PDA 8G and PDA-S Software

The 8th generation Pile Driving Analyzer®, see Figure 1 below, hence “model 8G” or “8G” (PDA-8G), from Pile Dynamics, is a powerful tool for measuring and determining the effects of impacts on a deep foundation element such as a driven pile.

Figure 1- PDA-8G

The impact is often applied by the pile driving hammer on a driven pile, but the strike may also be imposed by a significant drop weight applied to a bored pile to perform a dynamic load test.

The PDA monitors the acceleration and strain. The sensors, shown in Figure 2, are attached to the pile by bolts and process these signals after each impact during driving or restrike. The means for introducing and detecting the stress waves are based on the piezoelectric effect in certain crystals and ceramics, whereby an electrical field applied to the material causes a mechanical strain or the inverse effect, where a strain produces an electric field.

Detection is accomplished when a mechanical pulse (hammer anvil striking the top of the pile) strikes a piezoelectric crystal and generates an electrical signal.

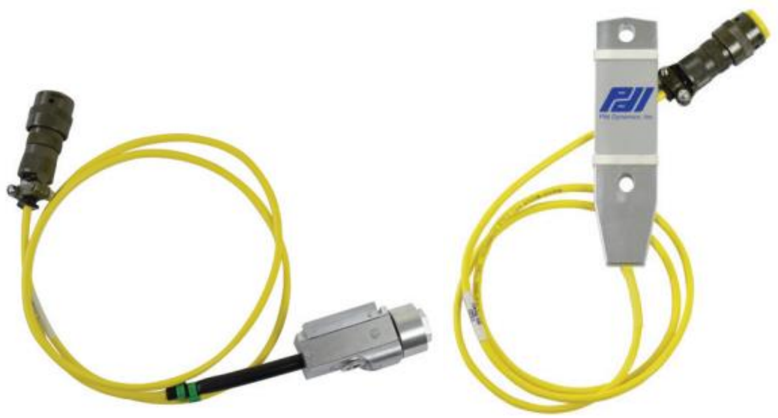

Figure 2 – 8G Accelerometer PR 40” and Strain Transducer 40” respectively, left and right.

The PDA digitises the signals, results are computed (see Figure 3), and the data array of the signals for a blow is stored. The PDA-S program controls the data acquisition for the 8G during the driving, allowing users to create graphs versus depth of penetration as outputs from the integrated PDIPlot2 program (see Figure 4) and reprocessing existing files on an office computer.

