GAMMA DENSITY LOGGING OF DRILLED SHAFTS – SOME OBSERVATIONS AND INTERPRETATIONS

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ABSTRACT

Integrity testing for concrete placement of many drilled shaft piers has been performed using gamma density measurements. Modern downhole wireline geophysical tools with power winches and portable microcomputer-based control, data collection and presentation provide profound improvements over earlier instruments that had to be positioned, read and recorded at discrete depths. Deployed in PVC or other plastic or metal access tubes cast into the shafts, these modern tools typically provide density measurements at depth intervals of 0.1 feet while moving up-hole at rates of 10 feet per minute. Results of the density measurements can be examined as they are acquired during logging, and hard copy can be produced once a PC-compatible printer is available. Access tubes that have become debonded from adjacent concrete are still effective so that integrity testing can be performed long after concrete placement, if necessary. Access tubes can be air or water filled. Density measurement baselines vary slightly if both air- and water-filled tubes or portions of tubes are present. On occasion, the overall density baseline has been observed to gradually change with depth; interpretation criteria based on statistical variation may need to take such gradual changes into account. Examples of documented flaws in drilled shafts and corresponding gamma density measurements are presented.

INTRODUCTION

Since at least the 1970's, non-destructive integrity testing (NDT) of drilled shafts, also called bored piles or drilled caissons, has been conducted using access tubes (typically four to six, depending upon shaft diameter) cast into the shafts. These plastic (typically PVC) or metal access tubes are normally attached to the reinforcing bar cage. Two primary NDT measurement methods are in use today, crosshole sonic logging (CSL) and gamma density logging (GDL). As geophysical techniques, each test method has inherent strengths and limitations. Using both methods together provides complimentary, effective, state-of-the-practice quality control of drilled shaft construction. CSL measures the modulus of shaft material through sonic energy. GDL measures the density of shaft material through its' electron density. CSL can investigate shaft integrity between fluid-filled access tubes, but can be effectively 'blinded' if the access tube becomes debonded from the concrete. GDL can investigate shaft integrity close to the access tubes, and can be used in air- or water-filled access tubes that can be bonded or debonded to the concrete. As Hertlein (2001) has observed, "One way to overcome the limitations of any test method is to combine the test data with data from another method that measures a different, but related, property."

THEORY, HISTORY AND EFFECTIVENESS

Gamma density logging uses the concept of gamma ray backscattering to measure the electron density of the materials in the vicinity of the instrument probe (Schlumberger, 1972). A radioactive source at the bottom of the probe emits gamma rays into the (hopefully shaft) materials surrounding the access tube. These gamma rays collide with electrons in the surrounding materials, lose some of their energy and change direction in a manner called Compton scattering. Some of those particles are scattered into a detector located in the probe. The number of these interactions is directly related to the number of electrons in the surrounding materials. Thus, the electron density of the surrounding materials is measured. Of course, the electron density of the access tube material and the air or water in the tube, as well as the surrounding concrete, steel rebar, and contaminants such as soil, slurry or formation water, all contribute to the measured density. Spacing between the radioactive source and the detector influences the volume of material investigated, and is typically about 25 to 30 cm to obtain a radial depth of investigation of about 10 cm. A shield separates the radioactive source from the detector in the probe. Probe response to the surrounding materials is greatest close to the probe and falls rapidly with increasing distance. Thus, the most reliably sampled materials are located close to the access tube. Too great a depth of investigation could result in measurements influenced by lower density soils surrounding the drilled shaft.

Origin of Gamma Density Method

The successful use of nuclear density methods (gamma ray scattering) for integrity testing of bored piles was reported in the literature (Preiss and Caisermans, 1975) in the 1970's. Reported experience with over 2,000 piles or diaphram wall elements at that time, mostly in Israel (Preiss, Weber and Caiserman, 1978) included several observations that may still be relevant today. Using a reading depth interval of 100 mm, no defects were observed in about 84 percent of the piles or elements tested. Defects were detected at only one access tube in 10 percent of the piles or elements; that condition may not have been structurally significant. Defects were detected at two or more access tubes at the same depth in 6 percent of the piles or elements. Such a condition required further action and possible repair. Coring was also performed at some of the piles. Coring missed about half of the flaws detected by GDL, and no flaws were detected by coring that were missed by GDL.

