MoDOT

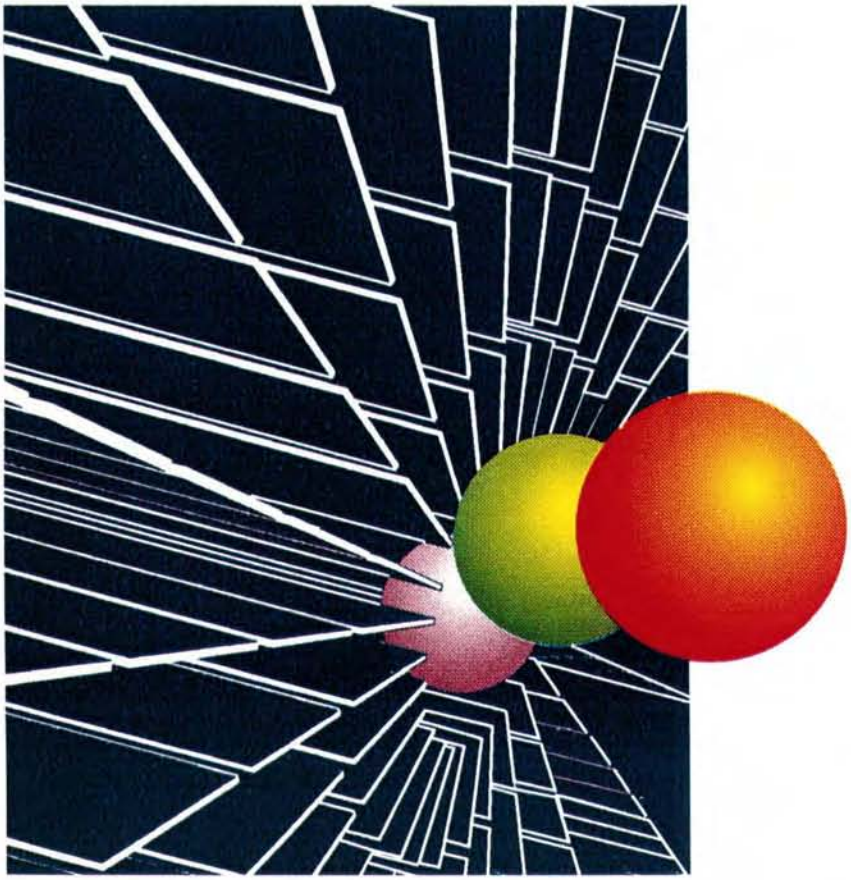
TE211
.N49
1998
c.2

DOT

Research, Development and Technology Division

RDT 98-004

Application of Innovative Geophysical Methods for Subgrade Investigations in Karst Terrain



Property of
MoDOT TRANSPORTATION LIBRARY

November, 1998

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
RDT-98-004		

4. Title and Subtitle	5. Report Date
Application of Innovative Geophysical Methods for Subgrade Investigations in Karst Terrain (Nondestructive Testing)	November 1998
	6. Performing Organization Code UMR & MoDOT
7. Author(s) Tim Newton, Dr. Neil Anderson, Dr. Allen Hatheway	8. Performing Organization Report No. RDT-98-004, RI97-028,SPR97-7
9. Performing Organization Name and Address University of Missouri Rolla, Department of Geology and Geophysics 125 McNutt Hall Rolla, Missouri 65409-0410	10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Missouri Department of Transportation Research, Development & Technology Division P.O. Box 270, Jefferson City, MO 65102	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code MoDOT

15. Supplementary Notes

The investigation was conducted by the University of Missouri Rolla in cooperation with the Missouri Department of Transportation

16. Abstract

Geophysical surveys were conducted for the Missouri Department of Transportation (MoDOT) by the Department of Geology and Geophysics at the University of Missouri-Rolla to determine the most probable cause or causes of ongoing subsidence along a distressed section of Interstate 44 in Springfield, Missouri.

Ground penetrating radar (GPR) and reflection seismic quickly assessed roadway and subsurface conditions with nondestructive, continuous profiles. The GPR proved to be of useful utility in defining upward-propagating voids in embankment fill material. The reflection seismic survey established the presence of reactivated paleosinkholes in the area. These were responsible for swallowing the fill material as water drained through the embankment.

On the basis of interpretation of these data, MoDOT personnel were able to drill into the voids that had developed beneath the pavement (as a result of washing out of the fine-grained material of the embankment fill), and to devise an effective grouting plan for stabilization of the roadway.

17. Key Words	18. Distribution Statement
ground penetrating radar, reflection seismic, karst, subsidence, voids, sinkhole, nondestructive testing, geophysics, subgrade investigation	No restrictions. This document is available to the public through National Technical Information Center, Springfield, VA 22161

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	29	

Form DOT F 1700.7 (06/98)

Application of Innovative Geophysical Methods for Subgrade Investigations in Karst Terrain

FINAL REPORT

RDT 98-004
Research Investigation 97-028

PREPARED BY

MISSOURI DEPARTMENT OF TRANSPORTATION

MATERIALS DIVISION

By

Tim Newton
Geotechnical Liaison

Dr. Neil Anderson
Professor of Geophysics
University of Missouri - Rolla

Dr. Allen Hatheway
Professor of Geological Engineering
University of Missouri - Rolla

November, 1998

The opinions, findings, and conclusions expressed in this publication
are those of the Missouri Department of Transportation

ACKNOWLEDGMENTS

It was the wish of MoDOT that as many "stakeholder" players as possible be included in the deliberations involving this investigation. Many state agencies and their personnel cooperated by providing input and expertise on the area being examined for this project. These welcome participants are listed below.

