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.

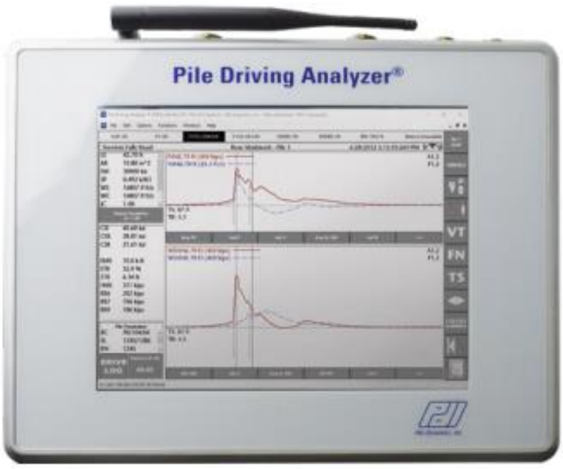


Figure 1- PDA-8G

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.

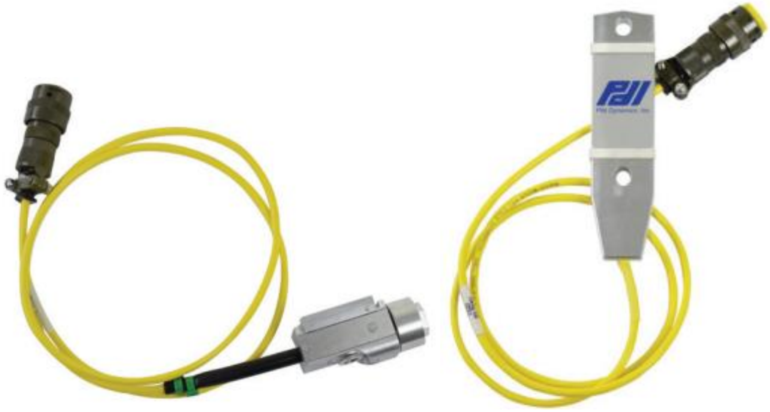


Figure 2 – 8G Accelerometer PR 40" and Strain Transducer 40" respectively, left and right.

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.

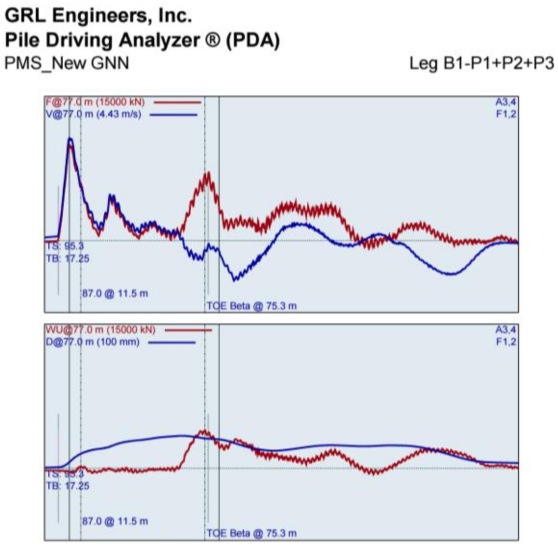


Figure 3 – Signal Digitised blow n2 at 20 m of penetration with IHC S500 hammer

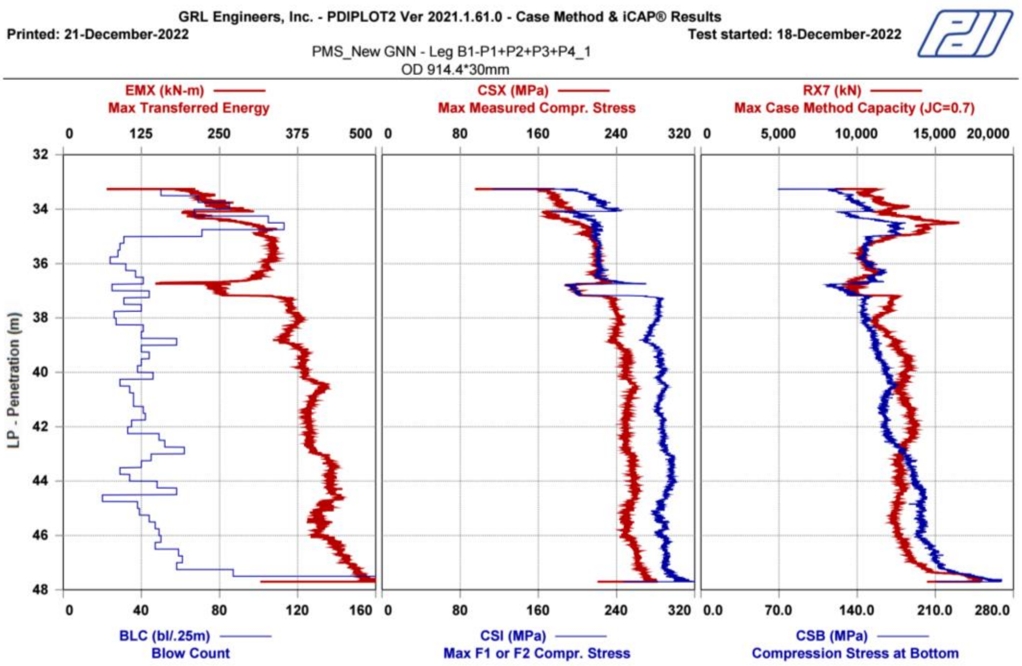


Figure 4 - Graphs showing blow counts, bearing capacity and stresses versus penetration depths.