'Early' Application of Gamma Density Method

One author (Rucker, 1990) has been interpreting results from GDL beginning in the late 1980's, using equipment with essential features little changed from the 1970's. Instruments were small enough to be handled by one person and could be carried to locations not immediately accessible by vehicle. Typical instruments were combination density and moisture content measuring devices with both gamma and neutron sources. While effective quality control work was performed with these instruments, they had frustrating limitations. Reading locations were set manually by the operator using marks on the probe cable for each reading. Depending upon the criticality of the structure or project specifications, readings were typically taken at 6-inch to 2-foot intervals. Each reading typically took 16 to 64 seconds to obtain statistically reasonable results. Readings were recorded manually. Final interpretations included entering these readings into spreadsheet programs for graphical plotting and statistical analysis. Typical probes were 1.9-inches in diameter, and depths of investigation were small. Maintaining consistent access tube effects on readings necessitated using 2-inch pipe for tubes. Different probe positions in the access tube (center or side) would then have minimal effects on the readings. Relatively small bends or kinks in the access tubes sometimes stopped the probes and blocked measurements through the entire depth of the shafts. Water in the access tubes was a problem. Minimal clearance restricted water flow around the probe so that vertical movement under water was difficult. Electronic cable connections to the probe were frequently affected by water. Thus, water in access tubes had to be removed, typically blown out with compressed air, by the contractor. Interpretations were based on relative changes in readings because maintaining absolute calibrations was difficult. Reference blocks consisting of access tubes cast into concrete filled drums with no, one or two vertical steel reinforcing bars adjacent to the access tubes were used to check relative instrument calibrations and to compare results from multiple instruments in use on one project.

Even with these limitations, this was an effective quality control technology. Results from gamma density testing at an example drilled shaft at a bridge at the Salt River in Arizona, completed using slurry-assist construction, are presented in Figure 1. Vertical gridlines in the figure represent changes in density of 10 pounds per cubic foot (pcf) as measured by the gamma density system. A total of six access tubes (Tubes 1 to 6 left to right in Figure 1) were cast into the shaft to the shaft bottom at a depth of about 93 feet. Readings were made at 1-foot intervals, with the operator following a pattern of recording the reading, setting the cable at the new reading depth and starting the new reading. The first (leftmost) tube had readings completed to a depth of 75 feet, and the fifth tube had readings completed to a depth of only 42 feet. Those tubes may have been damaged or bent during construction, and the probe could not be deployed below those depths. Alternatively, water may have been present in the bottom 18 feet of the first tube, and the contractor was not able to remove it before density logging.

