A DETAILED GEOPHYSICAL SURVEY TO CHARACTERIZE SUBSURFACE FAILURES ON INTERSTATE 40, PENDER COUNTY, NORTH CAROLINA

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Abstract

On August third, 2001, a 14-inch deep, 25-foot diameter depression developed in the eastbound lanes of Interstate 40, 10 miles north of Wilmington, NC. This area (and much of southeastern North Carolina) is underlain by the Castle Hayne Formation, in which solution cavities are common. After emergency 100 MHz ground probing radar (GPR) survey to confirm the lateral extents, the depression was remediated by excavating and installing a fabric/base course/asphalt "bridge".

Once the highway was reopened, a detailed geophysical survey employing microgravity, two-dimensional DC electrical resistivity (2DRES), and GPR, was undertaken centered on the known problem area. Drilling based on the geophysical data interpretation confirmed a void or zone of extremely soft soil approximately 80 feet southeast of the remediated depression.

Based on these findings three microgravity profiles, each one mile in length, were collected to determine how many other areas of concern might exist in the vicinity. Gravity results revealed a broad gravity low, approximately 3,500 feet long, within which four localized gravity lows as well as the remediated depression occurred. Two 4,250 feet long 2DRES profiles, and coincident GPR profiles, were collected to further investigate the localized gravity lows and intermediate areas revealed in the microgravity data. The final results of this study were that the broad gravity low represented an erosional feature, flanked to the north and south by more competent subsurface soil (cemented limestone). Within the erosional "channel", soils are prone to dissolution and piping, possibly leading to subsurface, and eventually surface, failure. Detailed stratigraphic analysis of two drill holes and exposures at a nearby quarry confirmed this interpretation. Quarry exposures also exhibited poorly consolidated, calcareous sand waves that may be particularly prone to dissolution and collapse.

Introduction

On August third, 2001, a 14-inch deep, 25-foot diameter depression developed in the eastbound lanes of Interstate 40, 10 miles north of Wilmington, NC. This area (and much of southeastern North Carolina) is underlain by soil and rock of the Castle Hayne Formation, within which solution cavities are common. After an initial emergency 100 MHz ground probing radar (GPR) survey to confirm the lateral extents and estimate the depth of the problem, the depression was remediated by excavating and installing a fabric/base course/asphalt "bridge". Eastbound traffic had been temporarily rerouted. Traffic was rerouted back onto I-40 after 32 hours.

The North Carolina Department of Transportation (NCDOT) now had three main concerns: i) to thoroughly investigate the extent of the depression; ii) to permanently remediate the depression; and iii) to determine if any other potential failures existed in the area. Logistic concerns included that summer traffic disruption should be minimal, and that all work would be completed under a limited Divisional budget. The decision was made to drill five holes at the site of the depression to evaluate the embankment and underlying soils, and to grout in and around the repaired depression. In addition, NCDOT would investigate the use of non-destructive (geophysical) technologies to evaluate the depression and surrounding areas.

In order to characterize the subsurface surrounding the depression, Geophex, Ltd. was retained to perform the geophysical survey. The aim of the survey was twofold: i) to determine if any other potential sinkholes existed in the vicinity of the remediated problem; and ii) to determine what geophysical method(s) would be best suited to the delineation of potential problems. The worst-case scenario was that all 10 miles of I-40 underlain by the Castle Hayne Formation would need to be studied in detail.

August 2001 Survey

Geophex decided to collect GPR, 2-D DC Resistivity (2DRES), and microgravity in the immediate vicinity of the depression. GPR data is easy to collect and would provide a detailed look at the roadway embankment, elucidating any immediate failure concerns. Further, in the sandy coastal plain geology of eastern North Carolina, low frequency GPR (100 MHz) can often attain significant (300 ns) ground penetration. 2DRES has long been a standard investigative tool in void (sinkhole) determination. Air filled voids are typically standout resistors in apparent resistivity profiles. However, the unconsolidated nature of the natural coastal plain soils and the shallow water table in this area mean that in general all the subsurface is conductive. Microgravity was added as a third investigative method in an attempt to eliminate any ambiguities in the resistivity data interpretation. While a gravity survey may not define a small individual void, the technique would certainly delineate areas of low density within and beneath the roadway embankment.

