CENTER FOR INFRASTRUCTURE ENGINEERING STUDIES

Ground-Penetrating Radar/Seismic Study—Branson/Springfield, Mo.

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16. Abstract

Acquire approximately 2000 feet of test GRP data using a low frequency antenna (120 MHz or lower). Data will be processed and interpreted in order to determine whether GPR can be used to image bedrock. If bedrock can be confidently imaged to a depth of 20 feet, will begin Phase II. If the GPR tool does not provide the necessary resolution, will proceed to Phase III. In Phase II, GPR data will be acquired along thirty-one, 2000 foot long, parallel profiles spaced at 50 feet. This data will be processed and interpreted, and used to generate a depth-to-bedrock map of the study area. In places, bedrock may not be imaged on GRP profiles, either because of poor data quality or because bedrock is too deep. Phase III, refraction seismic data will be acquired along a grid of twelve, 3000 foot long, parallel profiles spaced at 125 feet. Control on-line will be at 10-foot intervals.

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GROUND-PENETRATING RADAR AND SHALLOW REFLECTION SEISMIC STUDY OF KARSTIC DAMAGE TO I-44 EMBANKMENT, WEST SPRINGFIELD AREA, MISSOURI

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ABSTRACT

The University of Missouri-Rolla (UMR) conducted three geophysical surveys (1A, 1B and 2) for the Missouri Department of Transportation (MoDOT) along and adjacent to the study section of interstate I-44, west Springfield, Missouri. The goal was to establish the probable cause of ongoing subsidence and to locate undetected sub-pavement voids. In surveys 1A and 1B (May 1997), seven reflection seismic profiles and thirty ground-penetrating radar (GPR) profiles were acquired, respectively.

The interpretation of the reflection seismic data acquired in survey 1A indicated that the studied section of I-44 overlies three prominent karstic features. The interpretation of the GPR profiles acquired in survey 1B indicated the presence of isolated air-filled, sub-pavement voids in the immediate proximity of the westernmost karstic feature (in-filled sinkhole) identified on the seismic profiles. On the basis of this correlation and knowledge of karstic processes, the sub-pavement voids were attributed mostly to the piping of fine-grained soil into the westernmost karstic sinkhole. The sub-pavement voids identified on the GPR profiles were drilled and injected with grout.

In October of 1997, GPR survey 2 was conducted to ascertain the effectiveness of mitigation (grouting) efforts and to examine immediately adjacent sections of interstate. The interpretation of the survey 2 GPR profiles indicated that mitigation efforts have been successful, at least in the short term. No new sub-pavement voids were detected.

INTRODUCTION

In May of 1997, UMR conducted two geophysical surveys (1A and 1B) for MoDOT along and adjacent to a distressed section of Interstate I-44, in the West Springfield area, Missouri (Figures 1, 2, 3, 4 and 5). This 250 m section of I-44 partially overlies a man-made tunnel and has experienced gradual, but continual and visually-evident subsidence in areas bordering the paved roadway. Test borings revealed the presence of sub-pavement voids. The surrounding area shows visual evidence of karstic sinkholes. These subsidence features and sub-pavement voids were attributed to karst-related activity, as karstic sinkholes are prevalent in the surrounding area and the runoff waters that flow into the tunnel, drain rapidly through the fractured concrete floor. The sub-pavement voids were attributed to upward-propagating, piping-removal of embankment soil (i.e., washout of the fine-grained fraction of the embankment fill).

In survey 1A, seven reflection seismic profiles were acquired along or near the I-44 embankment (Figure 2). The goal was to map bedrock and identify structural trends in the area, with a view to determining the origin of the localized subsidence features and sub-pavement voids. In survey 1B, thirty GPR profiles were acquired across and along the shoulders of concrete-paved sections of I-44, in places immediately adjacent to minor subsidence features of relatively recent occurrence (Figures 2, 3, 4 and 5). The intent was to locate any sub-pavement voids.

In October 1997, the I-44 study site was revisited and survey 2 was conducted. A duplicate set of thirty GPR profiles (re: survey 1B) and twenty-five additional GPR profiles were acquired (Figures 3 and 4) to determine the effectiveness of the emergency grouting program, and whether substantive voids either remained or had developed between May and October.