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.

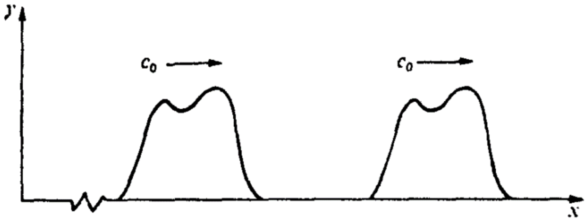


Figure 5 - Undistorted propagation of a pulse $f(x—c_0t)$.

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.

<u>For cohesive soils</u>, 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.

<u>For coarse-grained soils</u>, 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.

$F = F_d + F_u$ (eq. 3)

$v = v_d + v_u$ (eq. 4)

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

$Z = \frac{EA}{c_0}$ (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,

$F_d = Zv_d$ (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

$F_u = -Zv_u$ (eq. 7)

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

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

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

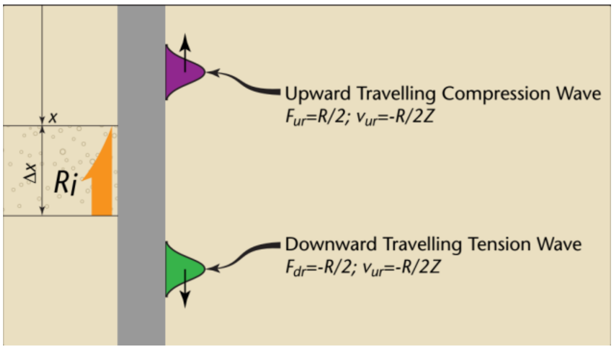
In other words, if we measure the force and velocity at a point of the pile, then the force in the downward travelling wave can be determined from the average force and velocity times impedance. Similarly, the force in the upward travelling wave can be calculated from one-half of the difference between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

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 and downwards travelling waves above and below R.

The two (2) waves generated by the soil resistance add/superpose force and velocity effects to the previous impact wave, and their resistance has an equal magnitude of R/2.

To satisfy equilibrium and continuity, the upward wave is in compression and the downward in tension, creating both an upward-directed particle velocity, satisfying the continuity condition at the force application point located at distance x, for not tearing the pile apart.



The forces in the resistance waves together balance R, as the compressive wave pushes downward above the resistance force application and the tensile waves pull downward underneath the force application.

According to Figure 6, 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)

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.

The end bearing R_b makes up for the total resistance R_{Total} .

Thus, the combination of all upward travelling waves contains the resistance and the bottom reflected (negative) impact wave of time.

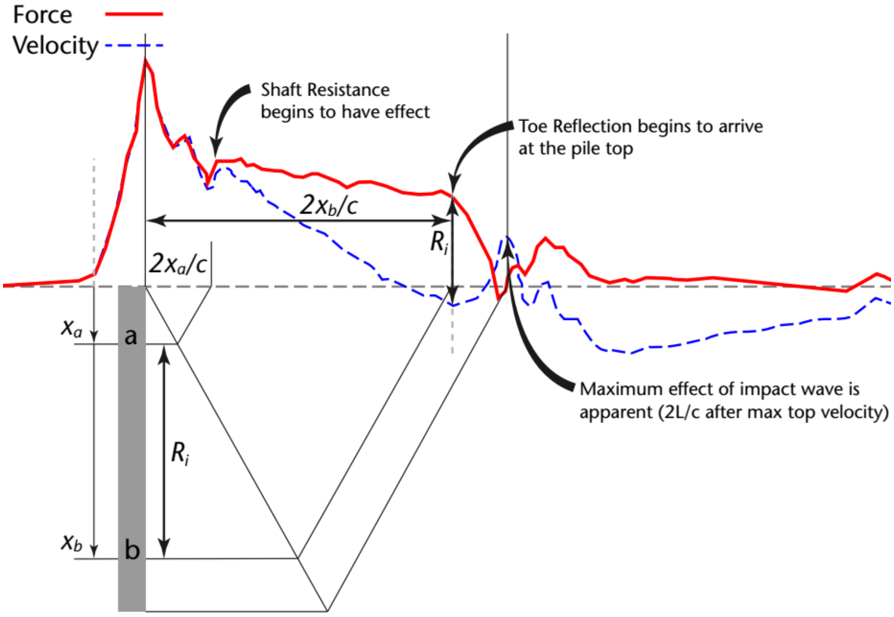


Figure 6 - Shaft Resistance Ri from force and Velocity times Impedance