STRESSWAVE '96

FIFTH INTERNATIONAL CONFERENCE ON THE APPLICATION OF STRESS-WAVE THEORY TO PILES

SEPTEMBER 11 - 13, 1996
ORLANDO, FLORIDA

Edited By:
F.C. Townsend
Mohamad Hussein
M. C. McVay

Assisted By:
Paulo Pinto
Pedro Ruesta

LOW STRAIN TESTING OF PILES UTILIZING TWO ACCELERATION SIGNALS

Mark Johnson[1], Frank Rausche[2]

Abstract

Low strain testing, also known as the Sonic or Pulse Echo method, is commonly used to asses the integrity of driven piles or drilled shafts. An accelerometer is placed on the free pile top which measures the motion caused by impacts from a hand held hammer. The acceleration signal is then integrated into velocity and qualitatively assessed for reflections from non-uniformities and the pile toe. Because of its simplistic nature, this testing method is easily adapted to piles under existing structures where the pile top is incorporated in the superstructure and the pile length is unknown.

However, two complications need to be addressed for proper evaluation of the velocity records: First, the concrete stress wave speed is often unknown. It is an important variable which directly affects pile length determination. Secondly, for piles tested below their head (when they are tied to a structure) or piles with non-uniformities, stress waves not only travel downward but also upward where they are reflected by the structure or pile top. These secondary reflections have to be identified so as not to be confused with reflections from pile impedance changes and the pile toe. For this reason, two acceleration signals are taken simultaneously along the pile shaft providing accurate means of determining the stress wave speed as well as the necessary information for tracking secondary reflections. Preliminary analysis procedures along with results from theoretical model pile tests are presented. The analysis has been prepared such that the engineer can make interpretations as for a single acceleration record taken on a pile with a free top.

[1] Project Engineer, Goble Rausche Likins and Associates, Inc., Orlando, FL, USA
[2] President, Goble Rausche Likins and Associates, Inc., Cleveland, Ohio, USA

ıtroduction

The non-destructive low strain (pulse-echo) method of testing cast-in-place piles, timber piles, and prestressed concrete piles for integrity is common practice in many countries (for example, de Vos *et al.*, 1992). Attaching a gage to the pile top and hitting it with a hand held hammer makes the test quick and simplistic. Modern testing equipment provides the engineer with immediate results and the ability to enhance and evaluate the data. For a uniform pile, the predominant reflection should come from the pile toe. Therefore, the method naturally lends itself to testing piling whose length is unknown. Moreover, these piles are usually in service making it difficult to apply hammer impacts to a free pile top. By taking two acceleration measurements along the pile shaft a known distance apart, the material stress wave speed can be determined for pile length evaluation. In addition, the two signals can be manipulated to determine the downward and upward traveling components of the velocity signal for identifying secondary inputs and reflections. This technique could also be applied to cast-in-place piles with non-uniformities.

Background

Typically, a low strain test is performed by placing an accelerometer on the pile top and hitting the top with a hand held hammer. The hammer impact induces a one dimensional stress wave into the pile that travels at a speed c (where c is a function of material elastic modulus, E, and mass density, ρ, and $c^2=E/\rho$). The acceleration record is then integrated into velocity, viewed in the time domain, and qualitatively assessed. Changes in the velocity record are attributed to soil resistance forces and pile impedance changes. Pile impedance, Z, is defined as the dynamic elastic modulus, E, times the cross sectional area, A, divided by the material stress wave speed (*i.e.*, $Z=EA/c$). Impedance changes are related to changes in cross sectional area or concrete quality. An increase in pile impedance and/or soil resistance force results in a decrease in the measured pile top velocity. Conversely a decrease in pile impedance results in an increase in the measurec velocity. Rausche *et al.* (1994) further describe the testing procedure typical results, and attempt to categorize the velocity traces. However interpretation of the velocity records does not take into account secondar; reflections.