Three survey lines were established centered over the remediated depression: one off the embankment; one in the right eastbound lane where the depression occurred; and one in the central median. All three data types were collected along each line. Resistivity data were collected using standard dipole-dipole geometry, along a 28-electrode spread, with a 6-m (19.6') electrode spacing. Within this, another 28-electrode spread with a 3 m (9.8 ft) spacing was also collected to gather more detailed information, directly over the sinkhole. Likewise a 208 m (682.2 ft) microgravity profile was established, with readings taken at 16 m (52.5 ft) spacings toward the extremities of the profile and closer 8 m (26.2 ft) spacings in the immediate vicinity of the depression. GPR data was collected using 100 MHz and 250 MHz antennas over the entire length of the microgravity profiles. Traffic was reduced to one lane for only one day as the data in the travel lane was collected. Data collection off the travel lanes required only shoulder closing (signage and cones).

Figure 1 shows an example of the 2DRES and GPR data along one survey line. The corresponding Bouguer-corrected gravity profile is superimposed on the 2DRES profile. The Bouguer gravity profile exhibits a steady decrease due to latitude, expected along an essentially North-South oriented line. However, in the vicinity of the depression, readings become variable. 100 MHz GPR data attained over 300 ns (approximately 45 feet) of penetration. 2DRES data, as expected, showed generally conductive subsurface conditions beneath the roadway embankment. This overlies a generally conductive layer, that is punctuated by two relatively resistive areas. One of these was associated with the known depression. The other, slightly smaller in size and magnitude, was located approximately 80 feet to the south. Both anomalies lay within the zone of variable gravity data, and both were associated with truncated subsurface reflectors in the GPR data (Figure 1). NCDOT drilled this anomaly and confirmed a void between 34.2 and 38.9 feet below the ground surface. A dense silty sand layer at approximately 40 feet depth, with SPT blow counts of 100+ blows per foot, was determined to be sands within the PeeDee formation, below the Castle Hayne. This sand layer was interpreted to be the limit of reading within GPR profiles (Figure 1).

Immediately following the geophysical survey, grouting began in the eastbound lane where a further three inches of subsidence had occurred. A grout volume of 127.3 yd^3 was pumped into 22 holes in the vicinity of the sinkhole. This was accomplished over a four-week period requiring only a single lane closure. Grout was pumped at the following depths and quantities: 55.6 yd^3 between 11 and 13 feet, and 71.7 yd^3 between 22.4 and 27 feet. Almost all grouting was pumped with little or no pressure. No other significant subsidence has occurred.