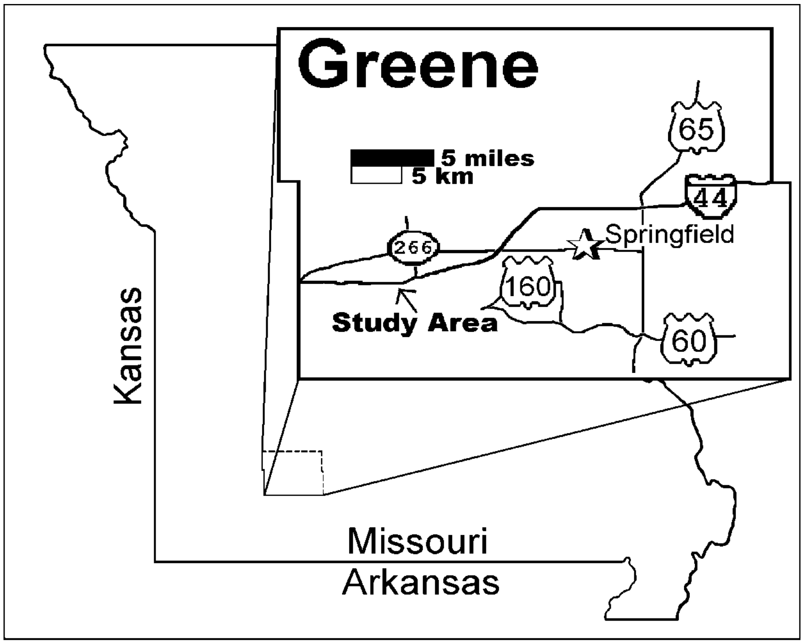


Figure 1: Map of Greene County, Missouri. The distressed section of Interstate I-44 is located in west Springfield, Missouri. The study area is characterized by active and paleo karstic sinkholes.

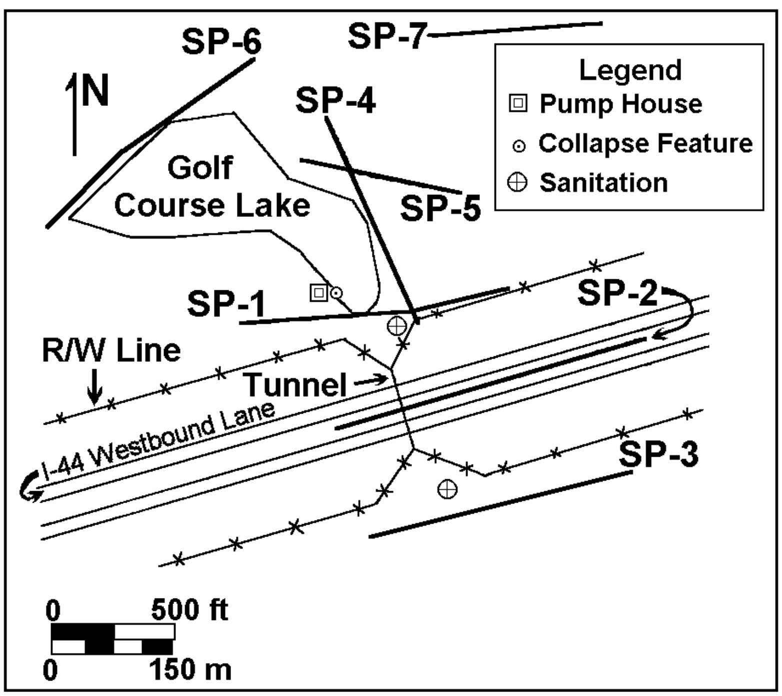


Figure 2: Map of study area, showing locations of seismic profiles SP-1 through SP-7 and GPR areas 1-6 (Figure 3). The distressed section of I-44 extends about 200 m from the eastern edge of the underlying golf course tunnel. This section of interstate has experienced continual and ongoing, localized, right-of-way, shoulder and median subsidence of probable karstic-origin. Test borings have revealed the presence of localized sub-pavement voids. The surrounding area shows visual evidence of karstic sinkholes.