Dr. Neil Anderson, Professor, Department of Geology and Geophysics, University of Missouri at Rolla

Ms. Cynthia Brookshire, Prof. Geologist, Division of Geology and Land Survey

Mr. Jimmy Brown, Prof. Geologist, Division of Geology and Land Survey

Mr. Mike Descamps, MoDOT Maintenance Chief

Mr. Mike Fritz, P.E., MoDOT Soils & Geology Section Director

Mr. Gary Goessmann, Prof. Geologist, MoDOT

Dr. Allen Hatheway, P.E., Professor, Department of Geological and Petroleum Engineering, University of Missouri at Rolla

Mr. Joe Kelly, MoDOT Maintenance Worker

Mr. Tim Newton, EIT, MoDOT Geotechnical Liaison

Mr. Tim Smith, P.E.,Greene County Resource Management Director

Dr. Kenneth Thompson, Professor, Department of Geology, Southwest Missouri State University

ABSTRACT

Geophysical surveys were conducted for the Missouri Department of Transportation (MoDOT) by the Department of Geology and Geophysics at the University of Missouri-Rolla to determine the most probable cause or causes of ongoing subsidence along a distressed section of Interstate 44 in Springfield, Missouri. The Springfield area is associated with sinkholes and karst terrain. This particular section of highway had experienced gradual, but continual subsidence that was visually detectable on the both the shoulders and median. A sudden 1 meter diameter, 2.5 meter deep collapse on the shoulder signified the need of a rapid subgrade assessment procedure to ensure the safety of the traveling public. Ground penetrating radar (GPR) and shallow reflection seismic technologies were applied to the site immediately.

GPR and reflection seismic quickly assessed roadway and subsurface conditions with nondestructive, continuous profiles. They expedited both the investigation and mitigation of karst related voids. The geophysical surveys were successful. The GPR proved to be of useful utility in defining upward-propagating voids in embankment fill material. On the basis of interpretation of these data, MoDOT personnel were able to drill into the voids that had developed beneath the pavement (as a result of washing out of the fine-grained material of the embankment fill), and to devise an effective grouting plan for stabilization of the roadway.

The reflection seismic survey established the presence of reactivated paleosinkholes in the area, that had developed along essentially north-northwest trending fault/fracture zones. These were responsible for swallowing the fill material as water drained through the embankment. The site was later revisited for confirmation of the effectiveness of the stabilization of the grouting plan. Duplicate GPR profiles were acquired and indicated that the grouting program had been effective and that no substantial voids had developed in the interim.

Table of Contents

	Page
Acknowledgments	i
Abstract	ii
Table of Contents	iii
List of Figures	iv
Preface	v
Introduction	1
Design of the Geophysical Exploration Program	3
Geological Overview	3
Reflection Seismic Equipment and Field Acquisition Parameters	5
Reflection Seismic Data Processing	5
Interpretation of Reflection Seismic Data	5
Ground Penetrating Radar Equipment and Parameters	11
Ground Penetrating Radar Data Processing	11
Interpretation of Ground Penetrating Data	11
Geophysical Conclusions	16
MoDOT Conclusions	20
Implementation / Recommendations	21
Appendix A - Geologic Situation Leading To The Phenomenon	22
Appendix B (Photographs)	25

List of Figures

	Page
Figure 1: Location of study area, along I44, Springfield Missouri.	1
Figure 2: Map of study area, showing locations of the reflection seismic lines SP-1through SP-7.	2
Figure 3: Map of study area. The locations of the GPR areas 1 through 6 are shown.	3
Figure 4: Map of study area. The locations of GPR areas through 6 are shown. Data was acquired along lines 1-30 in May 1997, and again in October 1997. Data was acquired along lines 31-55 only in October 1997 (Survey 2).	4
Figure 5: Map of area. The interpretation of the reflection seismic data has been superposed on this base map.	6
Figure 6: Reflection seismic Profile SP-1.	7
Figure 7: Reflection seismic Profile SP-2.	7
Figure 8: Reflection seismic Profile SP-3.	8
Figure 9: Reflection seismic Profile SP-4.	8
Figure 10: Reflection seismic Profile SP-5.	9
Figure 11: Reflection seismic Profile SP-6.	9
Figure 12: Reflection seismic Profile SP-7.	10
Figure 13: Map of GPR study area 1. Locations of ground-penetrating profiles 1-10, with associated GPR anomalies.	12
Figure 14: Map of GPR study area 2. Locations of ground-penetrating profiles 11-20, with associated GPR anomalies.	12
Figure 15: Map of GPR study area 3. Locations of ground-penetrating profiles 21-30, with associated GPR anomalies.	12
Figure 16: May and October versions of ground-penetrating radar profile 2 (Area 1; Figure 12). The upper GPR profile was acquired in May, the lower profile in October. Grout application borehole locations are shown.	13
Figure 17: May and October versions of ground-penetrating radar profile 4 (Area 1; Figure 12). The upper GPR profile was acquired in May, the lower profile in October. Grout-application borehole locations are shown.	14
Figure 18: May and October versions of ground-penetrating radar profile 5 (Area 1; Figure 12). The upper GPR profile was acquired in May, the lower profile in October. Grout-application borehole locations are shown.	15
Figure 19: Burden of Proof - Pre-construction drawing of area.	19

PREFACE

This project presented itself as a need for innovative methods to quickly assess the potential of roadway collapse or subsidence in a near-crisis situation. Indications were that sufficient amounts of roadway fill and natural soil below had been removed by a form of "piping". The net result appeared to be internal erosion of the foundation fill soils infilling karstic dissolution features in the highly erodable limestone. This growing network of voids appeared to be migrating upward through the highway embankment to the concrete pavement itself. This created the potential for roadway subsidence and threatened public safety.

The vitality of interstate highways makes timely and accurate investigative data essential to protect the traveling public and to keep the roads open. The implications of karstic subsidence attracted the interests of many government agencies, all of which approached MoDOT with a willingness to assist. These include Greene County, Missouri Department of Natural Resources, and University of Missouri at Rolla personnel. A voluntary site visit by the University of Missouri-Rolla showed immediately that ground penetrating radar had potential use as an investigative tool for locating voids under the roadway. This was worth researching.

