Construction Control Testing of Slurry-Assisted Soldier Wall Caissons with Inclinometer and Nuclear Density Probes

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A foundation system for the new Terminal 4 building at Sky Harbor International Airport in Phoenix, Arizona, incorporated subsurface support and space for a proposed rapid transit tunnel, which may be constructed beneath the groundwater table in a sand-gravel-cobble horizon after the building is finished and in use. Two walls consisting of slurry-assisted drilled shaft caissons were constructed along the sides of the proposed tunnel to provide foundation support for the terminal and to provide stability for possible future tunnel excavation. An inclinometer verified clearance tolerances for the proposed tunnel space that necessitated tight vertical plumbness specifications for the drilled shaft caissons. Placement of concrete in the slurry assisted caissons was verified using nuclear density probes. The presence of rebar splices and varying access tube positions relative to rebar steel required detailed analysis of nuclear density probe response characteristics, special calibration blocks and procedures, and interpretation of density data based on knowledge of the rebar and access tube geometries.

The objective of this paper is to describe the methodologies used to monitor slurry-assisted caisson (drilled pier) construction at the Sky Harbor International Airport Terminal 4 in Phoenix, Arizona. Foundation design included elements to permit future construction of a rapid transit tunnel (RTT) under the terminal building. The RTT space was flanked by two walls, each consisting of about 115 drilled piers on 10 ft centers connected by a grade beam located at building basement level. These walls were designed to serve as part of the foundation system with the tunnel in place.

Each wall pier consisted of a straight, drilled shaft with a neat diameter of 54 in. advanced to a depth of about 55 ft below the basement excavation. The shafts were installed in the Salt River sand-gravel-cobble (SGC) deposits underlying the site. Overbreakage of shaft excavations was anticipated due to the dense packing of cobbles and boulders in this material. Groundwater was present at depths of about 25 to 30 ft below construction grade, requiring bentonite slurry construction techniques be used to maintain hole stability.

CONSTRUCTION MONITORING OBJECTIVES

The proposed RTT placed unusually strict constraints on the true subsurface location and geometry of the caissons immediately adjacent to the proposed tunnel. A distance of only 21 in. separated the proposed tunnel walls from the caisson neat lines. A caisson could theoretically encroach on the space in either of two ways. Caissons with diameters in excess of 96 in. could encroach upon the RTT space, perhaps requiring partial demolition for future tunnel construction. Caissons with somewhat smaller diameters that drifted towards the proposed tunnel could also impact tunnel construction. Therefore, it was especially important to accurately document the as-built diameter and orientation of each caisson. The use of slurry dictated that caisson density monitoring be performed to verify the integrity of the concrete, especially at the caisson rebar cages.

Approximate caisson diameters were determined by monitoring concrete height gain versus concrete volume placed during caisson installation. The approximate orientation of each caisson was determined by measuring the verticality of the caisson rebar cage using an inclinometer. Downhole nuclear density gauges were used to verify concrete integrity in the caissons (*1*,*2*).

Instrumentation access was provided by PVC tubing installed by the contractor on the steel reinforcement (rebar) cages and cast into the caissons. These access tubes were tied adjacent to selected vertical rebar members during the cage fabrication. This positioning minimized both bending and crimping of the access tubes and the potential for restricting concrete flow around and through the rebar cages during concreting.

Daily field observations, instrumentation readings and initial field inclinometer data interpretations were performed onsite by engineering technicians. Final data analysis and interpretation was performed by the instrumentation engineer as construction proceeded. The engineer was continuously available for telephone consultation with the field technicians or, when necessary, site inspection visits.

CAISSON DIAMETER

The as-drilled diameters of caissons immediately adjacent to the proposed RTT were estimated by measuring concrete volume and height changes between each truckload of concrete tremied into each caisson. Using a weighted measuring tape, the technician would initially measure and record the depth of the hole prior to concrete placement. After each truckload of concrete was tremied into the hole, the technician

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would measure and record the depth to the top of the concrete, compute the change in height, and record the quantity of concrete placed (from the truckload). This procedure was repeated until completion of concrete placement for the caisson.