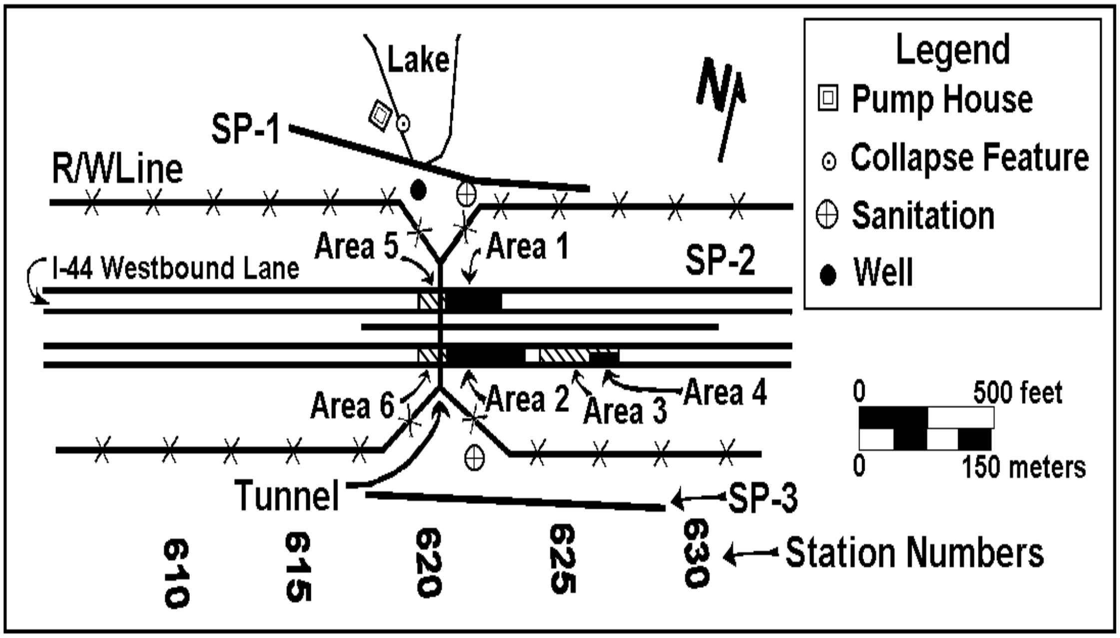


Figure 3*: GPR study areas 1-6 (Figure 4).*

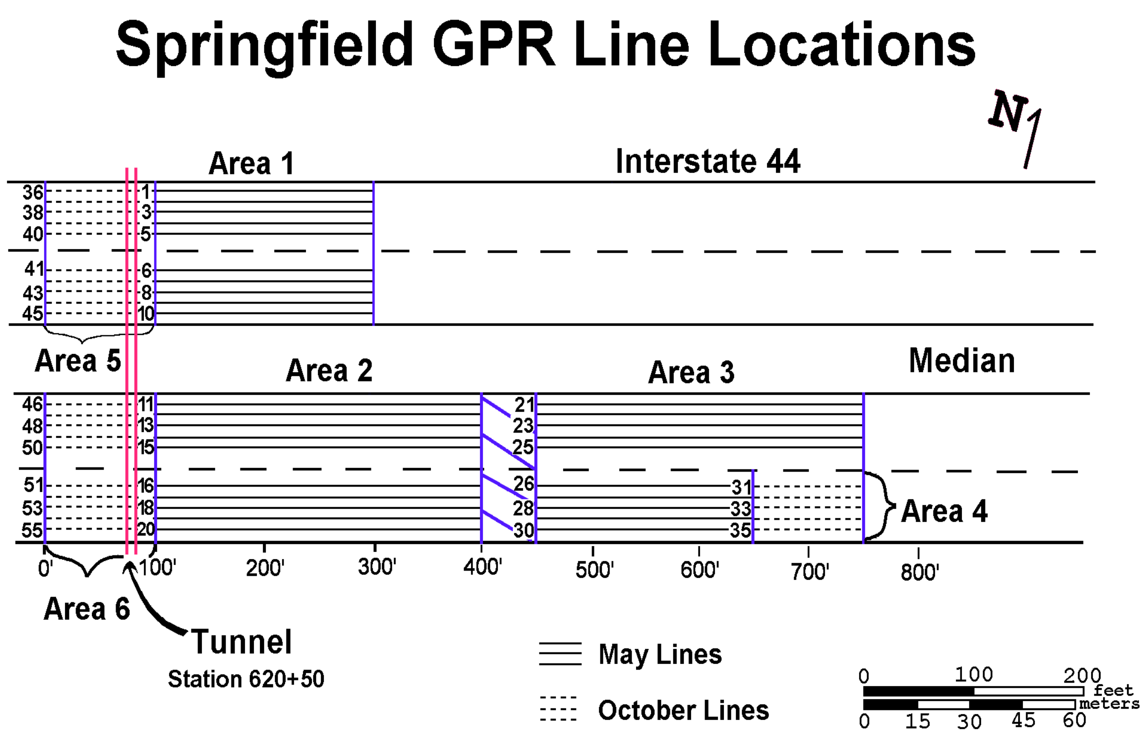


Figure 4*: Enlarged map of study area, showing locations of GPR areas 1–6 (Figure 3). Duplicate GPR profiles were acquired along traverses 1-30 in both May 1997 and October 1997. Data was acquired along traverses 31-55 only in October 1997.*

GEOLOGICAL OVERVIEW

Limestone bedrock in the embankment distress area is overlain by a thin veneer of soil (typically less than 10 m thick) and characteristically cut by persistent north-northwest trending joints. These fractures have provided conduits for vertically and laterally mobile waters since Pennsylvanian time. Area groundwater is slightly acidic and slowly leaches the limestone through which it flows. Over time, the structural integrity of the limestone bedrock can be compromised, but more importantly, the dissolution-widened joints have become in-filled with fine-grained sediment that is highly subject to removal by flowing groundwater. This is especially the case when new construction or development alters the local or site-area groundwater regime. Gradual to catastrophic collapse at bedrock level and surface subsidence can occur as a worst-case result (expressed as a reactivated paleo-karstic sinkhole).