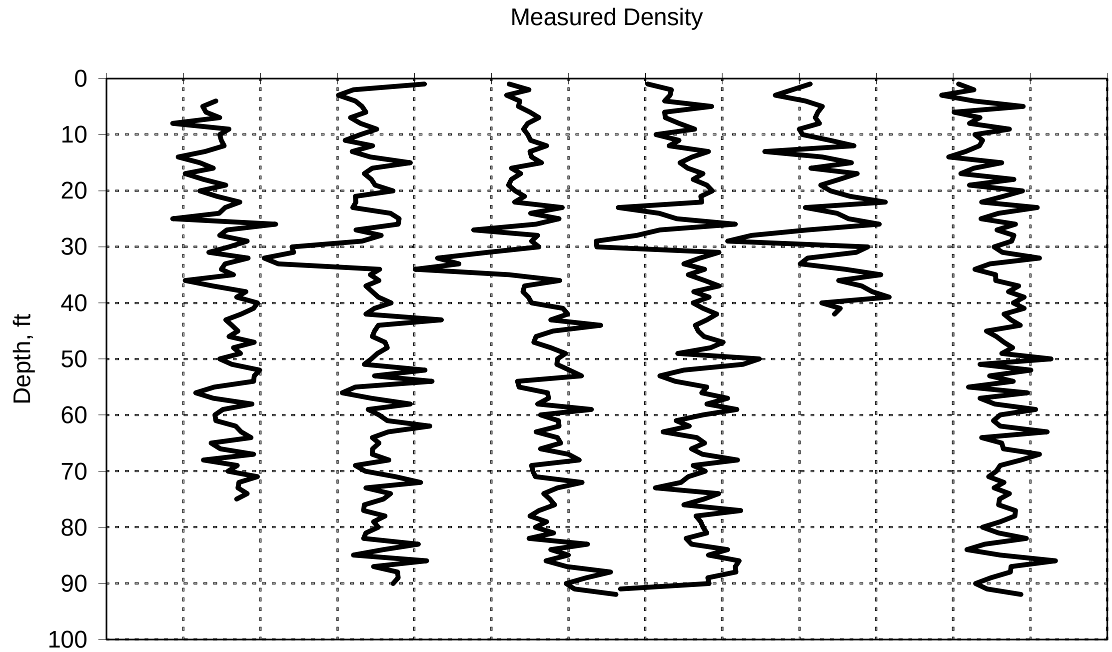

Figure 1. *Example drilled shaft with Tubes 1 through 6 (left to right) measured at 1-foot intervals using 1980's era instrumentation. Each vertical gridline is 10 pcf of density change, and typical densities for each tube are in the range of 140 to 150 pcf.*

A 'noise' level of several pounds per cubic foot is present in the data. At least some of that apparent variation was due to the probe. When a series of successive readings were taken at a single location, it was normal to have a standard deviation of 1 to 2 pcf in those readings. However, in parts of the depth range between about 24 and 35 feet, anomalous low readings were present at Tubes 2, 3, 4 and 5. These significant anomalies, each with several readings at 10 or more pcf lower than the general measured densities, indicated a significant flaw. That interpreted flaw appeared to extend around about two-thirds of the shaft, but did not appear to include Tubes 1 and 2. Given the locations of the access tubes tied to the reinforcing steel cage, it was interpreted that the rebar cage was not covered by concrete in the area of the anomaly. Reliable interpretation of such anomalies required information about the rebar cage configuration because changes in rebar could also lead to overall density changes. If the access tubes were tied to vertical rebars, and vertical bars overlapped or were joined with oversize couplers, then a gap in the vertical steel adjacent to the access tube at the joint could lead to a low density anomaly where the tube was away from the steel. This was especially noticeable with the relatively small depth of investigation of the older equipment, and was discussed in detail by Rucker (1990).

Another, perhaps localized flaw was possibly indicated by the low density reading at the bottom of Tube 4. Low readings at the bottom of a shaft could indicate the presence of a 'soft bottom' where end bearing may be compromised. However, this was a single low reading in that tube which was not corroborated at the other three tubes that had readings to the shaft bottom. Furthermore, a soft bottom condition might not be a significant concern for shafts with adequate capacity in side shear alone.

Finally, a trend of gradually varying measured density with depth is apparent in the Figure 1 data. The overall densities are several pcf higher in the lower portions of the shaft compared to the upper portions of the shaft. The authors have observed that gradual variations in density with depth commonly occur. For that reason, interpretations based on strictly quantitative statistical criteria of an entire set of readings, were not performed. Instead, interpretations involved both quantitative and qualitative aspects of the data, including the measured densities, patterns of changes in the measured densities, and when necessary, other information concerning the design and construction records for the shaft.

CURRENT EQUIPMENT CAPABILITIES AND OBSERVATIONS

Current gamma density logging equipment is based on a lightweight downhole geophysical system including power winch and 200 meter stranded steel single conductor downhole cable, with laptop computer control and data acquisition and storage. One person can set up and operate the system. Equipment can be carried to a measuring location from a nearby vehicle as needed. Setup at an access tube includes a pulley mounted over the tube to smooth travel for the cable and probe assembly from the power winch. Power requirements of 250 watts at 120 volts AC can be met with on-site power, a small generator or a suitable inverter using 12-volt DC vehicle power. Cable connections to probes are engineered to perform under water at pressures far in excess of shaft depths. Figure 2 shows typical equipment. Measurement results are presented on the computer screen as logging progresses and are moved on the computer to spreadsheet files after each tube is logged. Thus, initial field interpretations can be made and concerned parties can be notified immediately if potential problems are identified.