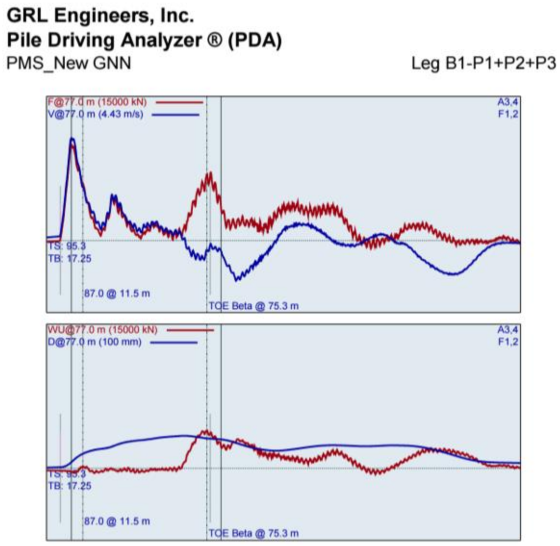

Figure 3 – Signal Digitised blow n2 at 20 m of penetration with IHC S500 hammer

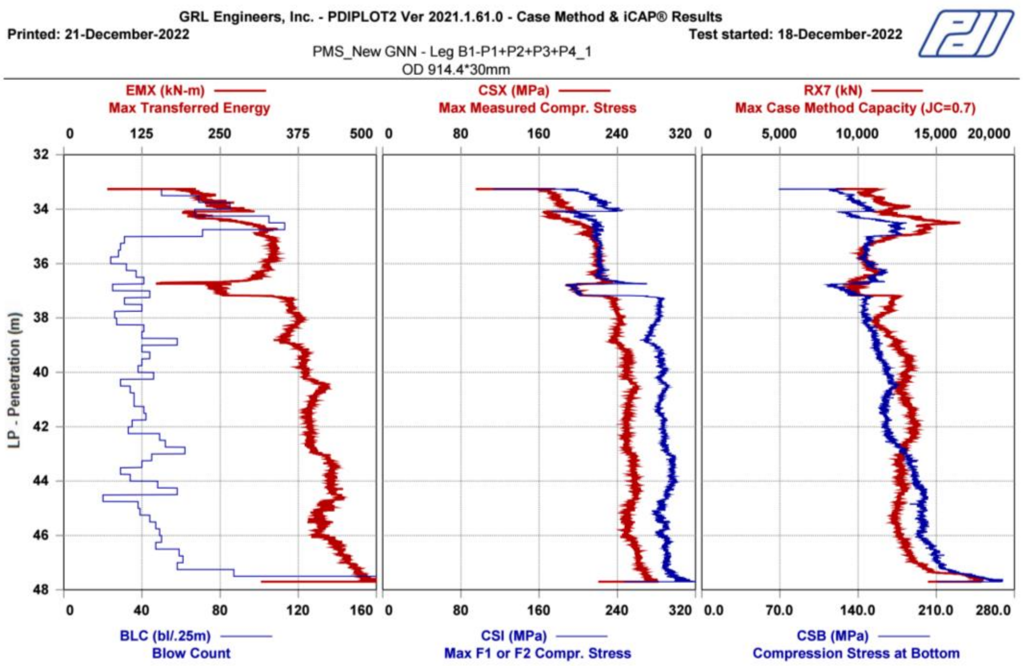

Figure 4 - Graphs showing blow counts, bearing capacity and stresses versus penetration depths.

Wave Mechanics and the Theory behind the PDA software.

PDA calculates specific quantities from pile-top force and velocity measurements using the underlying theory of closed-form solutions and examples developed by various mathematicians in the 19th century. These closed-form solutions have been applied to the Case (Case Western Reserve University) and Pile Dynamics method measurements. The collection of formulas and equations developed to calculate soil resistance, pile stresses, hammer performance parameters, pile integrity factors and other quantities are all part of the Case Method, set during the late 1960s and 1970s.

For clarification, a closed-form solution is one where the resolution of the governing partial differential equation is integrated directly, whether to a system of equations or an infinite series, without resorting to numerical methods.

The one-dimensional wave equation described in equation 1 below is a 2nd order partial differential equation, whose left and right hand are partial derivatives of the acceleration and strain in the rod, respectively.

$$\frac{\partial^2 u}{\partial t^2} = c_0^2 \, \frac{\partial^2 u}{\partial x^2} \qquad \text{(eq. 1)}$$

$u(x, t)$ - The particle displacement at time t and location x.

$c_0 = \sqrt{E}/\rho$ - Wave propagation velocity

E - Young´s Modulus

ρ - Mass density

The general solution, following D´Alembert, propagates along two linear characteristic lines (see equation 2). Thus, longitudinal waves propagate at the velocity c_0 (typical propagation velocities in most metals are 5.1X 10^3 m/s) in a thin rod without distortion.

$$u(x, t) = f(x - c_0 t) + g(x + c_0 t) \qquad \text{(eq. 2)}$$

The displacement pattern in the rod may consist of two components, f and g , being the stress, force, velocity, displacement, or acceleration wave fields of the incident wave and reflected wave, respectively.

The undistorted nature of the wave propagation is essential for two reasons. First, it represents a fundamental characteristic of the one-dimensional wave equation (Figure 5 illustrates this behaviour). Secondly, it will compare against many physical systems where the opposite is accurate, and pulse distortion occurs during propagation. The soil resistance or pile damage is an example of a pulse distortion creation.

The boundaries' conditions will also impact the type of response of pattern g, the reflected wave.

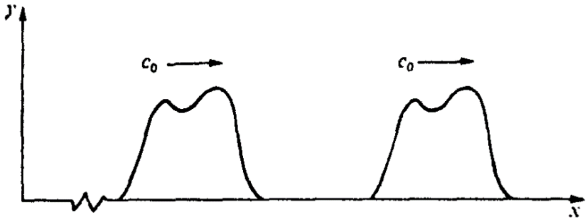

Figure 5 - Undistorted propagation of a pulse $f(x - c_0 t)$.