When the stress wave encounters changes in impedance along the shaf (from $Z1$ to $Z2$), part of the stress wave is reflected. Rausche and Goble (1979) have shown that the magnitude of the reflected wave is a function of the change in impedance and the magnitude of the input wave as follows:

$$Fd = Fi * \frac{(2 * Z2)}{(Z1 + Z2)} \quad \textbf{(1)}$$

$$Fu = Fi * \frac{(Z2 - Z1)}{(Z2 + Z1)} \quad \textbf{(2)}$$

Where *Fi* is the input wave, *Fu* is the reflected wave, and *Fd* is the transmitted wave. For a uniform pile, *Z1* and *Z2* are equal and the input wave travels unchanged. At the pile toe (or a free pile top) , *Z2* becomes zero and the wave is completely reflected with the opposite sign as *Fi*.

Two Point Measurement Theory

From the one dimensional wave equation, a particular solution for the displacement of a linearly elastic, uniform rod for point *x* at time *t* takes on the general form:

$$u(x,t) = f(x-ct) + g(x+ct) \quad \textbf{(3)}$$

Where *f(x-ct)* may be considered the downward traveling displacement wave and *g(x+ct)* is the corresponding upward traveling wave. Also, since the total stress at a point, σ, and the axial particle velocity, *V*, can be solved for by using superposition, the following equations are true:

$$\sigma(x,t) = \sigma{\downarrow}(x,t) + \sigma{\uparrow}(x,t) \quad \textbf{(4)}$$

$$V(x,t) = V{\downarrow}(x,t) + V{\uparrow}(x,t) \quad \textbf{(5)}$$

where the arrows indicate the wave travel direction.

Lundberg and Henchoz (1977) have shown that the downward and upward traveling stress wave at gage location 1, Lg_1, can be determined by taking strain measurements at two locations along the pile shaft (*i.e.*, Lg_1 and Lg_2). However, modern integrity systems measure acceleration (which is then integrated to velocity). Therefore, differentiating Equation 3 with respect to

x and t shows that the stress and velocity in the waves are related by the following two equations (considering compression stress and downward velocity positive):

$$\sigma\downarrow = \rho c V\downarrow \quad , \quad \sigma\uparrow = -\rho c V\uparrow \qquad \textbf{(6),(7)}$$

where ρ is the material mass density and c is the material stress wave speed. The stress wave speed, c, can be easily computed from the distance between the gages and the time it takes the impact pulse to travel from Gage 1 to Gage 2. It follows that since the stress and particle velocity are related by the constant, ρc, then the Lundberg and Henchoz approach for the downward traveling stress wave holds true for the downward traveling velocity wave:

$$V\downarrow(Lg_1,t) = V(Lg_1,t) - V(Lg_2,t-T) + V\downarrow(Lg_1,t-2T) \qquad \textbf{(8)}$$

Where

- $V(Lg_x,t)$ - Measured velocity at gage x at time t
- $V\downarrow(Lg_x,t)$ - Calculated downward velocity for gage x at time t
- T - Time period necessary for the stress wave to travel from Lg_1 to Lg_2 (*i.e.*, $T = [Lg_2 - Lg_1] / c$)

Computing the upward traveling velocity, $V\uparrow$, can easily be made by solving Equation 5 for $V\uparrow$ and substituting the computed $V\downarrow$ per Equation 8:

$$V\uparrow(Lg_1,t) = V(Lg_1,t) - V\downarrow(Lg_1,t) \qquad \textbf{(9)}$$

Thus, by taking acceleration measurements at two locations on the pile shaft it is possible to extract the downward and upward velocity components at the first gage location. These records can then be qualitatively assessed for pile impedance changes and the pile toe.

Model Pile Tests

Secondary Input Pulses

By using a continuous pile model the behavior of a "model pile" was simulated. The theoretical model pile tests were based on a 33.5 m pile with Gage 1 (LG1) and Gage 2 (LG2) located 3.0 m and 4.6 m below the pile top. The material stress wave speed was 4,020 m/s. On the following graphs, "Vel 1" and "Vel 2" show velocity traces calculated from measured acceleration records for the respective gages. "Vel↓" is the calculated downward velocity wave at LG1 and "Vel↑" is the calculated upward velocity wave at LG1 according to Equations 8 and 9, respectively.

