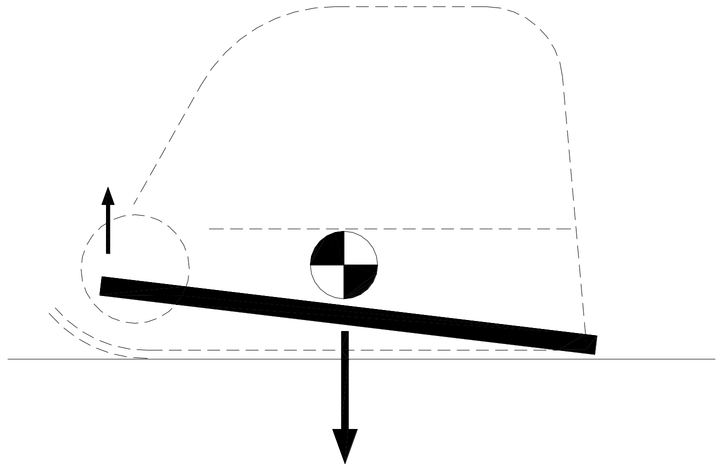
Slightly less than half the operating weight of a vibratory plate is typically attributable to the engine, engine deck, handle, water and fuel tanks. These components are physically connected to the base plate and exciter through shockmounts which substantially isolate them from the energy and vibration produced by the machine's exciter. In other words, the suspended or sprung mass (engine, handle, etc.) are vibrating less than the base plate and exciter because of the shockmounts. It follows then, that the weight to be used in any calculation of amplitude would be derived from the full weight of the base plate and exciter plus some portion of the suspended mass. The additive portion of the suspended mass is 25% based on a "transmissibility factor" associated with well designed isolation systems.

The amplitude formula for vibratory plates is expressed as follows:

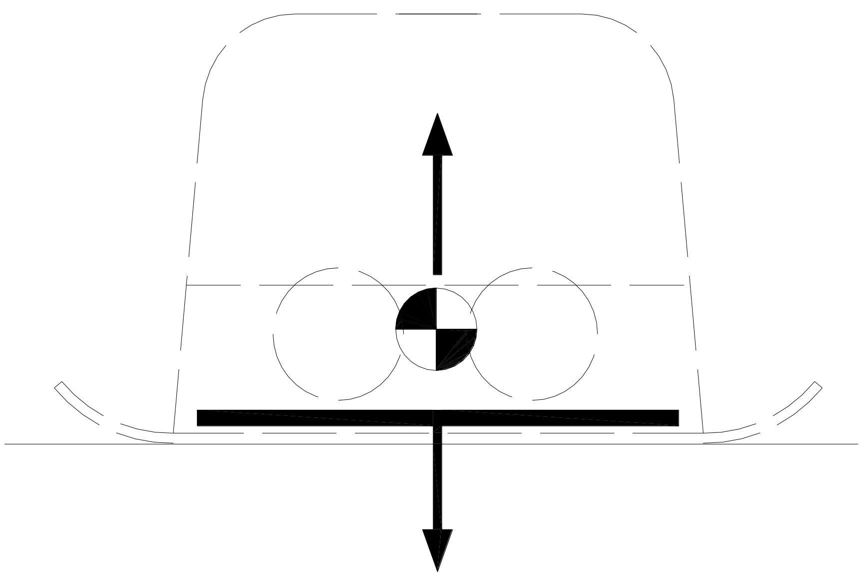
$$Amplitude = \frac{768 * CentrifugalForce}{\left(\pi * \frac{frequency}{30}\right)^2 * EffectiveVibratoryMass}$$

The amplitude formula now produces a realistic quantitative amplitude result because Operating Weight no longer overstates Vibratory Mass.

When viewing a single direction plate from the side, the center of gravity is located somewhat centrally in the envelope of the machine. The exciter which produces the motive force is located at one end or the "front" of the envelope. Imagine replacing the machine with a simple lever. See figure below. Lifting on one end of the lever gains a mechanical advantage in lifting the lever's center of gravity. When a plate's exciter is located significantly forward of the plate's center of gravity, the force produced by the exciter has the same effect, thereby increasing amplitude at the front end of the plate but producing much lower amplitude at the plate's trailing end. This is important in interpreting the result of the above amplitude formula. The amplitude result is the **average amplitude** for a single direction plate.



In the case of reversible plates, exciters are usually located very near the center of gravity and amplitude tends to be equal over the surface of the plate.. The same amplitude formula for vibratory plates applies to reversible plates, but in this case the result can be described as maximum amplitude. See figure below:



That said, a single amplitude value for a reversible plate is misleading. All reversible plates contain at least two counter-rotating eccentrics. The plate's travel is controlled by adjusting the orientation of the eccentrics with respect to each other. Published CF values always assume the eccentrics are in perfect phase with one another, but this occurs only in the spot compaction mode, i.e., not traveling in forward or reverse direction. In this mode, CF of the eccentrics is additive. To make the machine travel, the phase of one eccentric is altered, effectively canceling some of the CF. At full travel the cancellation effect is approximately 30%. Providing an amplitude range for reversible plates solves the problem. The range is easily established by running two calculations with the amplitude formula or AMPLITUDE CALCULATOR (see below UPDATE 1/11/2010). The first calculation factors in the published CF for a given reversible plate and results in amplitude at zero travel.. The second calculation factors in 70% of published CF and results in amplitude at full travel, thereby providing an amplitude range. Ignoring the cancellation effect of counter-rotating eccentrics overstates amplitude by approximately 40% at full travel.