Figure 2. *Portable downhole geophysical equipment used for gamma density logging. The probe is attached to the source that is stored in the shield when not in use. Pulleys are used to direct the cable from the power winch to the access tube being logged. When being used outdoors, a box is normally placed over the laptop computer to shade the screen so that it can be read.*

The downhole probe begins with a natural gamma (Sodium Iodide crystal-photomultiplier tube) detector probe attached to the cable. This portion of the system has other potential geophysical logging applications. It has been used by the authors to perform natural gamma logging in existing steel cased water wells to help qualify the presence, absence and relative portion of clays in alluvial basin aquifer materials. A 100 milliCurie gamma source with isolating shield is attached to the bottom of the natural gamma probe to complete the gamma density probe. Radiation safety procedures are followed. Measurements are typically made at intervals of 0.1 feet while the instrument is logging at a rate of 10 feet per minute. Significantly more readings are taken and automatically processed in much less time using this equipment compared to previous methods. Effective depths of investigation are greater for this probe configuration than the earlier probes used by the authors. Thus, steel rebar located adjacent to access tubes appears to have less influence on measurements than with the earlier equipment. Effective depths of investigation are still restrained to a few inches so that measurements are not made outside of the desired shaft concrete 'neat line.'

An excessive depth of investigation could result in measurements including influence of the surrounding soils.

Improved depths of investigation have allowed the use of nominal 2.5-inch pipe for access tubes. This larger diameter pipe results in fewer bends and kinks, so that blocked tubes have become less common. Access tubes can now remain filled with water, if desired. This makes it simple to perform both gamma density logging and crosshole sonic logging in the same access tubes. For nominal 2.5-inch tubes, the measured density appears to be about 4 pcf higher for water-filled tubes or portions of tubes compared to air-filled tubes. Finally, the frequent density measurement intervals increase the potential for observing small lower density anomalies that are consistent with access tube coupler locations. These small anomalies are frequently encountered at 20-foot depth intervals due to commonly available 20-foot lengths of PVC pipe often used for access tubes.

The author's firm has utilized GDL to resolve unusual results from CSL testing due to issues of access tube spacing. Qualitative results of CSL testing at a pair of drilled shafts did not indicate the presence of anomalous zones. However, quantitative analysis revealed alarmingly low apparent CSL velocities based on reported access tube spacing. At a minimum, access tube spacings were greater than the minimum spacing needed to obtain reasonable velocity measurements. Other access tubes were apparently debonded from the concrete at another shaft, so that CSL testing could not be performed in those tubes. The GDL system and operator was mobilized from Phoenix to the project in Albuquerque, and measurements with hard copy printed results were completed in part of a day on site. The gamma density logging verified that the shafts consisted of good quality concrete without significant anomalies.

Interpretations

Results from the current logging system in an example drilled shaft are presented in Figure 3. Overall, the Figure 3 data shows relatively little random 'noise.' Except in anomalous zones, measurements fall within a band of plus or minus 1 pcf for considerable depths. Yet, some essential