At the time surveys 1A and 1B were conducted, MoDOT engineers were not aware that the distressed section of I-44 overlies two in-filled karstic sinkholes (sinkholes A and C; Figure 5) that were mostly in-filled at the time the Interstate and golf course tunnel were constructed (early 1970's). The presence and areal extent of this in-filled (and apparently reactivated paleo-karstic sinkhole) was discovered only when pre-construction topographic maps (Figure 6) were examined and compared to the seismic bedrock map generated during the course of this study. These pre-construction topographic maps and geologic field mapping support the interpretation of the reflection seismic data presented herein.

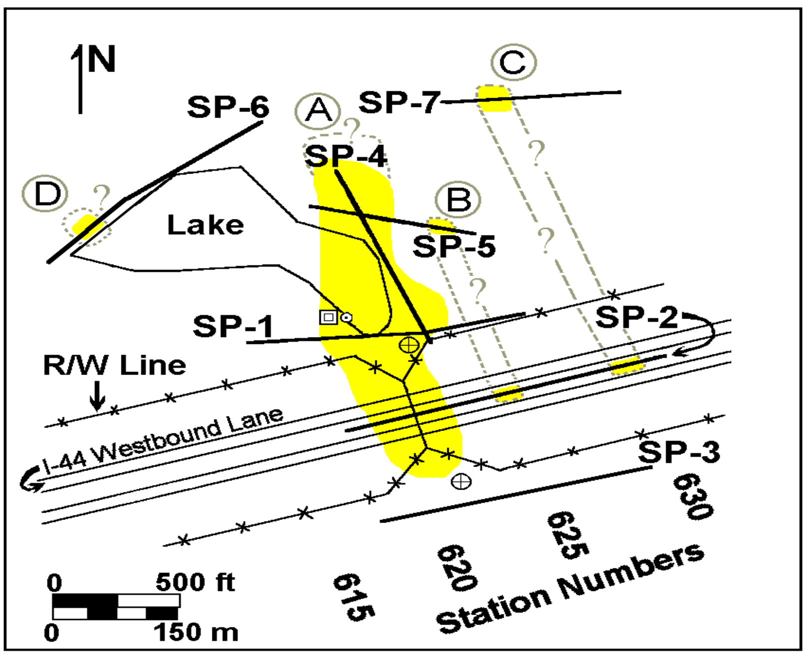


Figure 5: *Map of study area, showing interpreted aerial extent of karstic features A through D.*

REFLECTION SEISMIC EQUIPMENT AND FIELD ACQUISITION PARAMETERS

Seven reflection seismic lines 1 (SP-1 through SP-7; Figures 2 and 5) were acquired using a 24-channel Bison Engineering Seismograph with roll-a-long capabilities, single 40 Hz geophones, and an EWG weight drop source. Source and receiver intervals were 3 m, resulting in nominally 12-fold data. The near offset was 3 m. The weight drop source was impacted 6 to 10 times per shot record, dependent upon visual inspection of background noise on the shot gathers. Elevation control was acquired for each source and geophone location.