Pile Capacity Evaluation Considerations

The data may be interpreted for compression stresses induced at the top and bottom, tension stresses along the shaft, energy transferred to the pile or shaft, pile integrity and static pile bearing capacity.

For capacity evaluation by the 8G, CAPWAP® analysis is recommended to check the 8G Case Method result.

Hence, the standard of practice is to use both the Case Method and CAPWAP together, which increases reliability compared to the Case Method alone.

Capacity Gain

During driving, the natural soil strength along the shaft is often reduced temporarily by the installation process, which destroys the soil liaisons. Usually, the capacity increases with wait time, called "set-up", and is associated with increased shaft resistance (soil effective stress increasing). Testing the pile during a restrike will generally result in a higher capacity evaluation and, therefore, a more economical foundation can be achieved.

For cohesive soils, set-up is usually the result of pore pressure changes and thus is linear with log-time and may continue for many log-time cycles.

Along the shaft, short-term restrikes (15 min to 1 hr) with additional restrikes at one day may allow projection of the shaft to increase to later times using this principle of linear increase with log time. Performing a later restrike would be advised to confirm this projection.

For coarse-grained soils, set-up or restoration of the normal earth pressures and the long-term shaft resistance is generally a linear process with time, with a limited time duration (perhaps a week). "Aging" or restoration of chemical cementing is also more likely to increase linearly with time.

Selecting an early high-energy blow is recommended for analysis. The hammer energy must be increased quickly to optimum performance (rather than slowly being started over many blows). Ideally, the hammer will perform optimum by blow operation two (2) or three (3) of the restrike.

Capacity Mobilization

The set per blow must be at least 3 mm to mobilise the complete soil resistance. If the set per blow is less, the test has only mobilised part of the total soil resistance, and the capacity result will be only a lower bound estimate. This may often occur when the pile is driven to a low set (high blow count) at the end of driving, and then due to capacity increase with time (set-up), the set per blow will be even smaller (blow count higher) during restrike.

It may sometimes require a bigger hammer than the one used during installation to overcome this difficulty.

Capacity Calculation - Case Method

The biggest challenge for a PDA-8G user is to predict pile capacity accurately. However, it is rewarding when Dynamic testing can successfully substitute for expensive static pile testing.

All “Case Method” capacities are closed-form solutions that can be computed immediately for every blow in real-time. These solutions require that the pile be linearly elastic and the cross-section uniform along the pile length.

The CAPWAP program can accurately model non-uniform piles and should be used for static capacity determination. Even for uniform piles, the state of practice should require confirming any Case Method result with CAPWAP.

A brief explanation of the fundaments of the Case Method

As explained before, the solution to the wave equation shows that the total particle displacement, and all its derivatives, is the sum of the displacements in the incident and reflected wave.

Incident and reflected waves are now called downward and upward waves for easiness.

Taking the force (equation 3) and velocity (equation 4), displacement derivatives, the total force and velocity at time t and location x is the sum of F_d (force in the downward wave) plus F_u (force in the upward wave) and v_d (velocity in the downward wave) and v_u (velocity in the upward wave) respectively.

$$F = F_d + F_u \qquad \text{(eq. 3)}$$

$$v = v_d + v_u \qquad \text{(eq. 4)}$$

Considering that Z is the pile impedance, the resistance the pile offers to (impedes) the change in velocity.

$$Z = \frac{EA}{c_0} \qquad \text{(eq. 5)}$$

c_0 - Wave propagation velocity

E - Young´s Modulus, A - Pile cross-section

The proportionality condition between compressive force existent in the downward wave that causes downward directed particle velocities (positive in the direction of top to pile bottom) is,

$$F_d = Z v_d \qquad \text{(eq. 6)}$$

The upward travelling waves have a negative particle velocity (upward) for positive (compression) forces and positive (downward) for negative (tension) forces; therefore, proportionality between force and velocity in the upward travelling waves is;

$$F_u = -Z v_u \qquad \text{(eq. 7)}$$

Combining equations 6 and 7 in equation 3, we determine the relation between measured and propagated forces along the pile shaft.

$$F_d = \frac{(F+Zv)}{2} \qquad \text{(eq. 8)}$$

$$F_u = \frac{(F-Zv)}{2} \qquad \text{(eq. 9)}$$

In other words, if we measure the force and velocity at a point of the pile, then the force in the downward travelling wave can be determined from the average force and velocity times impedance. Similarly, the force in the upward travelling wave can be calculated from one-half of the difference between force and velocity times impedance.