Figure 1 shows velocity traces from the theoretical pile with a simple half sine compression input pulse. The input pulse applied at the pile top passes the gages, travels down the pile, is reflected at the pile toe, and then travels back up the pile to the gages location. Therefore, each gage "sees" the pile toe response after the wave has traveled twice the pile length below that gage (L_{bg}) which occurs at a time $2L_{bg}/c$ after the downward input pulse. (This is graphically illustrated in Figures 1 and 2 by the dotted or "ghost" pile above the velocity records.) It can be seen that the input pulse passes LG2 at 0.38 ms (graphically seen at 0.76 m) after it passes LG1. Likewise, the same time difference occurs as the reflected wave travels from LG2 to LG1. A secondary input pulse is then seen in Vel 1 and Vel 2 as the initial reflected wave travels to the pile top (3.0 m above LG1), is reflected, and travels down the pile again. By subjecting these two velocity traces to Equations 8 and 9, the downward and upward velocity components at LG1 were computed and graphed. Vel↓ shows the input pulse as it passes LG1 initially and after the pile top reflection; whereas Vel↑ only shows a single response from the toe reflection.

Figure 2 is similar to Figure 1 but also contains a secondary input pulse prior to the pile toe. In Figure 2, a compression-tension input pulse closely follows the half sine input pulse. In this figure, the Vel↓ and Vel↑ curves clearly show that changes in the velocity record between the initial input pulse and the pile toe are due to a secondary input, not to pile non-uniformities. This is seen by the secondary input visible in the Vel↓ curve, but nothing is present in the Vel↑ curve until the pile toe reflection.

Pile Non-Uniformities

For Figures 3, 4, and 5 a single input pulse was applied to a non-uniform model pile. In Figure 3, a 60% decrease in pile impedance occurs at 10.7 m below LG1 (also represented graphically in the pile schematic above the graphs). Because this impedance decrease occurs within the upper half of the pile, a secondary response from the impedance decrease is also seen beginning at 24.4 m below LG1 (taking into account the 3.0 m of pile that is above LG1). A clear pile toe reflection is seen in the Vel 1 and Vel↑ traces at 30.5 m below LG1. In Figure 4, a 60% impedance increase occurs at 9.1 m below LG1. Similarly, a secondary response is seen at 21.3 m and a pile toe response at 30.5 m. In Figure 5, a 60% impedance increase and decrease occur at 9.1 and 24.4 m below LG1, respectively. The secondary reflection from the upper impedance increase begins to mask the first reflection from the lower impedance decrease.

In all three of these figures, interpretation of the velocity records is greatly simplified by examining the Vel↓ and Vel↑ curves together. Reflections fror pile impedance changes are first seen in the Vel↑ curve (which also indicat that they are reflections and not an additional input). After the response i reflected at the pile top, it is again seen in the Vel↓ curve with the same sigr

Conclusion

By taking two point acceleration measurements, one is able to extract the material stress wave speed and the downward and upward components of the velocity records. By examining these components, secondary inputs can be identified as well as secondary reflections from pile non-uniformities. This paper clearly shows the usefulness of the technique and presents a foundation for additional research and study. Modification to existing hardware is currently underway that will enable accurate two acceleration measurements to be quickly and easily performed in the field. With this equipment, it is anticipated that specific analysis software will shortly follow.

References

Lundberg, B. And Henchoz, A., 1977. Analysis of elastic waves from two-point strain measurements. *Journal of Experimental Mechanics,* Vol. 17, No. 6: 213-218.

Rausche, F. and Goble, G., 1979. Determination of pile damage by top measurements. *Behavior of Deep Foundations* (Raymond Lundgren, ed.), Special Technical publication 670, ASTM, Philadelphia, Pa.:500-506.

Rausche, F., Likins, G., and Hussein, M., 1994. Formalized procedure for quality assessment of cast-in-place shafts using sonic pulse echo methods. *Transportation Research Record No. 1447*, National Academy Press, Washington, D.C.:30-38.

de Vos, J., Vester, A., and Liefting, H., 1992. Pile integrity testing in The Netherlands. *Proc., Forth International Conference on the Application of Stress-Wave Theory To Piles*, The Hague, Netherlands:357-361.