GROUND-PENETRATING RADAR (GPR) AND SHALLOW REFLECTION SEISMIC SURVEYS FOR MITIGATION OF KARSTIC DAMAGE TO I-44, SPRINGFIELD, MISSOURI

INTRODUCTION

In May of 1997, the Department of Geology and Geophysics at the University of Missouri-Rolla (UMR) conducted two reconnaissance-type geophysical surveys for the Missouri Department of Transportation (MoDOT) along and adjacent to a distressed section of Interstate 44, at Springfield, Missouri (Figure 1). This particular section of Interstate had experienced gradual, but continual and visually-detectable subsidence. Such subsidence was thought to be somehow related to the visual evidence of paleokarst features in the surrounding area. In Geophysical Survey 1A, seven (7) reflection seismic profiles were acquired (Figures 2). In Geophysical Survey 1B, thirty (30) ground-penetrating radar profiles were acquired (Figures 3 and 4). These data were processed at UMR, and interpreted by UMR researchers in consultation with Newton, Goessmann and other MoDOT staff.

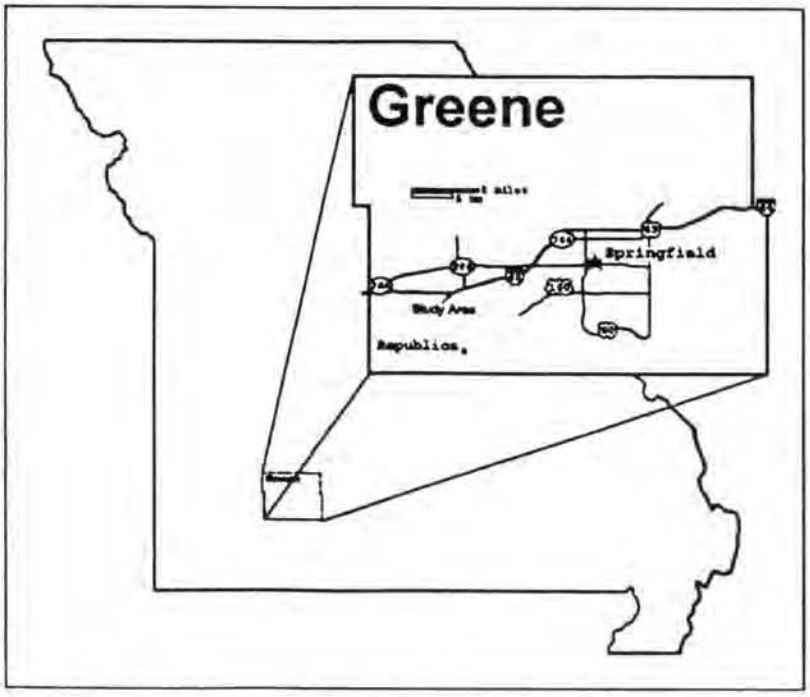


Figure 1: Location of study area, along I44, Springfield Missouri.

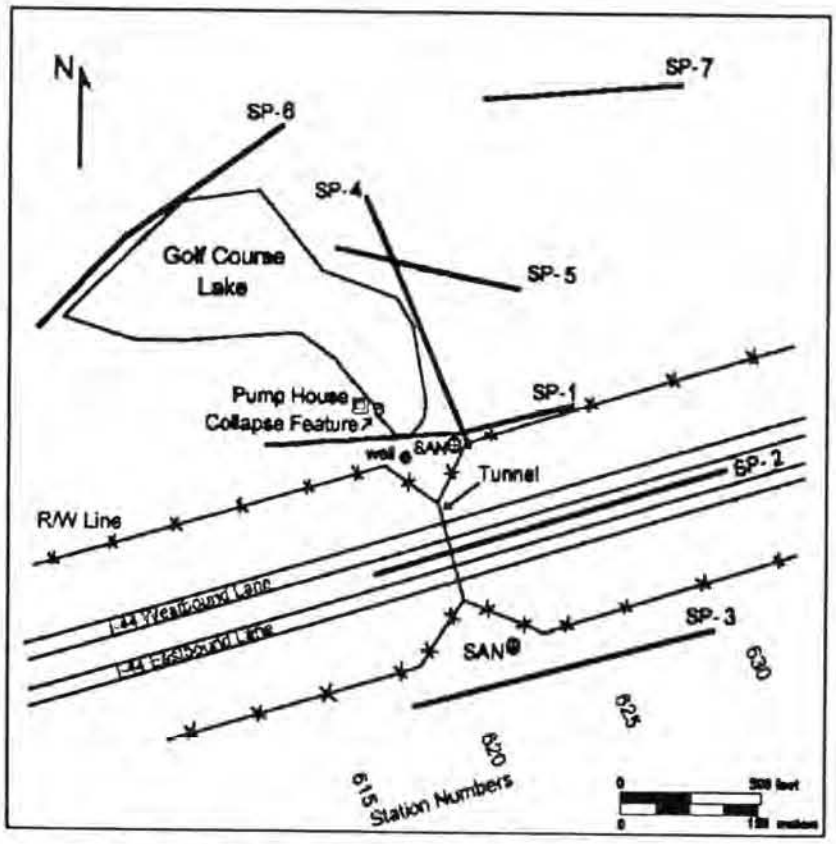


Figure 2: Map of study area, showing locations of the reflection seismic lines SP-1through SP-7.

In Survey 1A, seven reflection seismic profiles were acquired along and near the Interstate 44. The intent was to image the shallow subsurface (especially bedrock) to a depth of about 60 m. The goal was to identify structural / lithologic patterns in the area, with a view to better understanding the origin of the subsidence features along the right-of-way (ROW). In Survey 1B, 30 ground penetrating radar profiles were acquired along the concrete-paved sections of Interstate 44. The intent was to image the shallow subsurface to a depth of about 4 m. The goal was to identify any voids beneath the lengths of the GPR profiles.