Soil Resistance Wave

For soil resistance wave calculation, suppose an impact wave has reached a point along the pile located a distance x below the top where the shaft friction interacts with the pile. The impact wave reaches that point at a time x/c_0 after the impact (see Figure 6 below).

The soil responds to the pile's sudden downward motion, caused by the impact wave, with a sudden upward-directed resistance force R, creating upwards compression and downward tension travelling waves above and below R, respectively, with an equal magnitude of R/2 (see Figure 6). Both waves create an upward-directed particle velocity to not tear the pile apart.

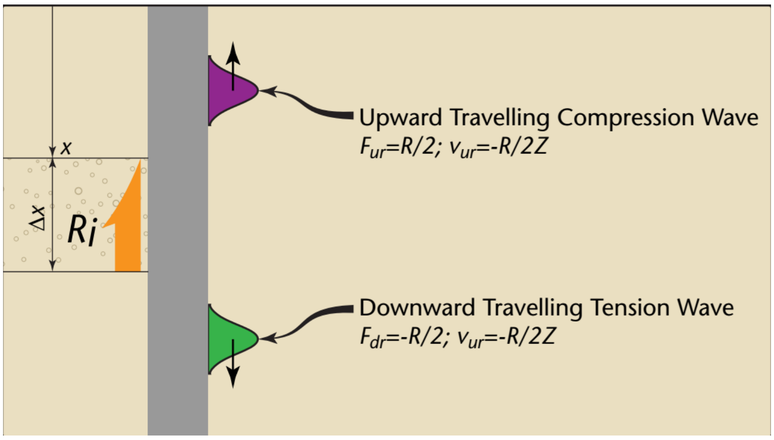

Figure 6: Soil resistance wave response scheme

The end bearing, R_b, is a force applied at the pile toe, generating only a single upward travelling compression wave with upward-directed particle motions. The impact wave only activates the end bearing at time $L/_{c_0}$ and its effect will be felt at the pile top at time $2L/_{c_0}$ after the impact.

Shaft Resistance from Force-Velocity Difference, Wave up

Upon arrival to the top at $2x/_{c_0}$, the upward travelling compressive shaft resistance wave causes a separation of the pile top force and velocity (times impedance Z) curves by an amount of R_i.

Considering the upward compressive resistance wave of magnitude $R_i/2$, having an upward particle velocity equal to $R_i/2Z$ the total difference between the force and proportional velocity $(F - Zv)$ is equal to R_i ($R_i = \frac{R_i}{2} - \left(-\frac{R_i}{2Z}\right)Z$).

We know that the wave up is equal to $F_u = \frac{(F-Zv)}{2}$ and so according to Figure 7, the shaft resistance Ri, acting on the pile between points A and B, is equal to twice the quantity of Wave-up force at time t_B minus the Wave-up force at time t_A.

$R_{i(B-A)} = 2(F_{uB} - F_{uA})$ (eq. 9)