As anyone who has used an ordinary carpenter's hammer will appreciate, the distance (amplitude) through which the hammer is swung has much to do with how efficiently one drives nails into a piece of wood. Amplitude quantifies the distance through which mass is accelerated and provides an arithmetic link connecting the three factors (CF, frequency, and vibratory mass) most important to a vibratory compactor's performance potential.

UPDATE 1/11/2010: *In January 2010 MBW published the* ***"AMPLITUDE CALCULATOR"*** *on www.mbw.com. This on-line service enables interested parties to develop their own amplitude analysis by entering the published data of vibratory plate manufacturers. The AMPLITUDE CALCULATOR applies the amplitude equation for vibratory plates discussed above.*

AREA OF COMPACTION and **LIFT DEPTH** are misleading, counterproductive specifications. Both specifications are controlled more by conditions of compaction, less by the compactor itself. LIFT DEPTH specifications are especially troublesome. Manufacturers claim their compactors are effective to lift depths that can only be achieved under ideal conditions, conditions infrequently encountered in the field. Plates rated from 18 to 30" lifts may, in fact, be unable to achieve density or stiffness goals on 6 to 12" lifts, given adverse conditions of compaction. Rammers are even more problematic. LIFT DEPTH specifications are based on the compaction of sand at optimum moisture content. Yet rammers are commonly used on inherently more difficult to compact cohesive soils, for which lift depth should be limited to 6 to 9 inches, and compaction attempted only within a narrow soil moisture range.

Tests conducted by MBW and others have illustrated how quickly induced energy dissipates in soil. LIFT DEPTH is controlled by this and other conditions of compaction. Suggesting otherwise is marketing hype.

WEIGHT - Manufacturers typically provide two weight specifications. "Shipping Weight" is useful only for calculating freight cost. "Operating Weight" is useful only in knowing how much weight a crew will have to lift into and out of a transport vehicle, or into and out of a trench. Neither should be mistaken for effective weight of the mass set in motion to perform compaction work. This meaningful information is not provided.

The weight of a vibratory plate's vibratory mass is the total weight of the vibrating components below the shockmounts, and 25% of the suspended mass above and including the shockmounts.

Rammers are more complicated and weight of the percussive mass is of less value for analytical purposes. Rammers are subject to frequent operator manipulation of engine rpm to minimize hand/arm vibration and to improve their ability to control the rammer. Variable operating speed makes it extremely difficult to compute meaningful stroke, thus the reduced value of effective percussive mass, a factor in the computation of stroke. MBW physically measures stroke over the typical operating rpm range of its rammers. We note, however, that even a physical measure of stroke is of questionable value in that stroke is inconsistent blow to blow, will change with the stiffness and type of test medium, and is influenced by how the machine is fixtured or operated for testing purposes.

TRAVEL SPEED. Published travel speeds are not representative of typical jobsite conditions. LEMB #s 1 & 2 allow manufacturers to base travel speed on ideal conditions, i.e., a flat surface, optimum moisture content, sand or gravel that is already partially compacted, all conditions of compaction most conducive to fastest travel. Users should know that travel speed will vary. Loose material will slow travel. Uneven lift surfaces will slow travel. Soil moisture content will affect travel as will soil type and gradation. The operator will influence travel speed. Engine rpm affects travel speed. Fortunately, travel speed expectations are quickly adjusted by simple observation. Of course, any adjustment that diminishes travel speed invalidates published values purporting to establish AREA OF COMPACTION.

What can be done to provide meaningful information?

We start with the above discussion on current light compaction equipment specifications. From there, we progress to the understanding that too much attention is focused on performance specifications, too little attention given to good compaction practice. The reality is that how hard the hardest hitting compactor "hits" is irrelevant when conditions of compaction control whether or not geo-technical objectives can be met**.** Attention should be focused on what is most relevant, compaction protocol and conditions of compaction.

To that end, we divide backfill soils into two broad categories; **essentially granular soil** – soil with not greater than 20% fines content* and **essentially cohesive soil** – any soil with greater than 20% fines content. Note that the "essentially cohesive" category, as it applies to soils with fines in the 21 to 50% range, suffers an obvious shortcoming in descriptive terminology, but for purposes of selecting compactor type and appropriate protocol, has merit.

Having identified the two broad categories of soil, we now apply appropriate lift protocol. Essentially granular soil lifts should not exceed 12" in depth regardless of the size of the compactor to be used. Essentially cohesive lifts should not exceed 9 inches, and special attention must be given to whether or not moisture is in the workable range.