Geophysical surveys 1A and 1B were successful. The reflection seismic survey established that there are reactivated paleosinkholes in the area, and that these had developed along essentially north-northwest trending fault/fracture zones. The ground-penetrating radar also proved to be a useful utility in defining upward-propagating voids in embankment fill material. On the basis of the interpretation of these data, MoDOT personnel were able to drill into the voids that had developed beneath the pavement (as a result of the washing out of the fine-grained material of the embankment fill), and to devise an effective grouting plan for stabilization of the roadway.

In October 1997, the study site was revisited for confirmation of the effectiveness of the stabilization of the grouting plan. At this time, a duplicate set of 30 ground-penetrating radar profiles and 25 additional GPR lines were acquired (Survey 2). The interpretation of the duplicate profiles suggested that the grouting program had been effective, and that no substantial voids had developed between May and October. No new, prominent GPR anomalies were observed on the newly acquired coverage (25 profiles across previously untested areas).

DESIGN OF THE GEOPHYSICAL EXPLORATION PROGRAM

Geophysical surveys 1A and 1B were conducted with two specific objectives in mind:

Objective 1: The seven high-resolution reflection seismic profiles (Figure 2) were acquired along or near Interstate 44 (in places immediately adjacent to observable ground-surface distress). The intent was to image the shallow subsurface (especially bedrock) to a depth of about 60 m. The goal was to identify any structural/geologic patterns in the area, that might prove to be linked with the disruption visible at the ground surface.

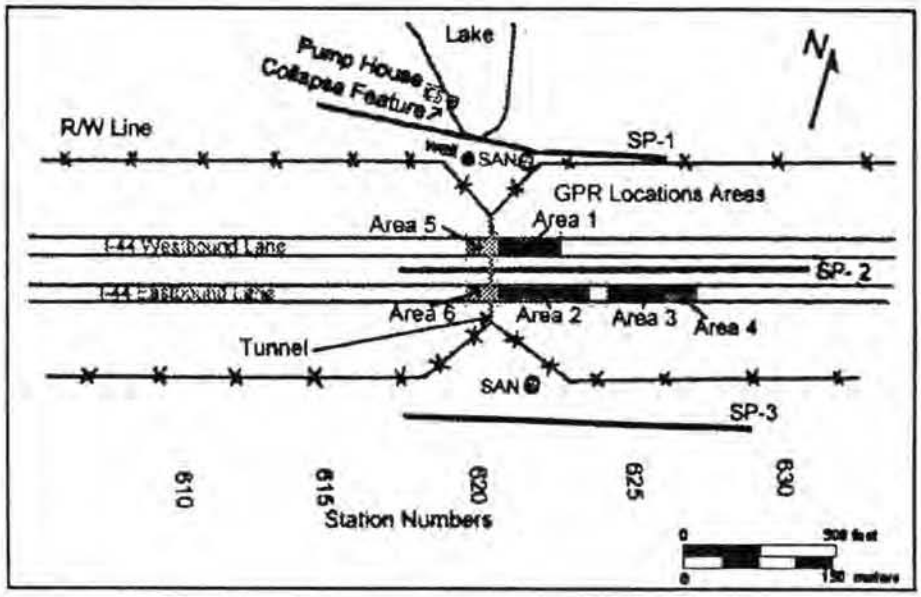


Figure 3: Map of study area. The locations of the GPR areas 1 through 6 are shown.

Objective 2. The ground-penetrating radar (GPR) profiles (Figures 3 and 4) were acquired along paved sections of Interstate 44 (in places immediately adjacent to recent subsidence features). The intent was to image the shallow subsurface to a depth of about 4 m and to identify any sub-pavement voids. The intent of MoDOT personnel was to drill and grout any areas designated as sub-pavement voids.

GEOLOGICAL OVERVIEW

Limestone bedrock in the distress areas is characteristically cut by persistent north-northwest trending joints/fractures. These joints/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 can become infilled with fine- grained sediment that is highly subject to removal by flowing groundwater. When new development alters the local groundwater regime, these fine-grained sediments can be removed. Additionally, gradual to catastrophic collapse at bedrock and surface subsidence can occur (expressed as a reactivated paleokarst sinkhole).