Given the change in height due to the volume of each truckload of concrete, and assuming a cylindrical shape for each section of caisson, an average diameter was computed. If a given caisson section did not have a uniform diameter, this assumption could underestimate the greatest diameter in that section. Such a condition was likely if, for example, a portion of the borehole wall in a section collapsed or caved.

CAISSON PLUMBNESS

Caisson plumbness was measured using an inclinometer in conjunction with casing referenced to the caisson rebar cage. A standard biaxial inclinometer sensor and readout was utilized, permitting simultaneous measurements in two directions. There was a possibility of damage to the inclinometer casing during lifting and handling of the caisson rebar cages. Therefore, inclinometer casing was temporarily assembled in a 4 in. diameter PVC access tube securely attached to each cage after the cage was set.

For purposes of construction control, accuracy of horizontal measurements to the full capability of the inclinometer system was not required. The accuracy was limited by the verticality of the access tube alignment on the rebar cage and the 0.5 in. play between the inclinometer casing spacers and the access tube. Inclinometer measurements consisting of a single set of readings at 5 ft intervals from the bottom to the top of the casing, completed in a few minutes, were found to be sufficient for monitoring purposes. Cages not meeting the verticality specification of 6.75 in. in 55 ft, some of which were in excess of 10 in. out of plumb, were quickly identified and corrected before placement of concrete. Plumbness measurements in caissons adjacent to the proposed RTT were repeated after placement of concrete in order to document the final position of the rebar cage in those caissons relative to potential future tunnel construction.

DENSITY MEASUREMENTS

The continuity of the caisson concrete was verified by density measurements using nuclear density gauges passed through 2 in. diameter Schedule 40 PVC access tubes attached to the caisson rebar cages. Four access tubes were installed along the length of each wall pier rebar cage. To assist in making density interpretations, the locations of PVC density access tubes relative to the vertical No. 14 bars were documented for 65 rebar cages. This information was utilized in evaluating the quantitative effects of the rebar on density data.

Standard downhole nuclear density and moisture gauges were used on this project. Density measurements were generally made at 2 ft depth intervals along the access tubes. Measurements were alternated between even and odd depths at adjacent tubes. Where measurements indicated a potential problem, density measurements were repeated at 1 ft intervals within the zone of interest. After initial verification of sampling time periods, reading periods of 32 seconds were deemed to provide sufficiently accurate results. Because of the large volume of testing required and equipment problems, four different nuclear density gauges were used. Differences in instrument response between the four gauges complicated density interpretations.

NUCLEAR DENSITY GAUGE RESPONSE CHARACTERISTICS

Although the qualitative response patterns and characteristics of individual density gauges were consistent, the quantitative density values reported by individual gauges varied widely. Consistent interpretation of the density data required that individual gauge readings be referenced to a known set of material densities, and that the nuclear density gauge response behavior to the materials in the caissons be sufficiently understood.

Density measurements were influenced by the materials immediately adjacent to access tubes. PVC pipe, concrete, and steel with densities of about 64, 145, and 490 pounds per cubic foot (pcf), respectively, were the materials encountered within a properly constructed caisson. Water or slurry, with a density range of about 64 to 75 pcf, or native soils, having a wet density in the range of 130 to 135 pcf, were expected to be encountered in a cutoff or other failure zone within a caisson.

Density readings were profoundly influenced by the response characteristics of the nuclear density probe technology. The typical range in density measurement for the type of instruments utilized (*1*,*3*) was about 70 to 170 pcf. Densities of PVC, water, and slurry were at the bottom end of this range, while the density of steel was far in excess of the upper limit. It was further assumed that the location and high density of steel would cause the rebar to act as a nuclear particle shield, with a "shadow zone" behind the rebar.