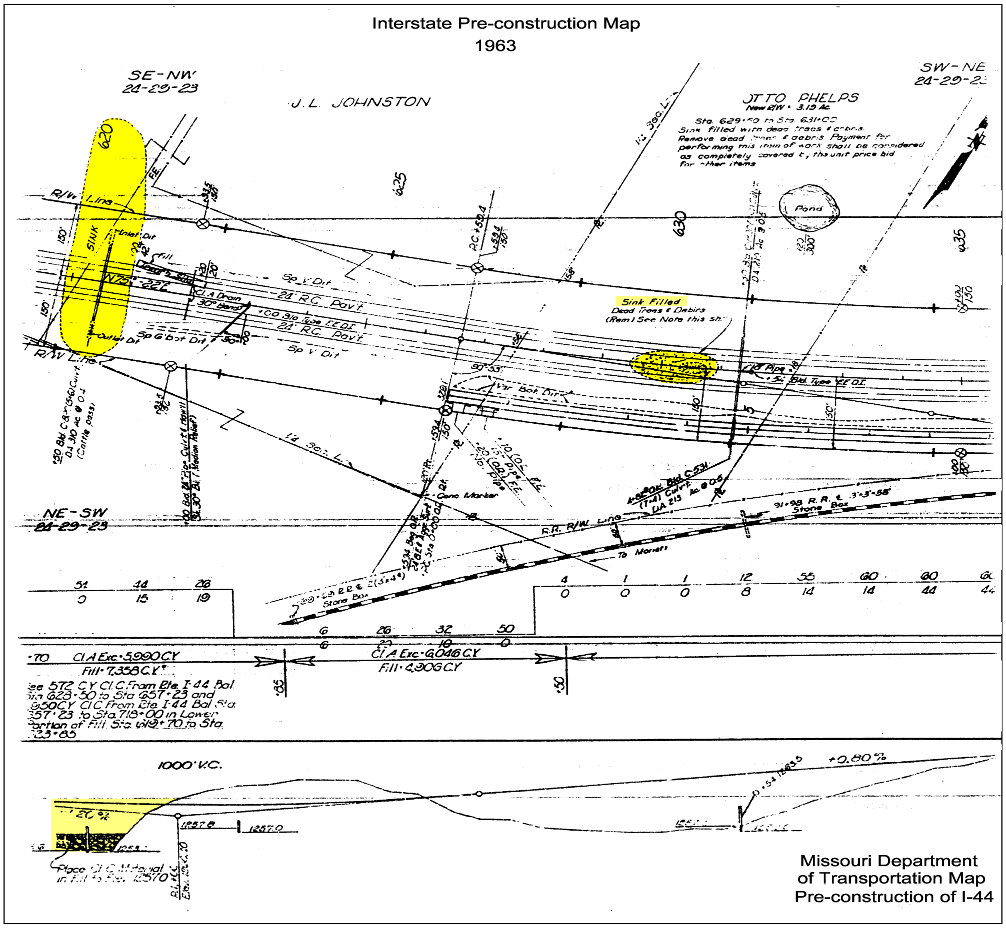


Figure 6: *Pre-construction (1963; refer to Figure 5) topographic map showing the areal extent of interpreted sinkhole A (extreme left) and sinkhole C (right center). These sinkholes were in-filled with embankment materials during highway construction.*

REFLECTION SEISMIC DATA PROCESSING

The reflection seismic data were processed on a pentium PC using WINSEIS, a commercial processing package developed exclusively for high-resolution reflection seismic data. A fairly standard processing run-stream was applied to the data. The processing routine consisted of:

1. Muting of first breaks and excessive ground roll.
2. Re-sorting the shot gathered traces into common midpoint (CMP) gathers.
3. Application of elevation corrections.
4. Determining appropriate velocity/time functions along the seismic traverses.
5. Application of normal moveout (NMO) corrections to CMP gathered traces.
6. Stacking the NMO corrected data.
7. Application of residual statics.
8. Re-stacking statically corrected data.
9. Post-stack bandpass filtering of data.

INTERPRETATION OF REFLECTION SEISMIC DATA

The locations of the seven reflection seismic profiles are shown in Figures 2 and 5. The reflection from bedrock has been correlated across these seismic profiles. Significant bedrock structural lows are interpreted on several of the profiles. These depressions in the bedrock surface are interpreted as karstic collapse, as opposed to top-of-rock erosional features. The more significant seismic interpretations have been superposed on the site basemap, itself prepared by MoDOT District surveyors (Figure 5).

On the basis of our interpretation of the reflection seismic data, we have identified and mapped several partially in-filled karstic sinkholes in the study area, some of which have been reactivated since the interstate was constructed. The most significant of these are denoted as sinkhole features A, B, C, and D on Figure 5.

The distressed section of I-44 overlies one prominent karstic feature (sinkhole A; Figures 5 and 6) and two less prominent karstic features (B and C; Figures 5, 6, 7 and 8). According to the pre-construction topographic map (Figure 6), feature A is an elongate, north-northwest trending karstic sinkhole, the southern part of which was mostly in-filled with embankment materials when the Interstate and golf course tunnel were constructed. The northern section was selected as a topographic low for the 1993-placement of the nearby golf-course irrigation pond and earth-fill dam (Figure 5). The interpretation of lines SP-1 (Figure 7) and SP-3 suggests that the karstic sinkhole extends southward beneath the Interstate, but that it does not extend across profile SP-3 (Figure 8). This interpretation is consistent with the pre-construction topographic maps (Figure 6).

Karstic feature B is imaged on seismic profiles SP-5 (Figure 5). The shear zone system along which sinkhole B developed appears to extend beneath the interstate (Figures 5 and 7).

Karstic sinkhole C is imaged on seismic profiles SP-2 and SP-7 (Figure 5). It is characterized by recent surface subsidence immediately adjacent to profile SP-7, however sub-pavement voids were not detected along I-44 immediately in the immediate vicinity of feature C. There is no evidence to suggest sinkhole C has been reactivated in the immediate vicinity of I-44, or that it constitutes a potential long-term threat (re: highway stability).