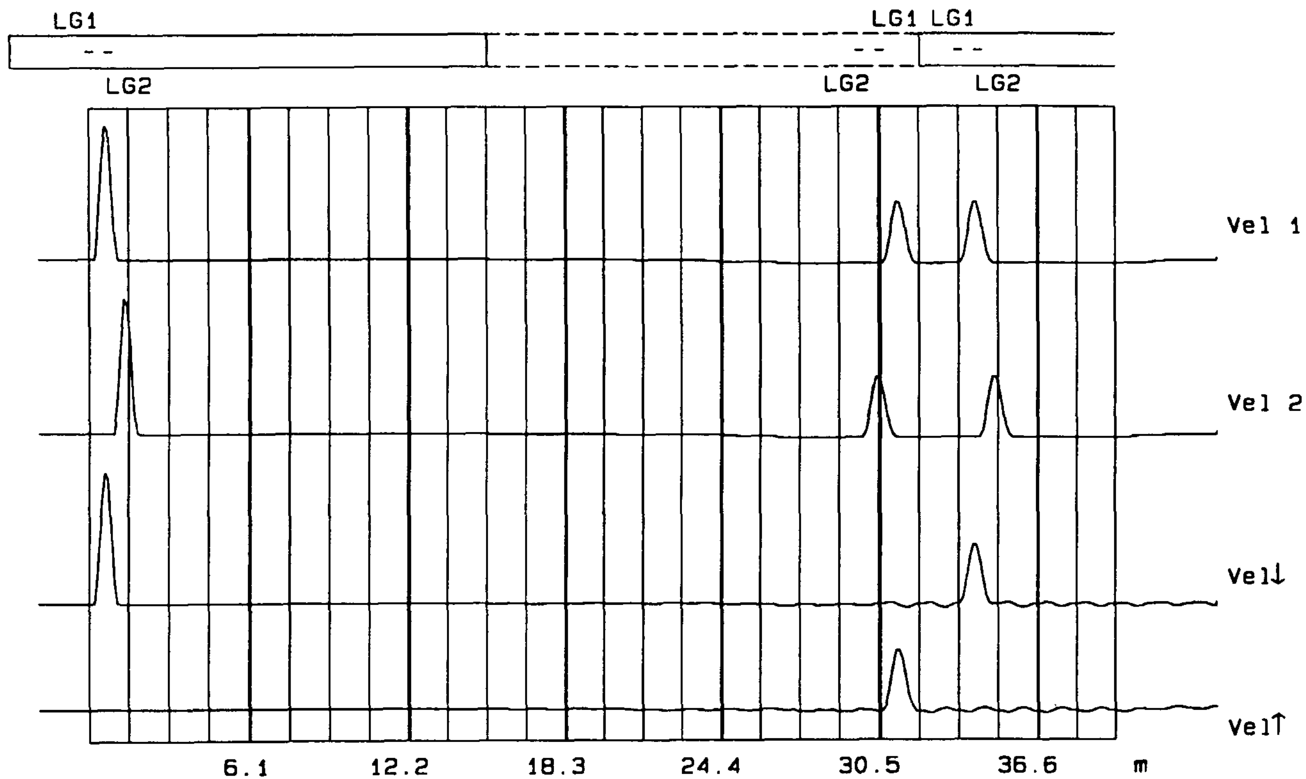

Figure 1: Simple Half Sine Input Pulse On Uniform Theoretical Pile

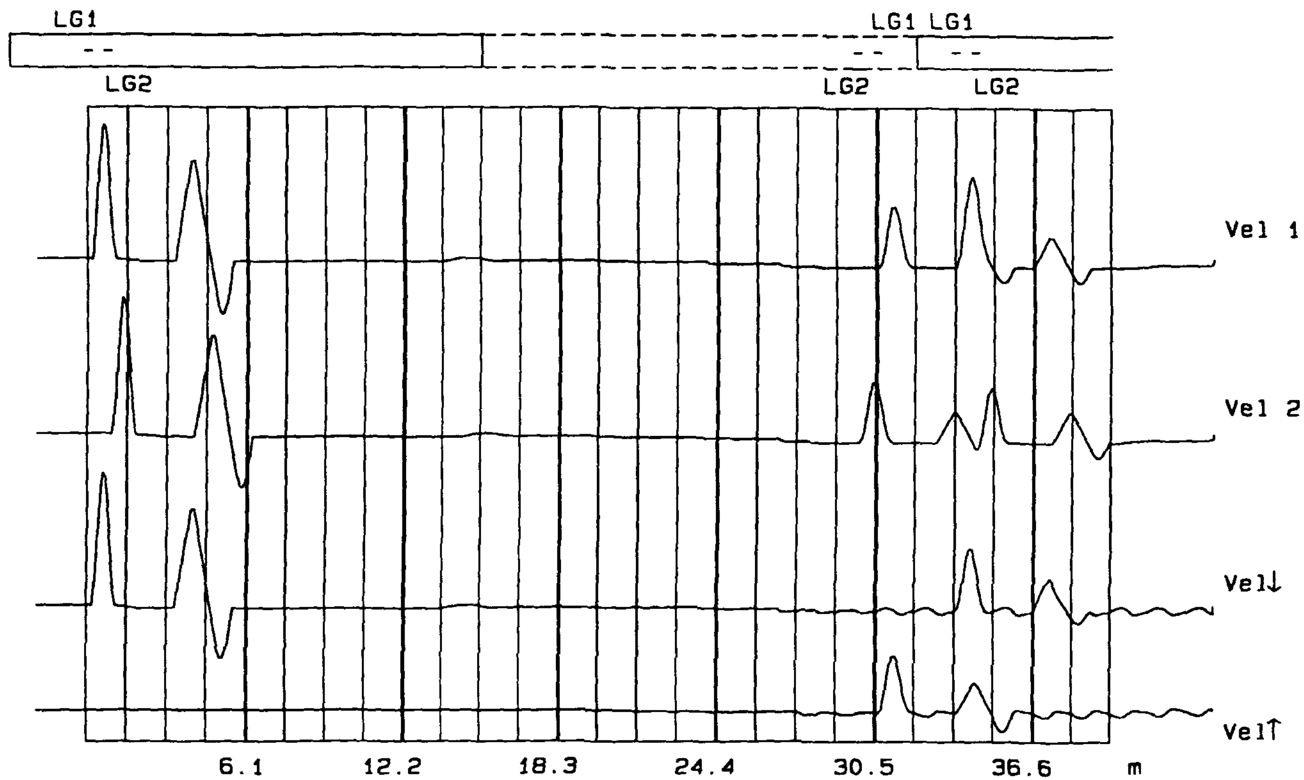