Instrument response was, of course, also dependent on the distance from the probe. The nuclear density probe was designed so that 95 percent of the response was from a roughly cylindrical volume of material within a distance of 2 in. of the edge of the probe (Mancusa, unpublished data). Detailed performance data concerning the probe response as a function of distance was not available. However, a general downhole nuclear probe response pattern as a function of distance was obtained from a study by Champion (unpublished data) and scaled to fit the 95 percent response at 2 in.

FIELD CALIBRATION OF DENSITY GAUGES

To ensure that representative density readings were obtained, three field calibration blocks fabricated from 55 gallon drums filled with caisson concrete and with a PVC access tube in the center were used both to verify and to monitor the nuclear density gauge response. In addition, one block had a single No. 14 bar tied adjacent to the PVC, and one block had two No. 14 bars tied adjacent to the PVC. The three field calibration blocks were designed to represent "normal" caisson density conditions: an access tube without adjacent steel, an access tube with a single adjacent bar, and an access tube with two adjacent bars. Due to the assumed shielding effect of steel, it was deemed unnecessary to fabricate barrels with spliced bundles of three or four bars.

Once the calibration blocks were fabricated, the nuclear density gauges were checked on a regular basis. The first set of calibration block readings were used to develop a simplified model to predict and interpret various normal and abnormal caisson conditions. Continued calibration block readings were used to verify instrument readings for interpretation purposes. These readings also documented changes in instrument performance during the intensive construction monitoring, control, and documentation process.

DENSITY RESPONSE MODEL

In order to determine and analyze acceptable and unacceptable density conditions in the caissons, a simple model for prediction of the nuclear density probe response characteristic was developed. Incremental 5 percent response "rings" were intersected by rays at 5 degree intervals to generate a field of equal response points around a "probe." Response was analyzed only in the radial plane; a three dimensional analysis was not attempted. One-fourth of the response field, along with outlines of typical materials such as access tube and rebar that might be found within the response field, is presented in Figure 1.

This model yielded 1,440 points of equal response. The total density reading was a weighted average of the material densities for the 1,440 points. Seventy-two points were in the air gap between the probe and PVC access tube, and 216 points were in the PVC access tube. Where PVC access tubing was joined by a PVC coupler, the coupler contained another 216 points. Including a "shadow zone" behind the steel, a single No. 14 bar adjacent to the access tube contained 135 points, allowing for the space occupied by the rebar corrugations. The same bar at 0.5, 1.0, and 1.5 in. from the access tube contained 74, 38, and 20 points, respectively. An annular space which contained no concrete aggregate, leaving only slurry, was generated when two bars were placed adjacent to the access tube; this space contained 38 points. If the access tube was placed adjacent to the borehole side, as many as 338 points may have fallen within native soils, and another 64 points may have been contained in an annular space between the tube, bar, and hole sidewall.

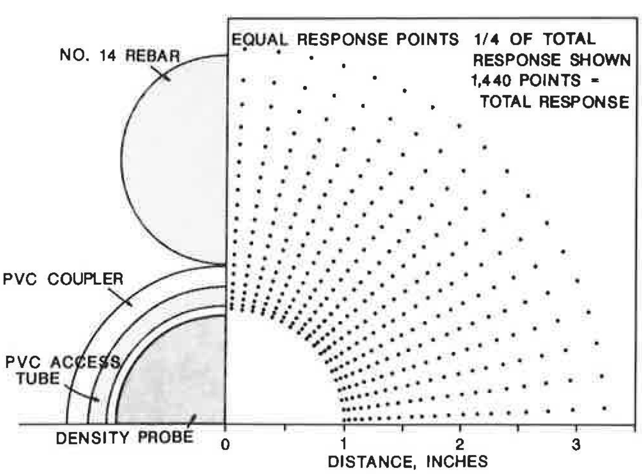

FIGURE 1 Density response model for equal response points and typical material sizes.