Active sinkhole D is manifested as recent collapse features (mapped in field studies), and is imaged on profile SP-6 (Figure 5). The shear zone systems along which this sinkhole developed could extend beneath the interstate, however, neither surface subsidence nor evidence of sub-pavement voids have been observed along the projected south-southeast extension of this sinkhole, and further investigation at this time is probably not warranted.

The correlation between areas of surface distress and seismic evidence of karstic sinkhole development, supports our interpretation that distress is caused by the downward seepage of run-off waters through the highway median, and possibly pond leakage from the unlined golf course lake. The sub-pavement voids are attributed to the upward-propagating, piping-removal of embankment soil (i.e., washout of the fine-grained fraction of the embankment fill) mostly through karstic feature A.

GPR EQUIPMENT AND FIELD ACQUISITION PARAMETERS

In May of 1997 (survey 1B), thirty GPR profiles were acquired along paved sections of Interstate 44, in places immediately adjacent to recent subsidence features (lines 1-30; areas 1, 2 and 3; Figures 4 and 9). The intent was to image the shallow subsurface to a depth of about 3 m, to detect possible piping voids. In October of 1997, the study site was revisited (survey 2) and a duplicate set of 30 ground-penetrating radar profiles and 25 additional GPR lines were acquired (lines 31-55; areas 4, 5 and 6; Figure 4). The duplicate set of 30 profiles was acquired to determine the effectiveness of the grouting program and to determine if any new piping voids had developed since the May survey. The 25 additional lines were acquired to extend GPR control into previously untested areas, with a view to identifying any voids (if present).

A GSSI SIR-8 GPR unit equipped with a 500 MHZ mono-static antenna was used to acquire the survey 1B and survey 2 GPR data (Figure 4). The sampling interval was 50 scans/m. The trace length was 50ns, providing for depth penetration on the order of 3 m.

GPR DATA PROCESSING

The GPR data were processed on a pentium PC using RADAN, a commercial processing package developed exclusively for ground-penetrating radar data. A fairly standard processing runstream was applied to the GPR data. The processing routine consisted of:

1. Trace normalization.
2. Application of vertical gain.
3. Horizontal filtering.
4. Vertical filtering.

INTERPRETATION OF GPR PROFILES

Two sets of GPR data (surveys 1B and 2) were acquired at the subsidence site, Interstate 44, Springfield Missouri. In survey 1B, thirty GPR profiles were acquired along paved sections of Interstate 44, in places immediately adjacent to recent subsidence features (profiles 1-30; Figures 4 and 9). On the basis of the interpretation of these data, MoDOT personnel were able to locate voids that had developed beneath the pavement (as a result of the washout of fine-grained sediment), and devise an effective grouting plan. Sub-pavement voids are characterized by high amplitude events on the GPR profiles (Figure 9). All areas designated as anomalous (i.e., overlying sub-pavement voids) accepted grout.

In October of 1997, geophysical survey 2 was conducted. A duplicate set of thirty ground-penetrating radar profiles and twenty-five additional GPR profiles were acquired (Figures 3 and 4). The duplicate set of GPR profiles was acquired with a view to ascertain the effectiveness of the grouting program and determine if any new voids had developed since the May survey. The 25 additional lines (lines 31-55; areas 4, 5 and 6; Figure 4) were acquired to extend GPR control into previously untested areas, with a view to identifying any substantive voids. The interpretation of these survey 2 data suggests that the grouting program effectively in-filled most of the previously imaged sub-pavement voids. No new, prominent GPR anomalies were observed on either the duplicate data set (30 lines) or the newly acquired coverage (25 profiles across previously untested areas).

An example set of original and duplicate GPR profiles is shown as Figure 9. The high-amplitude diffractions observed on the survey 1B data set, are conspicuously absent on the survey 2 data set, suggesting that the grouting program effectively in-filled the sub-pavement voids.

SUMMARY

Geophysical surveys 1A and 1B were successful. The interpretation of the reflection seismic profiles established that the distressed section of I-44 overlies a previously in-filled, north-northwest trending, apparently reactivated karstic sinkhole, and other karstic features. The correlation between areas of surface distress and seismic evidence of karstic sinkhole development, supports our interpretation that distress is caused by the downward seepage of run-off waters through the highway median, and possibly pond leakage from the unlined golf course lake. The sub-pavement voids are attributed to the upward-propagating, piping-removal of embankment soil (i.e., washout of the fine-grained fraction of the embankment fill) mostly through karstic feature A.

The GPR technique proved useful in locating sub-pavement voids. MoDOT maintenance personnel drilled into these piping voids and injected grout, in an effort to stabilize the roadway embankment.

Survey 2 was also successful. The interpretation of the duplicate profiles suggested that the emergency grouting program had been effective, and that no substantive voids either remained or had developed between May and October. No new, prominent GPR anomalies were observed on the twenty-five newly acquired GPR profiles.