Figure 2: Half Sine and Compression-Tension Input Pulses

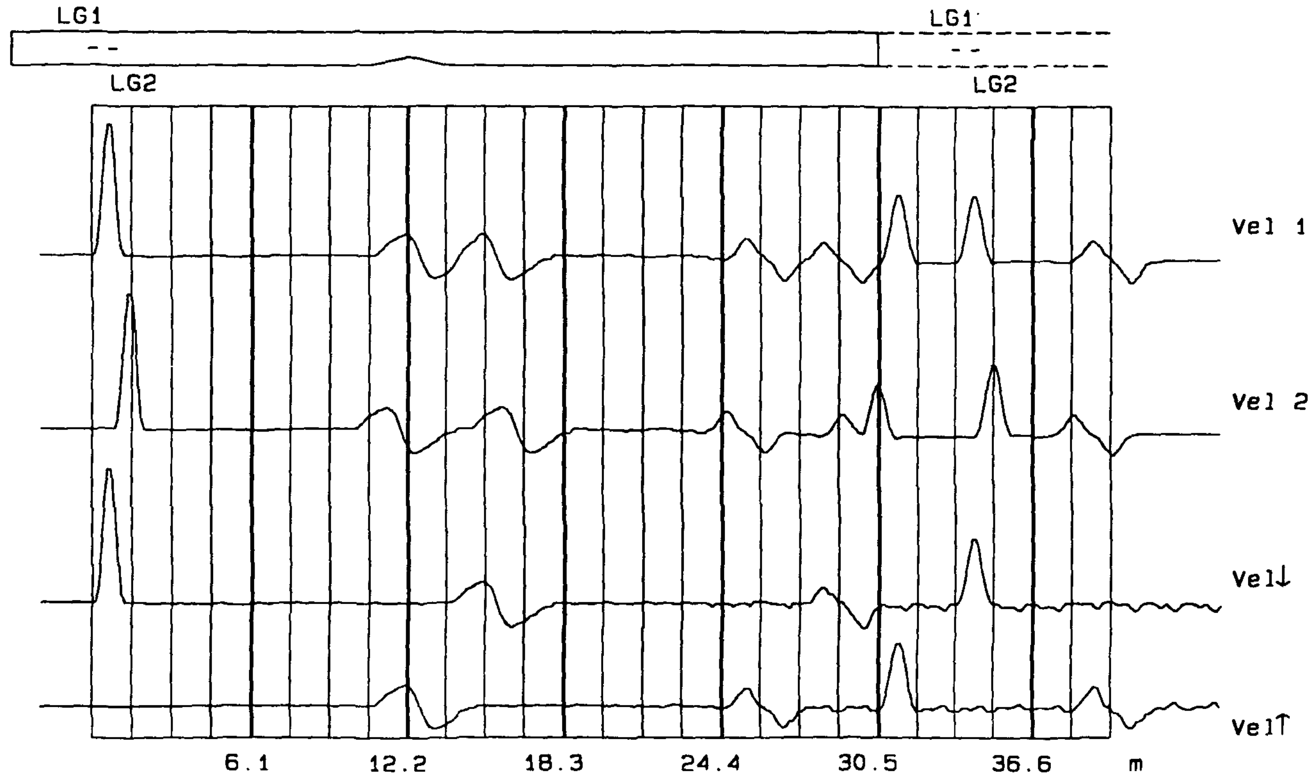

Figure 3: 60% Impedance Decrease