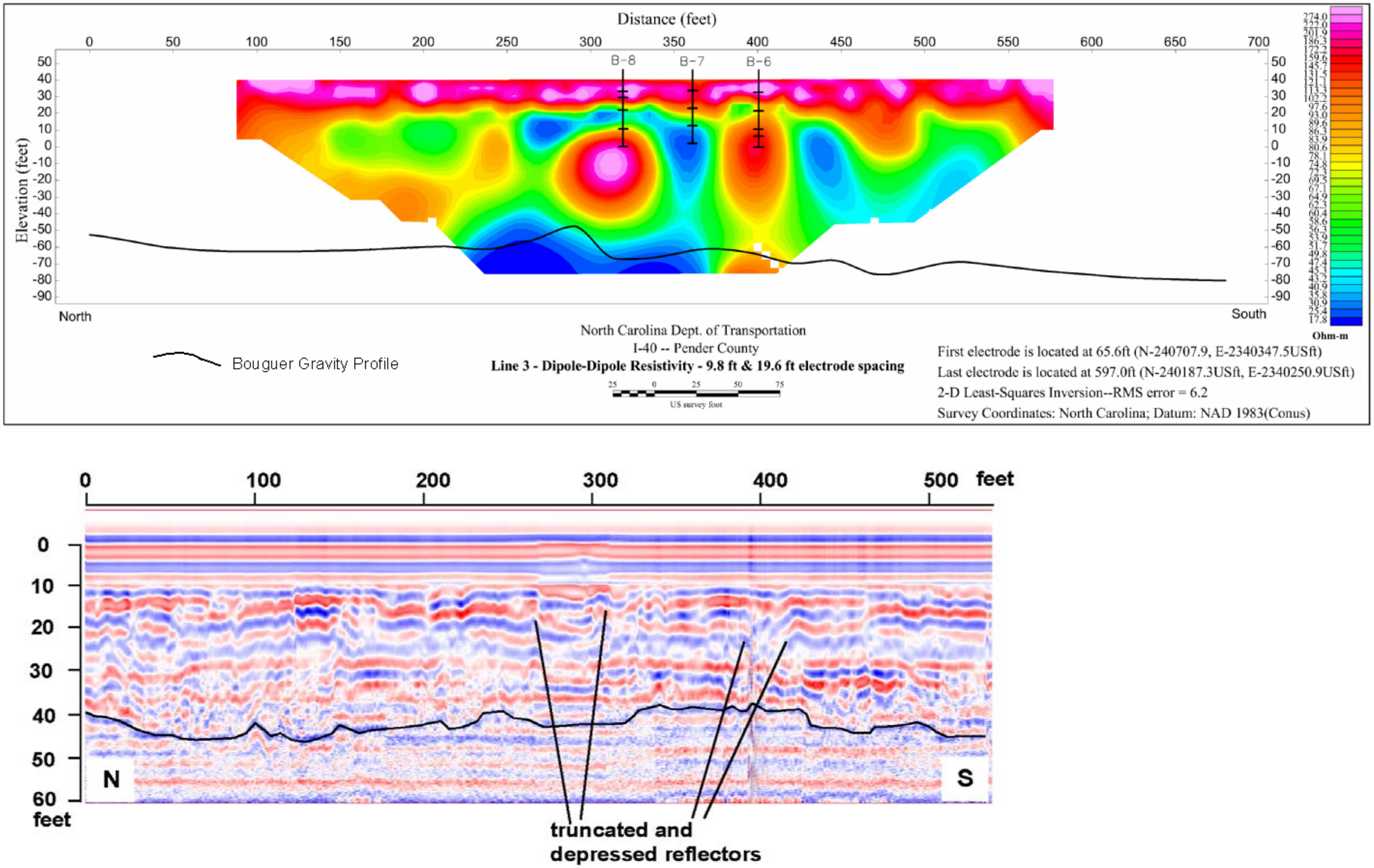

Figure 1: Examples of the DCRES and GPR data, collected in August 2002, immediately surrounding the depression. The Bouguer gravity profile is superimposed on the resistivity profile.

January 2002 Survey

Concern still existed for the remaining section of the Interstate, approximately 10 miles in length, underlain by the Castle Hayne Formation. Based on the results of the previous survey, it was determined that a larger scale microgravity survey would be most beneficial and cost effective. Although GPR data was good quality, coastal plain stratigraphy by nature contains discontinuous, interfingering units that made anomaly interpretation of GPR data problematic. Similarly although the DCRES data identified a subsequently confirmed void space, interpretation of the data set was difficult because of the generally conductive nature of the soil due to the shallow water table. In January 2002, due to budget considerations, three lines of microgravity data each only one mile in length were collected. The lines were collected between mile markers 410 and 411, the mile containing the remediated depression. Gravity readings were collected at stations spaced 30 feet apart.

Gravity profiles were 2-D forward computer modeled. Forward models attempt to find a viable geologic model for the observed gravity data. Depth and layer descriptions were based on NCDOT drill data from August 2001. Densities were assigned to these units based on published average densities of similarly described units. The absolute depth of the void was presumed to be no deeper than 40 feet below the ground surface. The top profile in Figure 2 shows the August 2001 gravity data over the depression, prior to remediation, inserted in the data collected January 2002. The bottom profile shows the complete January 2002 gravity profile. Clearly, the grouting program was effective in remediating the depression.

Observed and calculated values in both cases match well. Within this mile of roadway, the gravity data show a broad low that extends from approximately 750-5200 feet. The crux of this low is approximately 100 μGal below the flanks. Additionally, the August collapse shows a further 50-100 μGal anomaly below this low. Based on these data, collapse zones of immediate concern were interpreted to be anomalies greater than 50 μGal (below the baseline average). Zones of future concern were interpreted to be anomalies of 20-50 μGal (below the baseline average).

August 2002 Survey

Based on the results of the extended gravity survey, it was determined that detailed surveys of the five 20-50 μgal gravity anomalies were necessary using 2DRES and GPR. Rather than collect five individual resistivity profiles, recently acquired equipment made it cost effective to collect continuous resistivity data spanning all five gravity anomalies. An 8 channel 56-electrode Earth Resistivity meter was used to collect profiles using a 3 m (9.8 ft) electrode spacing.
An overlap of 14 electrodes between 10 deployments made possible the inversion and contouring of 4172 linear feet of resistivity data into continuous profiles. Two such profiles were collected, one in each eastbound travel lane. Traffic control closed off one lane at a time for an entire mile to facilitate freedom of movement along the survey line for easy data collection. It took two workdays in each lane to collect the resistivity and GPR data. The work schedule (and ultimately the GPR data quality) was affected by torrential storms that dumped over 7 inches of rain in the Wilmington area during data acquisition. GPR data was severely attenuated, penetrating only 150 ns (approximately 20 feet), half of what was achieved previously.