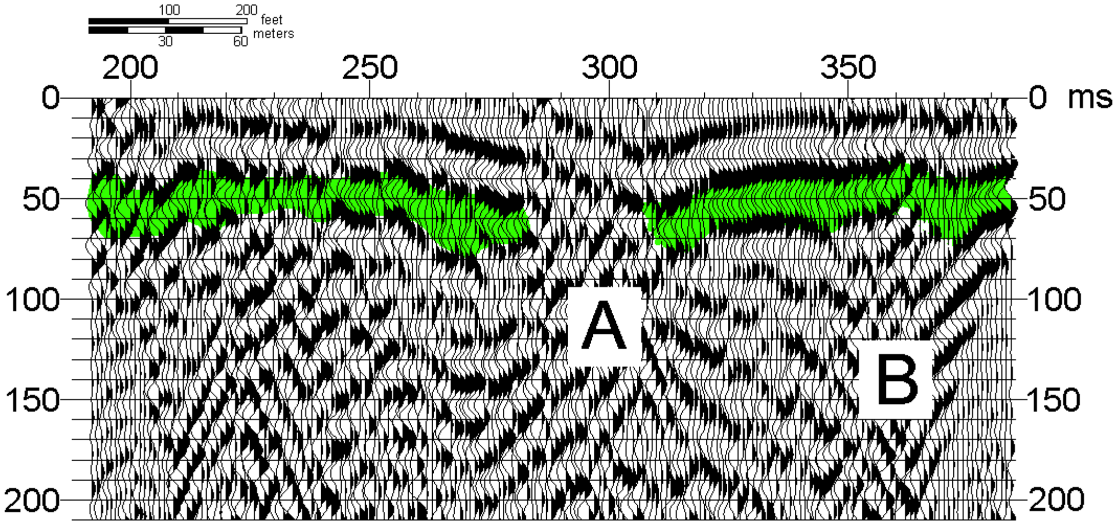


Figure 7: *Reflection seismic profile SP-1 (Figure 5).*

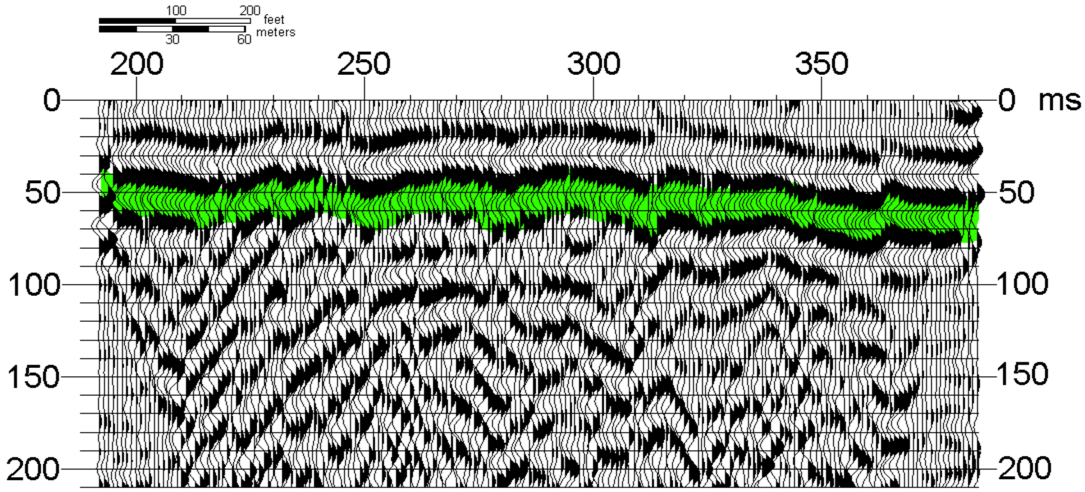


Figure 8: *Reflection seismic profile SP-3 (Figure 5).*

CONCLUSIONS

On the basis of our site inspections, our knowledge of the area, and our integrated interpretation of the geophysical data, we conclude that the tested section of Interstate overlies two reactivated karstic sinkholes (sinkholes A and B). The gradual, but continual and visually-detectable subsidence in areas bordering the paved roadway in the study area and the sub-pavement voids, are attributed to the upward-propagating, piping-removal of embankment soil (i.e., washout of the fine-grained fraction of the embankment fill) through this sinkhole. As far as the sub-pavement voids are concerned, we believe that the grouting program has effectively stabilized the shallow subsurface in the short term. Long-term mitigation should involve the redirection of surface run-off waters away from the median in the distress area and the underlying tunnel.