At 10.7 m (35 ft) Below LG1

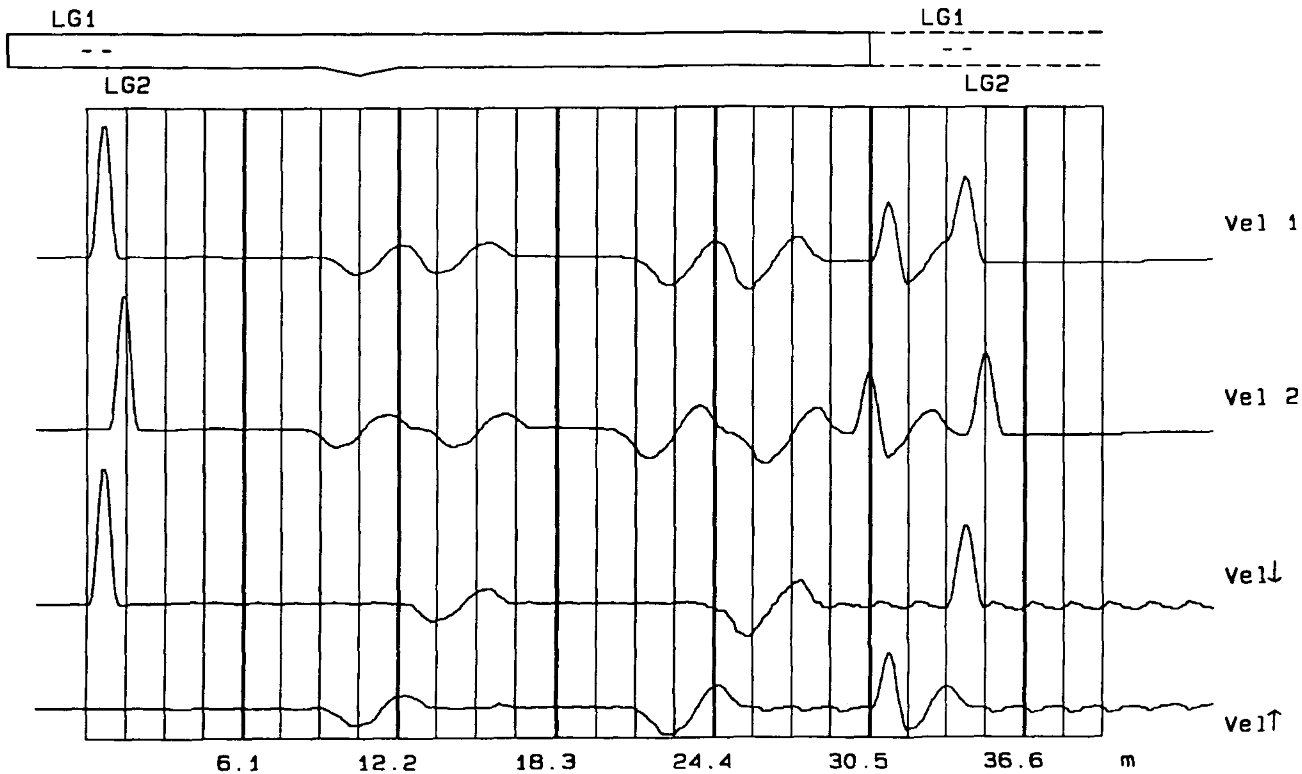

Figure 4: 60% Impedance Increase At 9.1 m (30 ft) Below LG2