Initial readings from the field calibration blocks were used to calibrate the density response model. Material densities for PVC pipe, concrete, slurry, and wet native soils of about 64, 145, 64 to 70, and 130 to 135 pcf, respectively, were expected to be accurately measured by the density probes. Air was assumed to have a density of zero and was ignored. The steel rebar density of 490 pcf was not expected to be measured accurately by the probe. An "equivalent rebar density" of about 335 pcf was backcalculated from the readings in the no-bar, one-bar, and two-bar field calibration blocks.

Once the density response model was calibrated, different anticipated material configurations representing normal and abnormal conditions within a caisson were analyzed. For example, the model of concrete around an access tube with one adjacent rebar included 72 air gap points, 216 access tube points at 64 pcf, 135 steel rebar points at 335 pcf, and 1,017 concrete points at 145 pcf, resulting in a total or average density of 143.4 pcf. Normal conditions included one, two, or no bars; bars at different distances; and a PVC coupler at the access tube. Abnormal conditions included wet sand or native soils around the access tube or an access tube adjacent to the boring sidewall. Results of the density response model are presented in Table 1.

Finally, the field calibration data was analyzed to verify the relationship between the measured densities of the field calibration blocks for different reported densities and the instrument calibrations. Densities for concrete with no rebar varied from 98.8 to 137.5 pcf, depending upon the instrument and the selected calibration for that instrument. However, instrument responses followed the same trend, and density readings could be related to actual density conditions in the caissons. A plot of the measured densities for cases of one and two

TABLE 1 CALCULATED DENSITIES FOR POSSIBLE CAISSON CONDITIONS

Condition	Density Reading (pcf) Actual	Calculated
Rebar adjacent to PVC access tube		
Wet sand only, no concrete	—	116.1
Concrete with PVC coupler	—	114.3
Concrete only	125.2	125.6
Concrete & one bar	143.4	143.4
Concrete & two bars	156.8	—
Concrete in annular space	—	159.2
Slurry in annular space	—	157.1
One bar at 0.5 in. from PVC access tube		
Wet sand only, no concrete	—	126.4
Concrete only	—	135.4
Against boring sidewall	—	128.9
One bar at 1 in. from PVC access tube		
Concrete only	—	130.6
One bar at 1.5 in. from PVC access tube		
Concrete only	—	128.2

NOTE: From initial field calibration block readings and density response model from Figure 2. No. 14 rebar is assumed. Annular spaces with both concrete and slurry are presented. Densities of 64, 133, 145, 335, and 64 pcf are assumed for PVC, wet sand or native soils, concrete, rebar, and slurry, respectively.

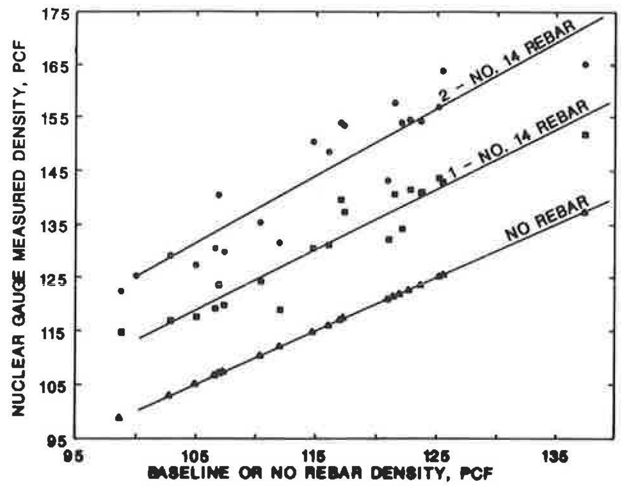

FIGURE 2 Field calibration block readings and characteristics.

bars versus the measured densities for the case of no rebar are presented in Figure 2.