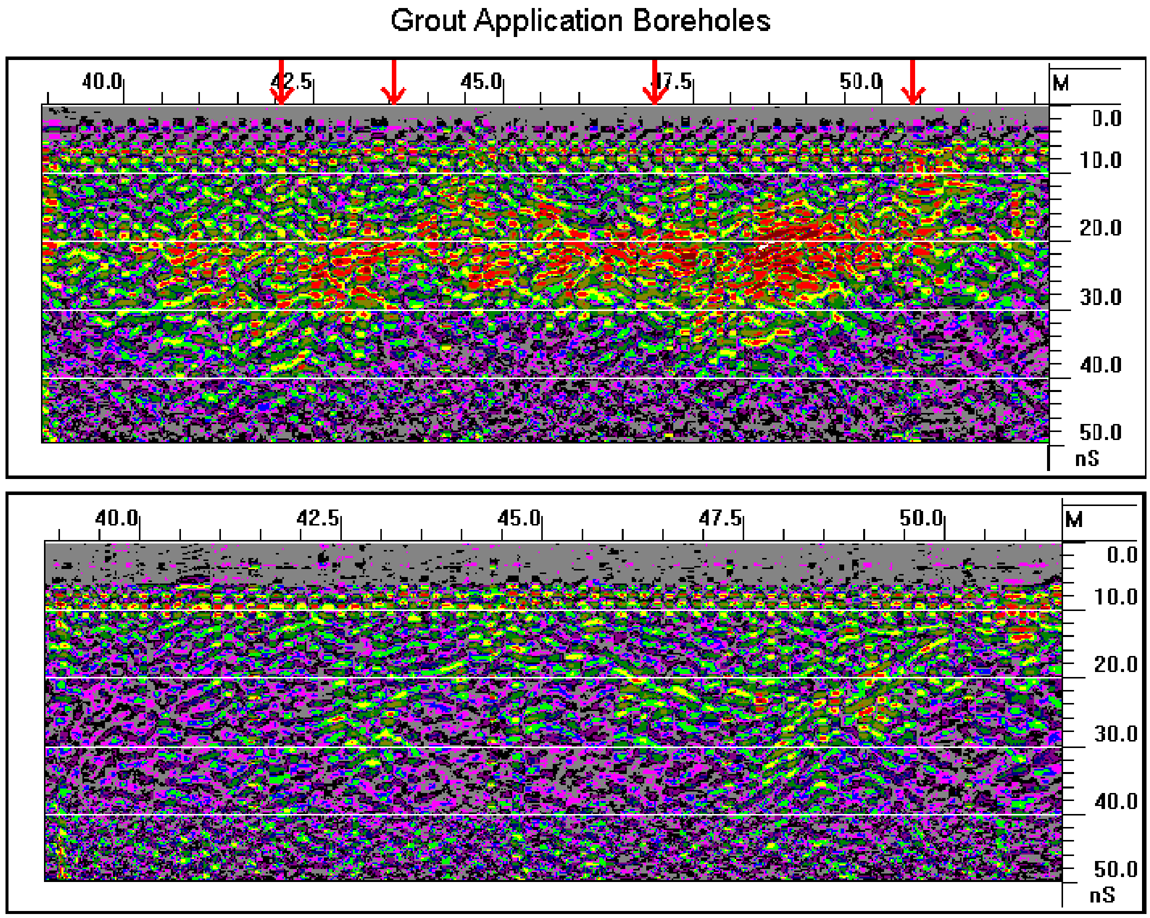
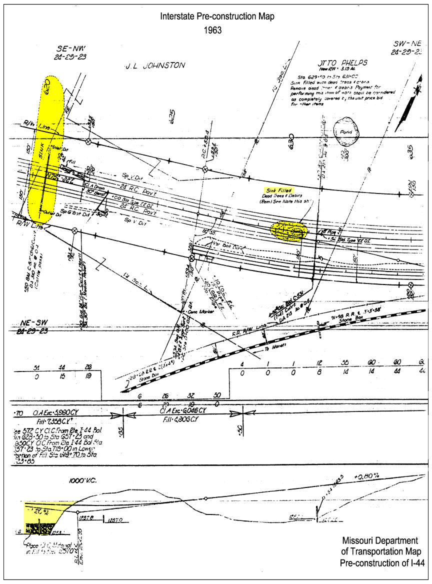


Figure 9*: Survey 1B (upper) and survey 2 (lower) segments of GPR profile 2 (Area 1; Figure 3 and 4). Interpreted sub-pavement voids are characterized by high amplitude, prominent diffraction patterns on the upper GPR profile (survey 1B data). These diffractions are conspicuously absent on the lower GPR profile (survey 2 data), suggesting that the grouting program effectively in-filled the identified sub-pavement voids. The vertical arrows depict the locations of grout application boreholes.*

Sequence 50: Ground-Penetrating Radar/Seismic Study-Branson/Springfield, MO



Interstate Pre-construction Map
1963

Missouri Department
of Transportation Map
Pre-construction of I-44