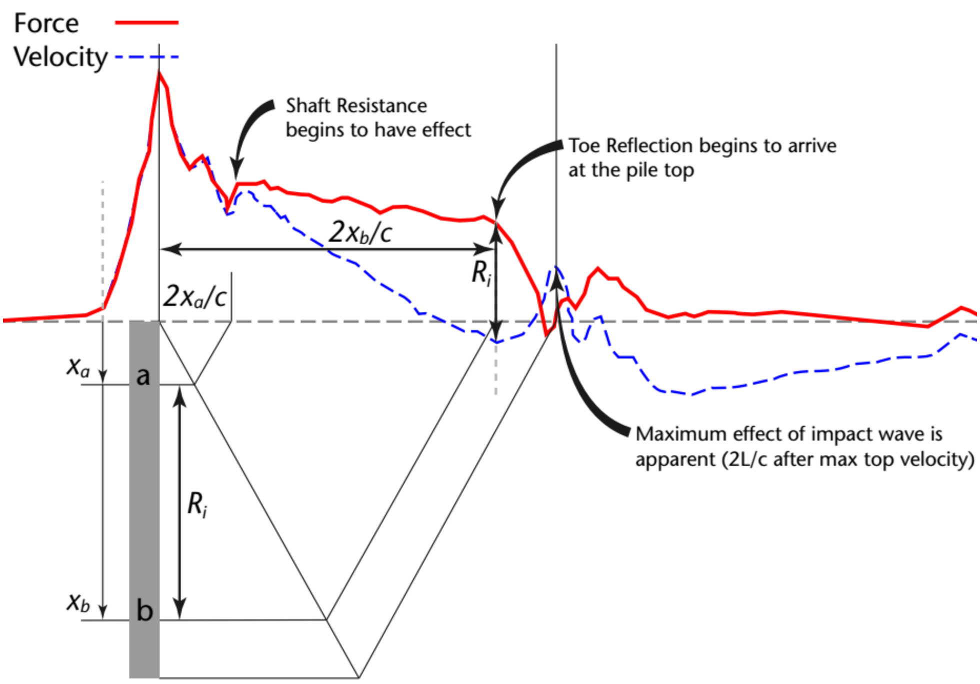

Figure 7 - Shaft Resistance Ri from force and Velocity times Impedance

Calculating the Total Soil Resistance, Shaft and Toe from Wave-up and Wave-down

We can now use the information in the propagating waves up and down to determine the total resistance shaft and toe.

Let us designate as time t_1 the time when the impact wave passes by the sensor location, and as time $t_2 = t_1 + {}^{2L}/_{c_0}$ when the toe reflected impact wave returns to the sensor location.

Thus, the combination of all upward travelling waves at time t_2 contains the shaft resistance and the bottom reflected (negative) impact wave, F_{d1}, added to the end bearing R_b that makes up for the whole resistance, R_{Total} (see equation 10 to 12 and Figure 8).

$$F_{u2} = -F_{d1} + \frac{R_i}{2} + \frac{R_i}{2} + R_b \qquad \text{(eq. 10)}$$

If R_{Total} is the total shaft friction and end bearing (See equation 11)

$$R_{Total} = \frac{R_i}{2} + \frac{R_i}{2} + R_b = R_i + R_b \qquad \text{(eq. 11)}$$