Too long to display here, a portion of one resistivity profile is displayed in Figure 3. In general, the resistivity data exhibited a near surface resistivity high, 10 to 20 feet thick, associated with the roadway embankment. Beneath this was a 60 to 80 foot thick layer of variable resistivity. At depth, profiles indicate generally conductive sediments. The near surface resistivity high (roadway embankment) is thicker between Stations 1460 and 4550 feet, which correlates to the extents of the broad gravity low identified in the January 2002 data. At the north and south extremities of both profiles, between elevation 0 and –40 feet, an essentially continuous resistive layer occurs only. Its occurrence corresponds to the flanks (high points) of the broad gravity anomaly, and to the thinning of the embankment resistor (Figure 3). It was interpreted that this resistor represented firm substrate, probably cemented limestone, which is not present between Stations 1000 and 5000 feet.

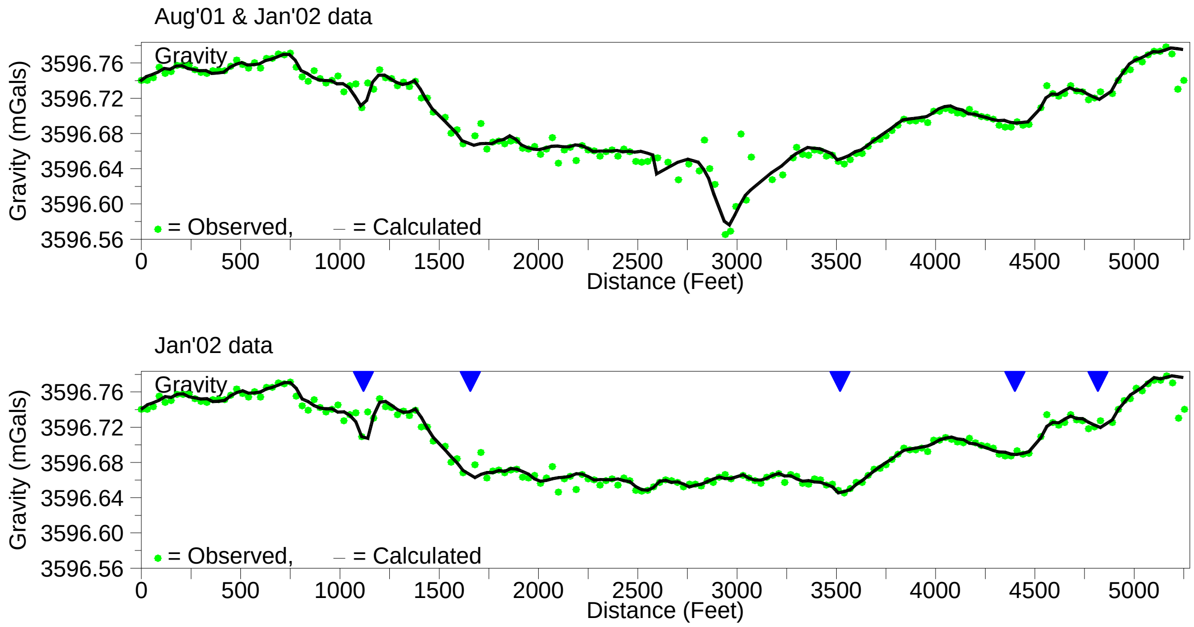

Figure 2: Modeled and observed Bouguer gravity profiles. The top profile shows the model and observed gravity incorporating the data collected over the depression, in August 2001. The lower profile shows only the January 2002 data. A broad gravity low exists between 750 and 5200 feet. Within this occurred the August 2001 depression which was clearly remediated by grouting by the time of the January 2002 survey. The blue triangles denote 20 to 50 µgal anomalies of concern.

Two borings were performed based on the results of the resistivity and gravity data. At Station 3550 a discrete gravity low corresponded to a distinct, vertical, conductive zone delineated in the resistivity data. Such a conductor may indicate a groundwater pathway, accentuated by the rainfall during data collection. The second drill target was at Station 5000 to determine if the resistive layer that appeared on the flanks of the broad gravity low was in fact a cemented limestone (compare Figures 2 and 3). Beneath the roadway embankment, at station 3550, the boring confirmed a very soft, wet zone between 20 and 25 feet below the ground surface, drill rods dropped between 34.5 and 37.0 feet, and two loss-of-drill-fluid zones. At station 5000, an eight-foot thick, hard, pelecypod-mold limestone was encountered 36.5 feet below the ground surface.