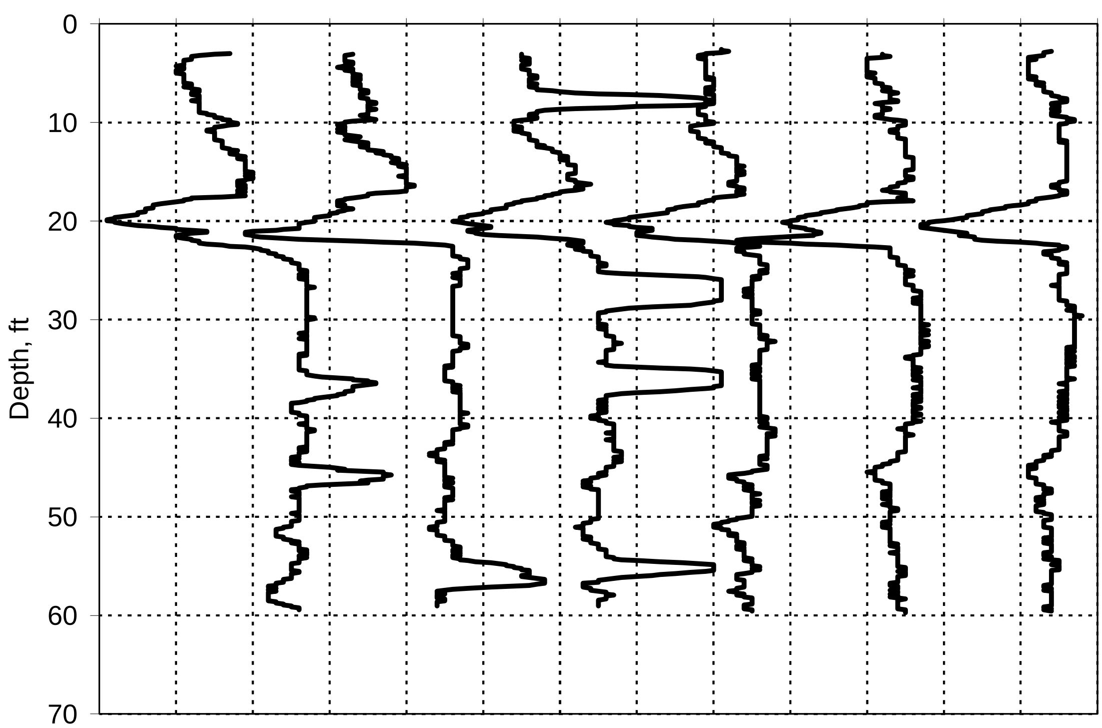

Figure 3. *Example drilled shaft with Tubes 1 through 6 (left to right) measured at 0.1-foot intervals using current geophysical density logging equipment. Each vertical gridline is 10 pcf of density change, and typical densities for each tube are in the range of 140 to 150 pcf.*

characteristics of significant flaws in both Figures 1 and 3 are obvious. These characteristics include large density reductions, multiple low density readings in each access tube, and low density readings at similar depths at adjacent tubes. In Figure 3, a major anomaly appears to be centered at a depth of about 20 feet. Tubes 1 through 3 also indicate a significant anomaly or anomalies in the upper 20 feet of the shaft along one side. These interpretations are straightforward. However, densities in the upper 20 feet at Tube 4, and at several tubes at depths of about 46 and 51 feet are several pcf lower than in other portions of the readings. Whether these density reductions were sufficient to represent actual flaws was not known. The obvious flaws were sufficient for a quality control interpretation for this shaft. One artifact of some readings was occasional apparent high densities such as in the traces for Tubes 1 through 3. Whether that was a result of a true condition, probably adjacent reinforcing or other steel in the shaft, or occasional instrument 'glitch,' has not been verified.

Figure 4 presents an interpretation case where smaller quantitative changes in density nonetheless indicated significant flaws. The shape of the Tube 1 measurements curve (left trace) indicated possible flaws in the upper ten feet of the shaft even though the measured density differences below a depth of 5 feet were only about 5 to 8 pcf. Excavation at the top of the shaft at Tube 1 revealed rebar without proper concrete cover. Very low readings of 144 to 150 pcf in the upper 1 to 2 feet of Tube 1 were corroborated by an absence of concrete along that tube at the upper 4 horizontal rebars. Concrete was present to the horizontal rebars for the next few feet as was indicated by density readings between 151 and 153 pcf. Measured densities then dropped from 151 pcf down to