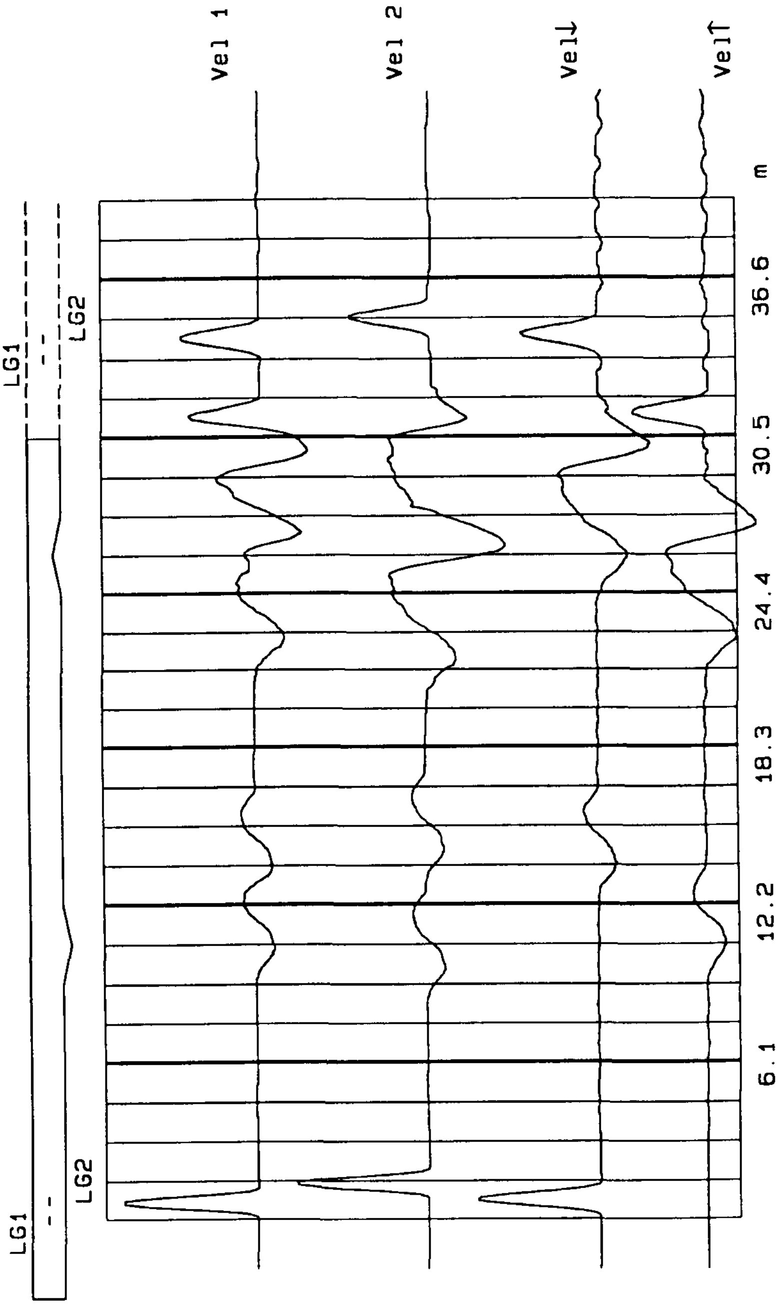

Figure 5: 60% Impedance Increase at 9.1 m (30 ft) and 60% Impedance Decrease at 24.4 m (80 ft) Below LG1