DENSITY ANALYSIS AND INTERPRETATION

Density data collected in the field was processed and analyzed in the office using a spreadsheet computer program before final interpretation was performed. The first step in the interpretation process was to determine the appropriate "baseline" density for the caisson, that is, the density reading with no rebar. The density data was examined to find a consistent low density value that was close to the particular instrument field calibration. In all but a few cases, the baseline was readily identified. Where possible, readings from access tube sections with no nearby vertical rebar (shown by rebar cage maps) were used to determine the baseline density.

Once the baseline density was determined, expected densities for different conditions in the caisson were determined. In general, the conditions presented in Table 1 at a baseline density of 125 pcf were adjusted to levels appropriate to the caisson baseline density using the relationships shown in Figure 2. Any density significantly lower (by at least 5 pcf) than the caisson baseline density represented a potential abnormality. However, a single, isolated point of very low density could be due to a PVC coupler. Low density readings across a set of access tubes, with some readings at even and some readings at odd depths, would confirm that an abnormality was present. Lastly, two contiguous vertical low density readings in one access tube eliminated the possibility of a PVC coupler as the cause.

Significant portions of each access tube were near or adjacent to bundles of vertical rebar. Interpretation of these sections could potentially prove very complex. A length of access tube in wet sand without concrete, but with rebar at a distance of 0.5 in., was expected to exhibit a density at or above the caisson baseline density. Rebar cage mapping significantly aided density interpretations of normal and abnormal conditions in these situations. For example, in areas where a vertical bar splice ended, an access tube suddenly had no nearby steel instead of two adjacent bars, with a resulting density drop of more than 20 pcf. Such conditions were often noted for several tubes in a given caisson. Changes in density for normal caisson conditions were anticipated by knowing where rebar splices were located; familiarity with such typical project details (through mapping) simplified interpretation. Alternatively, when readings were not at a bar splice, a 15 to 20 pcf drop in density for two or more contiguous vertical readings, with density drops in the same vicinity at adjacent access tubes, indicated a seriously abnormal caisson condition.

DATA INTERPRETATION AND ANALYSIS

Caisson diameter, plumbness and density data collected in the field required varying degrees of interpretation and analysis for construction monitoring and documentation purposes. As shown in Figure 3, severe abnormal density conditions were identified in one caisson. These conditions were in the vicinity of severe borehole caving, as indicated by caisson diameter measurements. Based on the density information, the caisson was rejected. Subsequent coring of the caisson confirmed voids in the concrete, and another caisson was placed adjacent to the rejected caisson. It was postulated that the concrete placement tremie pipe was raised at the normal rate through the isolated zone of very large hole diameter. Concrete filling the large void did not rise sufficiently in the hole at that point. The tremie pipe was exposed above the concrete level and a cutoff was created.

CONCLUSIONS

The integrity, plumbness, and in-place geometry of slurry-assisted caissons was verified through a comprehensive construction monitoring program. Special procedures were required to effectively interpret density data obtained from nuclear density gauges. By applying these procedures, caisson integrity in the vicinity of each caisson rebar cage was assured.

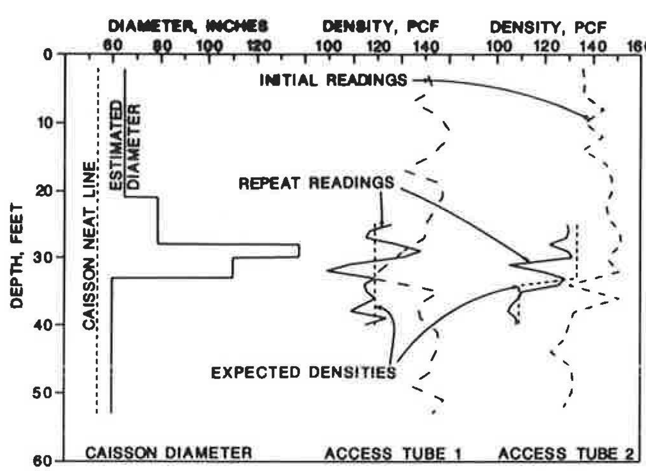

FIGURE 3 Diameter and density data showing abnormal caisson condition.

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