Then

$$R_{Total} = F_{d1} + F_{u2} \qquad \text{(eq. 12)}$$

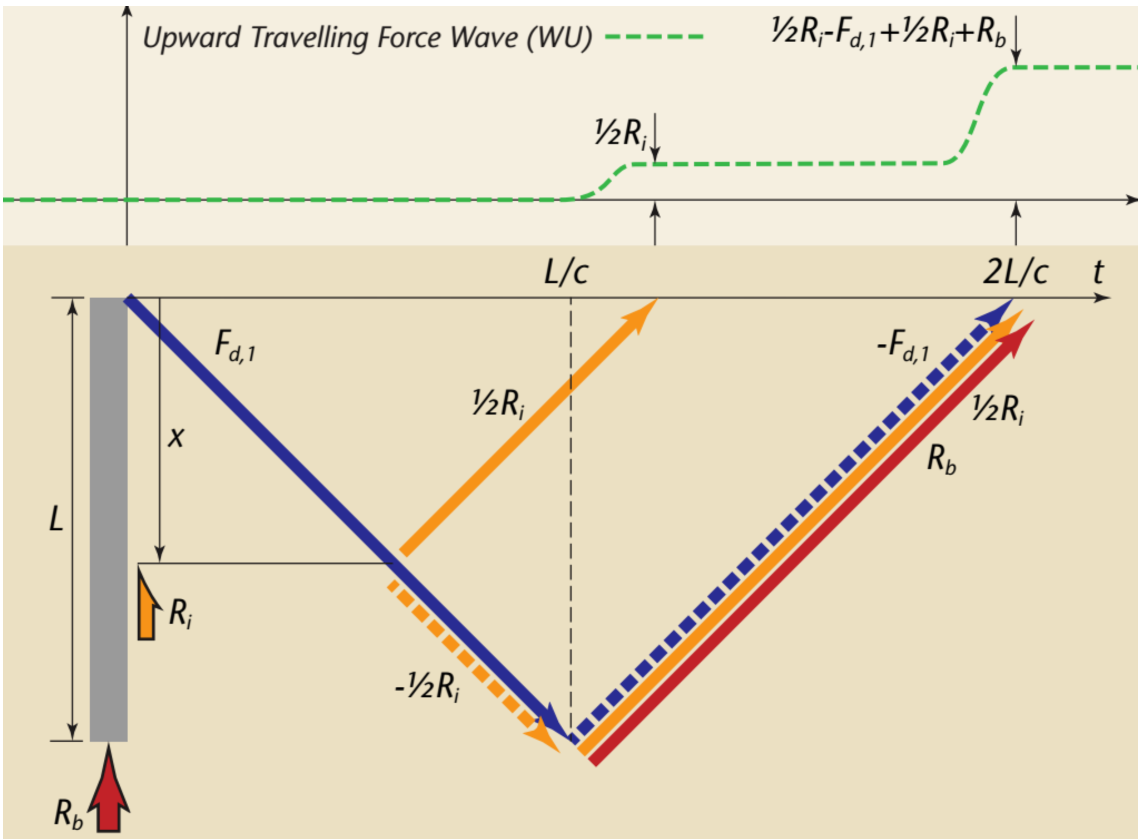

Figure 8 – Scheme of the sum of upward travelling waves at time 2L/C

Substituting equations 8 and 9 in equation 12, R_{Total} can also be expressed in terms of measured forces and velocities at time t_1 and t_2 (at the transducers, strain, and acceleration, point of measurement in a pile).

$R_{Total} = \frac{(F_{t1} + F_{t2})}{2} + \frac{Z(v_{t1} + v_{t2})}{2}$ (eq. 13)

R_{Total} is the total resistance encountered during a complete passage of the wave between time t_1 and t_2, corresponding to the period of $2L/c_0$.

Calculating the Total Static Soil Resistance

The total soil resistance and the ultimate static capacity of the pile are different identities and have different values.

Among various considerations, soil damping is the most critical input to find the ultimate, or better, mobilised static resistance.

Damping is associated with the pile velocity, and a simplification can be made that the significant soil damping occurs at the pile tip. We can calculate the pile base velocity using the following considerations:

We suppose some force F_{d1} to be acting on the end of the pile, such as that due to the resistance of some load R_b (toe resistance), plus the tensile shaft friction R_i against which the pile is moving.

The situation is shown in Figure 8, where the incident wave is F_{d1} and the reflected waves friction R_i and $-F_{d1}$ are F_{u2}. R_b indicates some hypothetical load which is the balance of forces $R_b = (F_{d1} - F_{u2})$.

Thus, the velocity of the pile end is v_b.

$v_b = \frac{F_{d1} - F_{u2}}{Z}$ (eq. 14)

$R_{Dynamic}$, and calculated from a simple linear damping model like equation 15.

$R_{Dynamic} = J_v v_b$ (eq. 15)

The viscous damping factor, J_v, has units of N/m/s.

For simplification, let´s use a non-dimensionalise damping factor J_c, dividing J_v by the pile impedance Z, which has the same unit.

$R_{Dynamic} = J_c\ (F_{d1} - F_{u2})$ (eq. 16)

If the total resistance is the sum of the static and dynamic resistance, the static resistance is the difference between total and dynamic resistances, equation 17.

$R_{Static} = R_{Total} - R_{Dynamic}$ (eq. 17)

R_{Static} can be expected to be the ultimate static resistance, R_u , if the pile has been penetrating the soil permanently under the hammer blow.

Thus R_{Static} can be expressed as per equation 18.

$$R_{Static} = (F_{d1} + F_{u2}) - J_c\,(F_{d1} - F_{u2}) \qquad \text{(eq. 18)}$$

The damping constant primarily relates to the soil grain size near the pile tip or the major bearing layer and can be retro calculated from equation 18.

If measurements of the strain and velocity have been taken on the pile F_{d1} and F_{u2} are known.

If the ultimate static capacity, R_{Static} is know by a Static load test conducted till failure or from CAPWAP, J_c is known as well.