Soil moisture content is less of a problem in connection with essentially granular soils due to their wide and forgiving workable moisture range. Typically, an essentially granular soil can be compacted to specified goal from Standard Proctor Optimum Moisture to 75% dry of that number. When significantly dry of optimum, however, the number of passes required to achieve geo-technical goals may increase significantly.

Essentially cohesive soils are far more problematic in that their workable soil moisture range progressively narrows as the percentage of fines increases. For clays, lean or fat, it has been found that rammers and pole tampers are effective between Standard Proctor Optimum Moisture and 3 percentage points dry of that number. Lean clays, for example, have a Standard Proctor Optimum Moisture of approximately 18%. Their workable range is between 15 and 18%. Moisture contents above or below that range result in a very high probability of subsidence. It should also be noted that Modified Proctor Optimum Moisture, as pertains to clay, is problematic for light compaction equipment. Modified Proctor Optimums are too dry for rammers and pole tampers to consistently produce satisfactory results on clay.

Hand testing for workable moisture range is acceptable in connection with essentially granular soils. Hand testing to ascertain the presence of a workable moisture range for cohesive soils is strongly discouraged due to the narrowness of the range and high probability for error.

MBW recommends that an agricultural soil moisture gauge be used to determine moisture content in cohesive soils. The gauge's probe is inserted into the soil and a digital readout is given for moisture content. Because moisture is measured by volume in agriculture and by weight in construction, the volume readout should be divided by 2** to get a result by weight. The result is not perfect, but is easily obtained, at low cost, and has the potential to decrease errors (in comparison to hand testing) by 75% or more. Compaction of cohesive soils badly out of range should be eliminated.

A final word on good compaction practice: The number of passes made with a plate, rammer or roller over a lift of soil should never be specified. Number of passes is dependent on conditions of compaction; namely soil gradation, moisture content and depth of lift. For example, in an independent third party (UMASS Dartmouth) correlation study on MBW's ***Soil Compaction Supervisor***, it was found that heavy (to 25,000 lbs) vibratory rollers achieved passing nuclear densitometer and sand cone results on 12" lifts of highway grade granular backfill after 2 passes early in the day, 6 to 8 passes at mid-day and up to 14 passes in late afternoon. The variable was decreasing soil moisture content during the course of the day.

Summary – Compactors vary in design. Some produce lower levels of noise and hand/arm vibration. Some are more productive than others. Some experience less maintenance over their useful life. Life expectancy varies. Costs vary from brand to brand, model to model. In other words, manufacturers are not wanting for things to "sell". That in mind, there is no good reason for confusing and misrepresenting compaction equipment in so far as performance specifications are concerned. Indeed, users should know that when good compaction practice is rigorously applied, most of today's compactors are capable of achieving acceptable results, although with variable attention to health and safety issues, productivity, maintenance, life, ease of service, cost, etc.

It might be interesting to see how a more meaningful set of performance specifications would look in reference to a single direction plate.

Performance Specifications MBW GP3000H		
	Current LEMB Specs.	Suggested Specs.
Operating Weight	236 lbs	236 lbs
CF	3550	Not Provided as a stand alone performance spec.
Weight of Effective Vibratory Mass	Not provided	126 lbs
Frequency	4400	4400
Amplitude (refined method)	Not provided	0.075
Lift Depth	18"	Not to exceed 12"
Travel Speed	90'/min	variable up to 90'/min

The above “Current Specifications” (LEMB # 2) provide a single, somewhat limited specification of value - Operating Weight. The remaining specifications are of questionable value lacking additional information, are regularly mistaken for things they do not describe, or promote inflated performance expectations. Suggested Specifications also provide Operating Weight but more importantly **Effective Weight of Vibrating Mass** and **Amplitude**. We choose not to provide CF value knowing CF has been mistaken for “how hard the plate hits” for decades and is useful only as a factor in the calculation of amplitude, which is now provided. Lift depth no longer refers to a maximum that can be achieved under ideal conditions, but to good compaction practice. Travel speed is stated as variable to a maximum under ideal conditions.

We have not provided an answer to the question … “How hard does the compactor hit?” At some point, users have to be educated, told that they are asking the wrong, in fact, an irrelevant question, and informed that there are no shortcuts or substitutes for good soil compaction practice. The bottom line is that while standards exist to provide uniformity in the development and presentation of data, performance specifications of any derivation offer little assurance that geo-technical goals will be met. Good compaction practice and, where called for, soil testing are the only reliable means of achieving consistent, acceptable and improved compaction results.

* 20% is arbitrary. The intent is to provide a cut-off point at which protocol shifts from essentially granular to essentially cohesive soils. For low amplitude, very light weight vibratory compactors, it may be wise to recommend a cut-off point at a lower fines ratio.

** The number “2” provides rough conversion from percentage by volume to weight. For specific soils, a more refined number can be developed from the comparison of dry and wet weights of the material. In any event, our purpose in recommending use of an agricultural moisture gauge is not precise measurement, but improvement in the method of evaluating pre-compaction moisture of cohesive soils. Crew inability to judge whether or not cohesive soils are in a workable moisture range by hand testing is an all too common cause of earthwork failure.