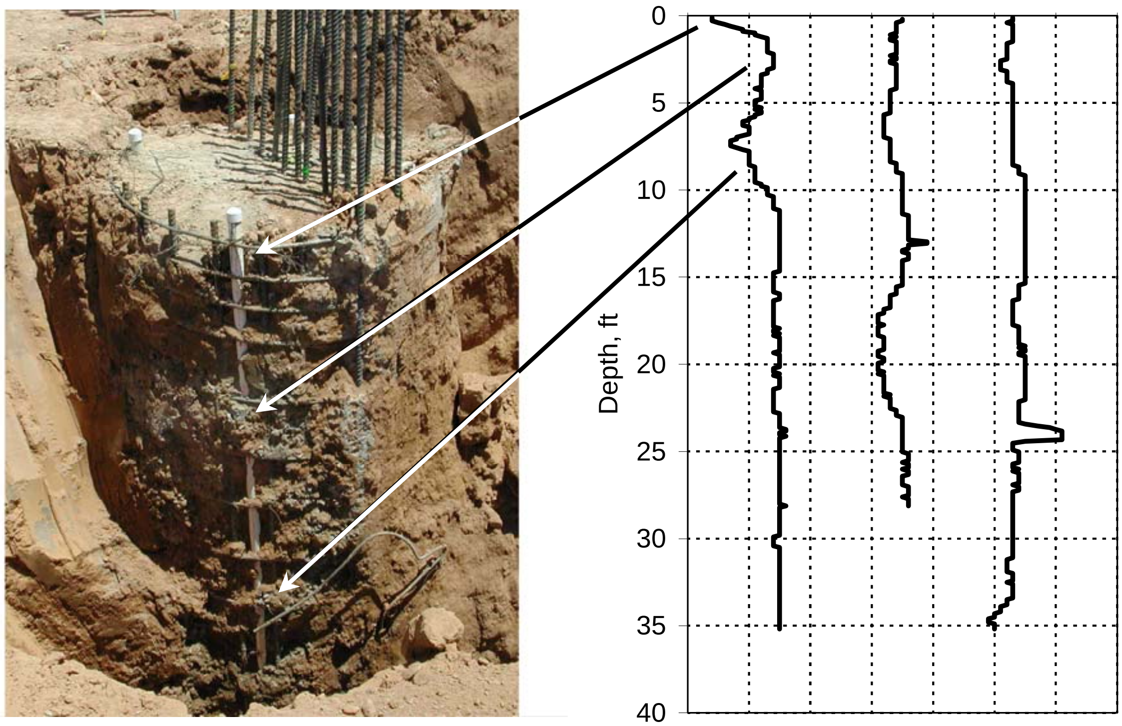

Figure 4. *Excavated upper portion of drilled shaft with Tubes 1 through 3 (left to right) measured at 0.1-foot intervals using current geophysical density logging equipment. Each vertical gridline is 10 pcf of density change, and typical densities for each tube are in the range of 150 to 160 pcf. Low density zones in the Tube 1 trace are matched to corresponding area on exposed drilled shaft.*

145 pcf at depths of about 5 to 10 feet. The photo shows that again, neither Tube 1 nor the horizontal rebar in this area were covered by concrete. Below about 10 feet in depth, the typical density reading at Tube 1 was 155 pcf, and typical readings in all of the tubes ranged between 153 and 156 pcf. Unconfirmed possible problems with that shaft could also be interpreted. A somewhat lower density zone (151 to 152 pcf) that might indicate the presence of a possible or marginal flaw

was measured at Tube 2 at depths of about 17 to 22 feet. A potential ‘soft bottom’ condition was indicated at one tube. Two isolated high density anomalies were also present in the data.

CONCLUSIONS

Gamma density logging using downhole geophysical equipment provides an effective means to perform quality control for drilled shafts. Results can be verbally presented on-site, and hard copy of results can be generated as soon as a computer printer is available. Interpretation can be a simple matter of comparing measured densities, but experience (perhaps extensive experience) is necessary to understand nuances of moderate variations in densities. Although the basic physics and measurements are fundamentally different from crosshole sonic logging, both gamma density and crosshole sonic logging can be performed in the same access tubes. Thus, these two methods together provide a powerful means to perform geophysical non-destructive testing for drilled shafts. When the results of one method do not provide conclusive quality control results, the other method can be employed to improve on the quality control information. Furthermore, when debonding of access tubes prevents effective use of crosshole sonic logging, gamma density logging can still provide effective measurements and results.

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