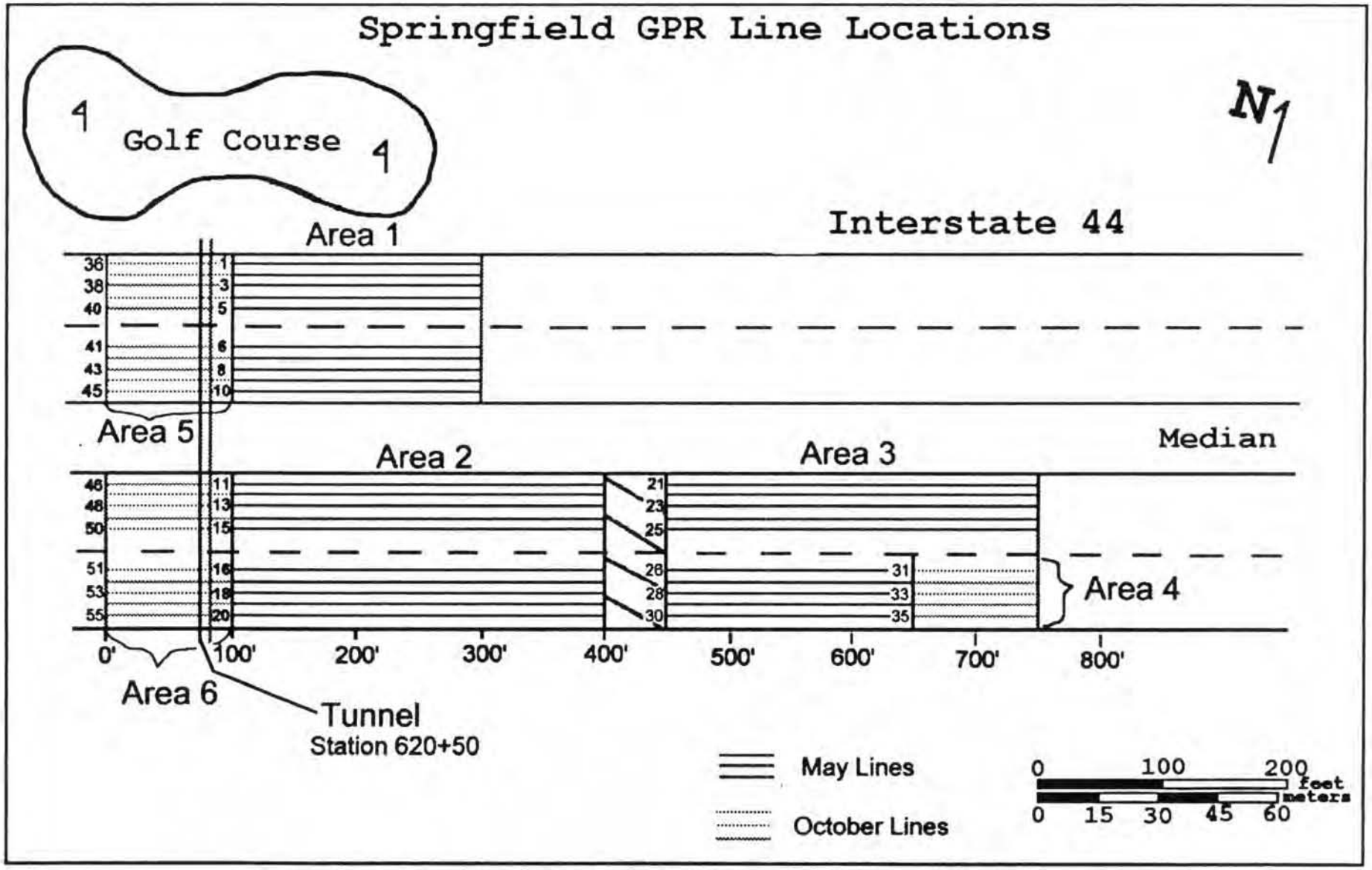


Figure 4: Map of study area. The locations of GPR areas through 6 are shown. Data was acquired along lines 1-30 in May 1997, and again in October 1997. Data was acquired along lines 31-55 only in October 1997 (Survey 2).

REFLECTION SEISMIC EQUIPMENT AND FIELD ACQUISITION PARAMETERS

Seven reflection seismic lines 1 (SP-1 through SP-7; Figure 2) 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. Each source location was used once with a near offset of 6 m, resulting in nominally 12-fold data. 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.

REFLECTION SEISMIC DATA PROCESSING

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

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

INTERPRETATION OF REFLECTION SEISMIC DATA

The locations of the seven reflection seismic profiles (Figures 6-12) are shown in Figure 2. The reflection from bedrock has been correlated across these seismic profiles. Significant bedrock

Structural lows are interpreted on several of the profiles (Figures 6, 7, 9, 10 and 12). The depressions in the bedrock surface are interpreted as karstic, as opposed to top-of-rock erosional features. The more significant seismic interpretations have been superposed on the site basemap, itself prepared by District surveyors (Figure 5).

On the basis of our interpretation of the reflection seismic data, we have identified and mapped several apparent, hidden sinkholes in the study area, some of which have been active recently. The most significant of these are denoted as Sinkhole Features A, B, C and D on Figures 6-12 . We have also identified two possible shear zones or clusters of closely spaced rock joints immediately beneath the tested segment of Interstate (F and G; Figure 7).