Stratigraphy

In all, ten borings were completed during the investigation of the depression on I-40: five were advanced to approximately30 feet; three were advanced between 60 to 80 feet; and two more were advanced over 120 feet. Two formal stratigraphic units, the Castle Hayne Formation and the underlying PeeDee Formation, were observed in these borings. All borings encountered soils of the Castle Hayne Formation. Only borings advanced greater than approximately 40 feet encountered the PeeDee. Stratigraphic analysis of the cores was confirmed at the nearby quarry at Rocky Point, approximately 3000' north of the study area.

Quarry exposures provided a greater spatial view of both the Castle Hayne and PeeDee Formations. Only three of the five depositional sequences of the middle Eocene Castle Hayne Formation are present within the vicinity of the study area (Harris, 2003). Sequences 1 and 2 (the basal sequences) are similar, composed of tan-grey, fine to medium grained bryzoan rich sand. In both sequences, these sands can thicken into large sand waves, on the order of 5 to 10 feet thick. Quarry exposures of these sand waves reveal them to be unlithified and completely unconsolidated. The underlying PeeDee Formation has been divided into two depositional sequences (Zullo and Harris, 1991). The upper sequence is a sandy, pelecypod-mold grainstone (sandy limestone), the lower is a massive, uncemented, dark greenish-grey fine-grained sand.

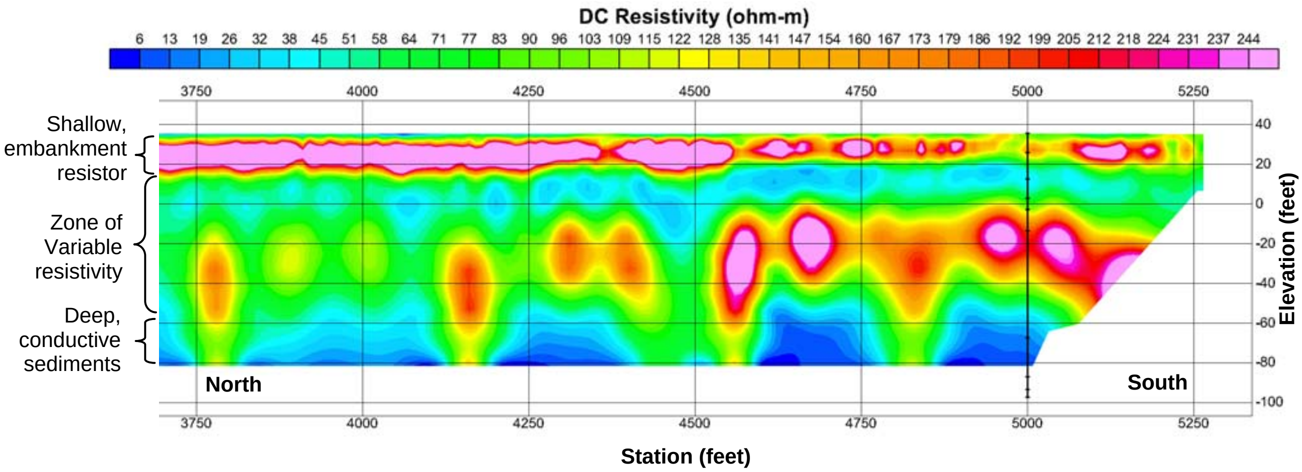

Figure 3: A portion of the 4172 foot profile of 2DRES data collected in the eastbound lane. Note the thickening to the north of the resistive layer associated with the roadway embankment, beginning at approximately Station 4550. South of this, an essentially continuous resistor begins at an elevation of approximately –5 feet. This resistor was interpreted to be competent substrate. Drilling confirmed well-cemented limestone at elevation –2 feet, at Station 5000.

Conclusions

Subsurface solution cavities leading to the development of surface depressions are limited, in this area, to within the 3000-foot long gravity low. This low appears to represent an erosional channel, within which the Rocky Point Limestone member of the PeeDee Formation is missing, and unconsolidated sands of the Castle Hayne directly overly sands of the PeeDee. The absence of the hard pelecypod-mold limestone may create a hydraulic conduit for groundwater flow. Large scale, unconsolidated sand waves within the lower Castle Hayne may not only act as hydraulic conduits, but may be particularly susceptible to dissolution.

References

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Zullo, V.A., and Harris, W.B., 1991, Eocene and Oligocene Stratigraphy of the Outer Coastal Plain, *in* Horton, J.W. Jr., and Zullo, V.A., eds., The Geology of the Carolinas, Carolina Geological Society Fiftieth Anniversary Volume, The University of Tennessee Press, p. 251-262.