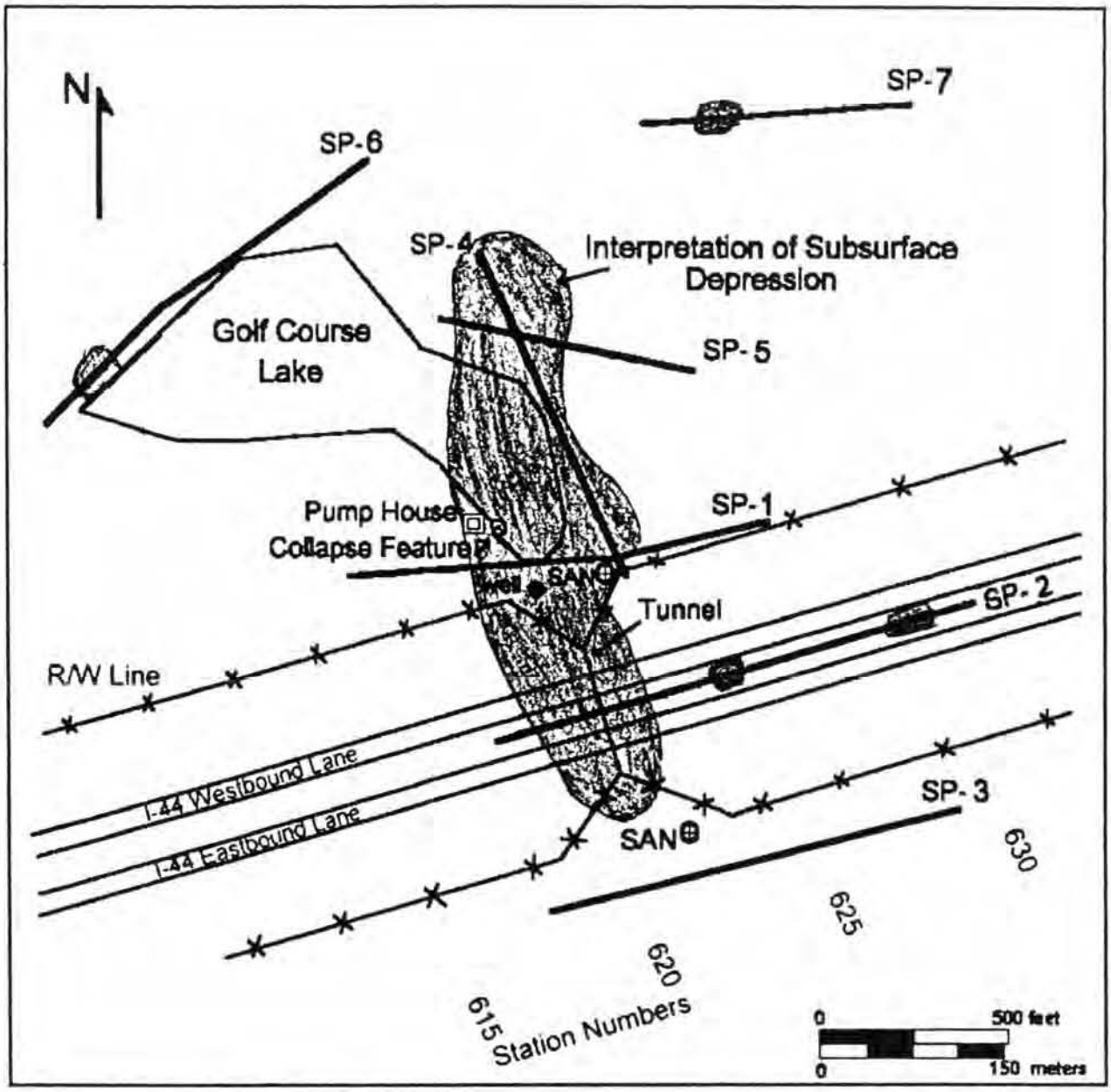


Figure 5: Map of area. The interpretation of the reflection seismic data has been superposed on this base map.

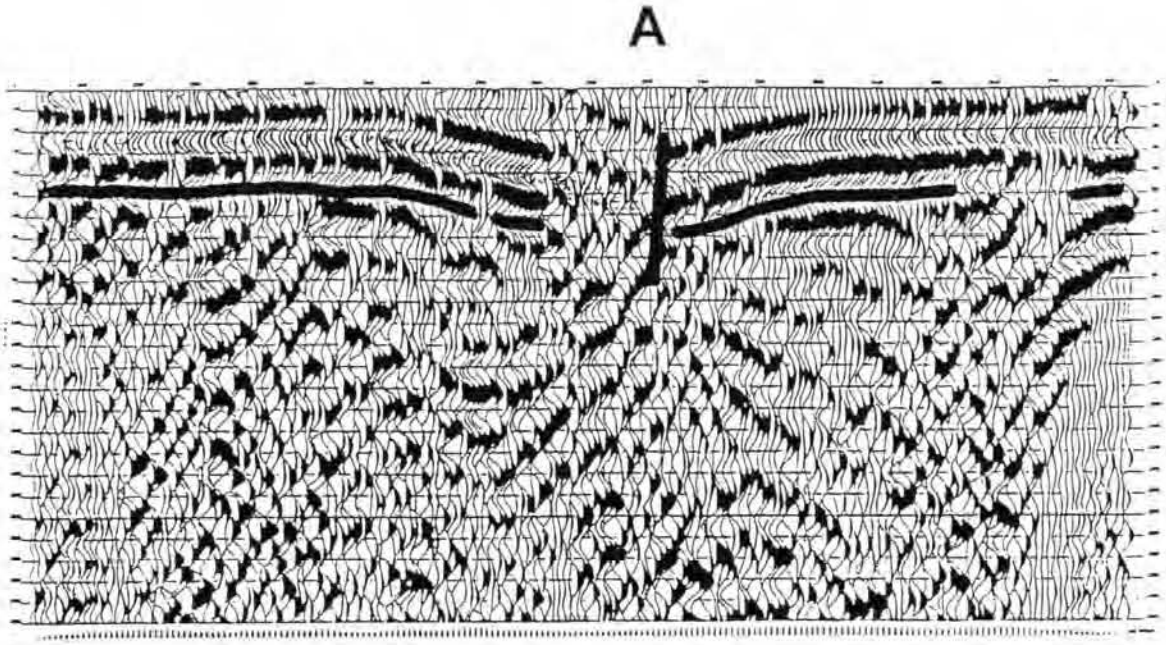


Figure 6: Reflection seismic Profile SP-1.

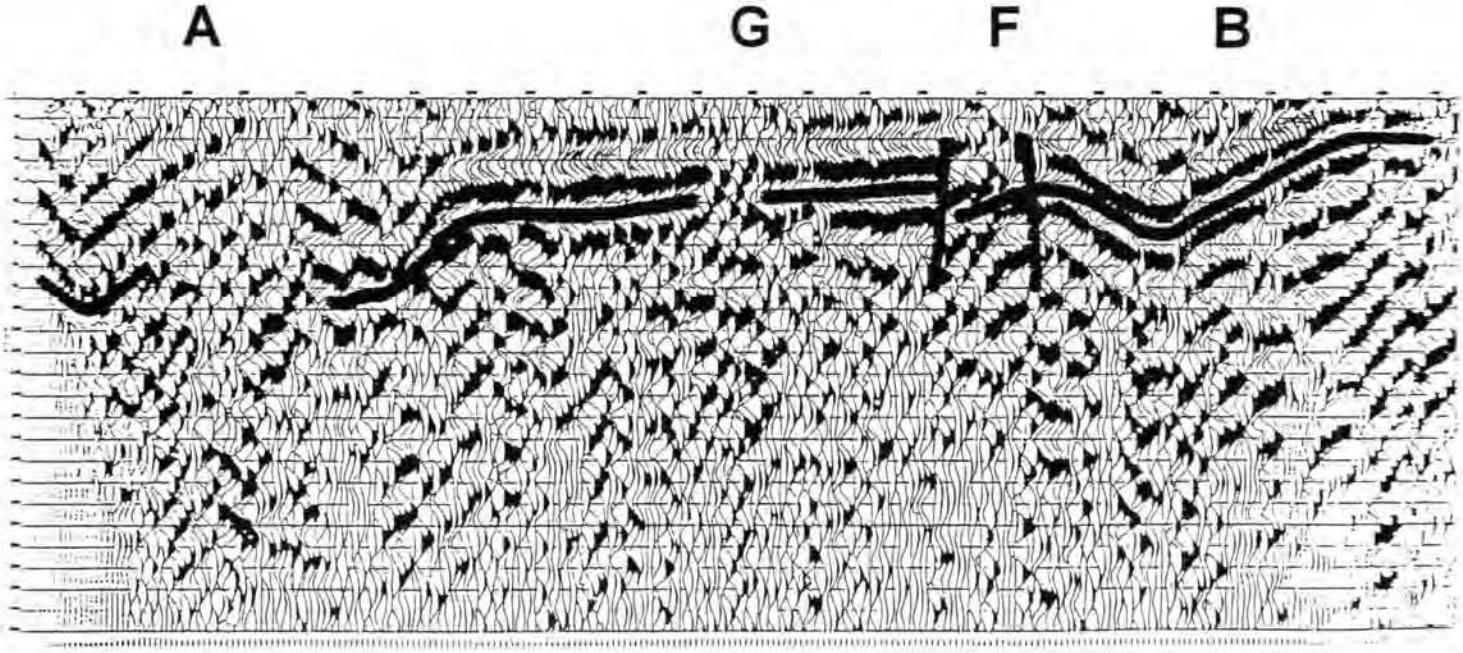


Figure 7: Reflection seismic Profile SP-2.

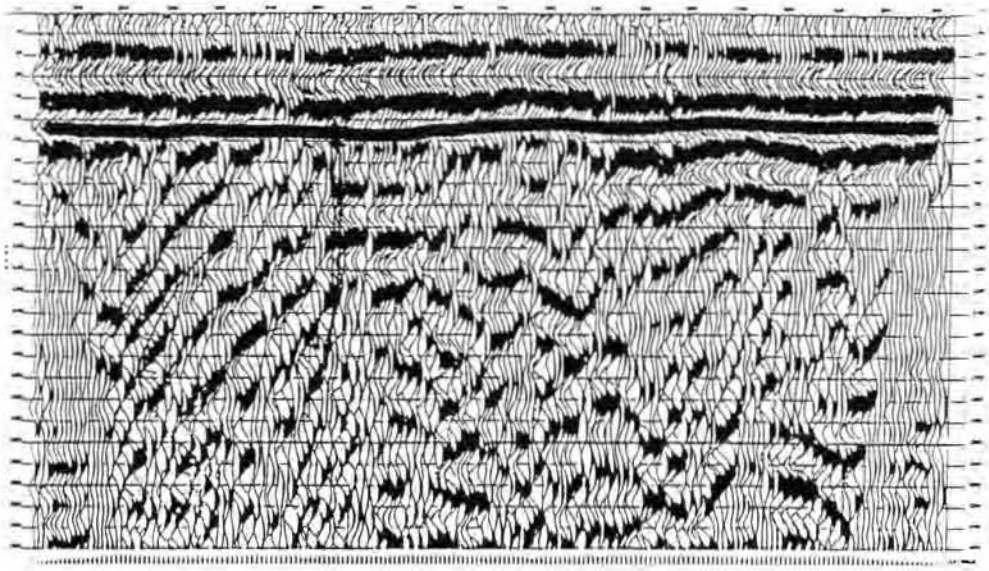


Figure 8: Reflection seismic Profile SP-3.

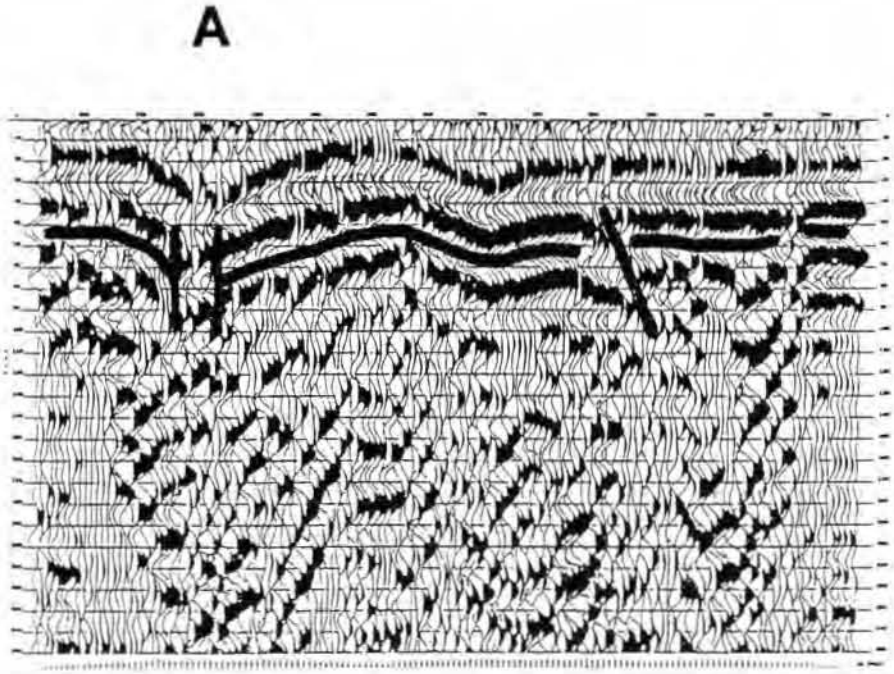


Figure 9: Reflection seismic Profile SP-4.

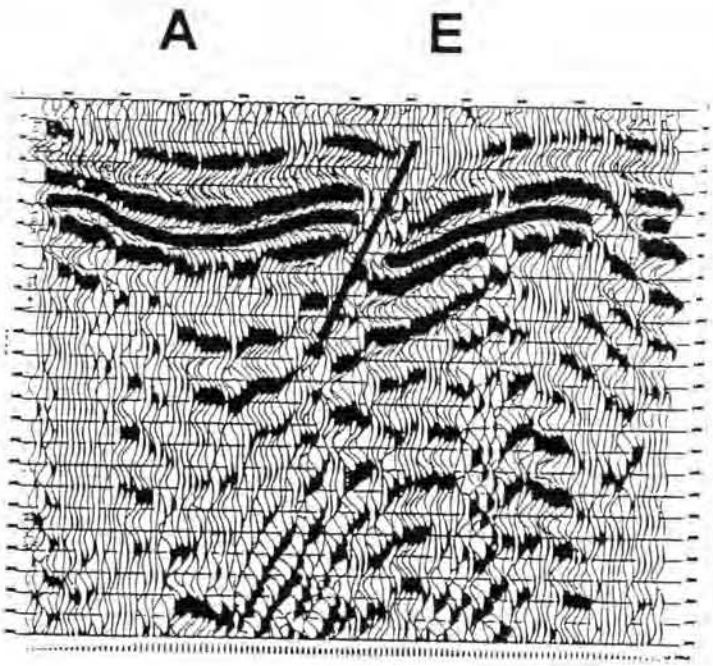


Figure 10: Reflection seismic Profile SP-5.

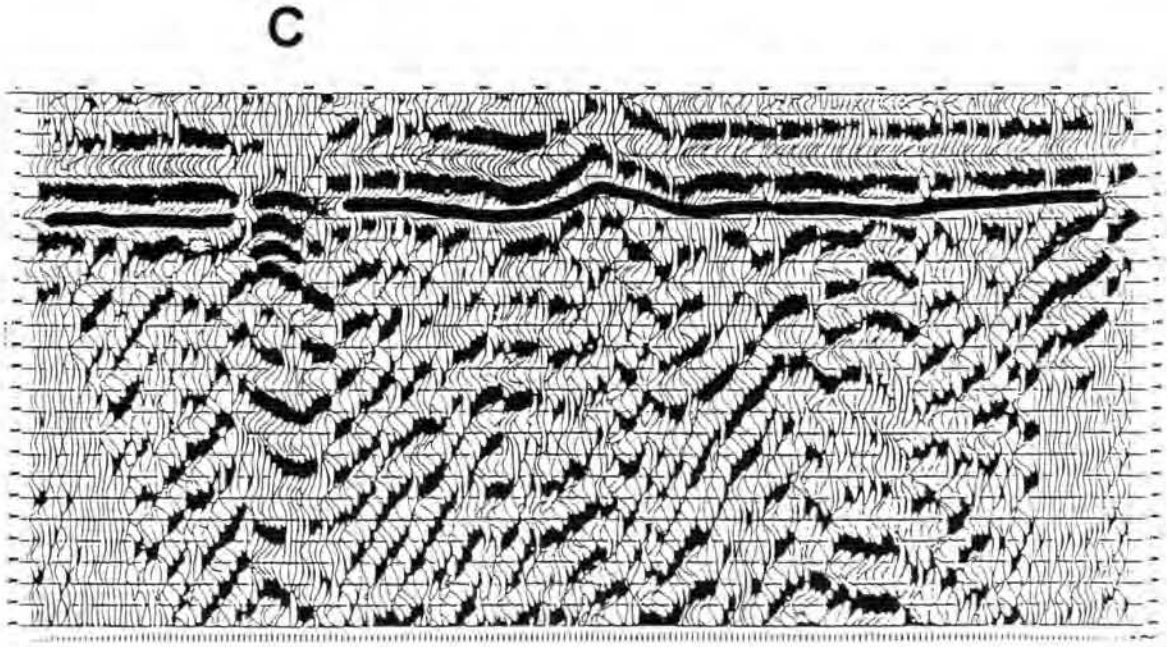


Figure 11: Reflection seismic Profile SP-6.

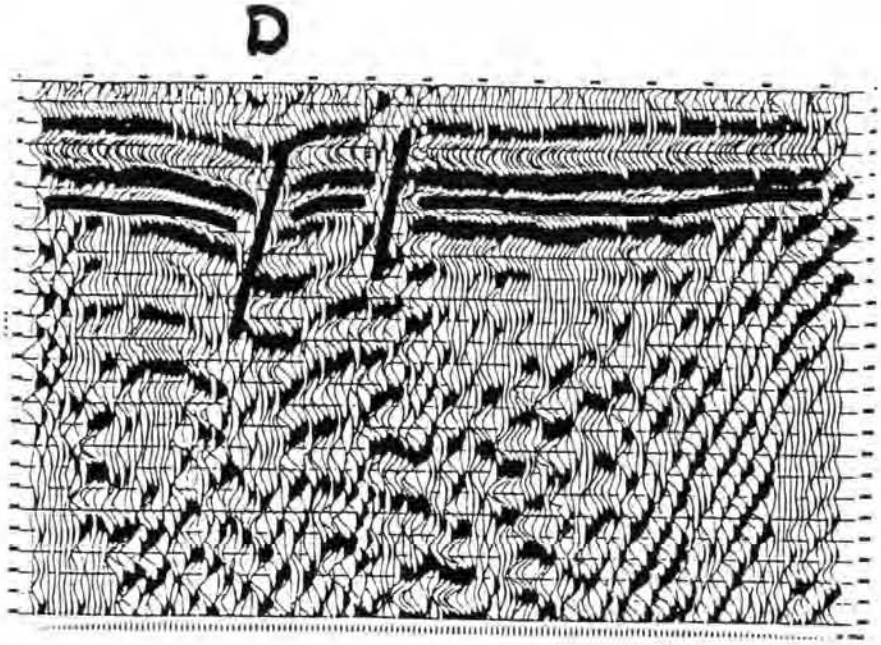


Figure 12: Reflection seismic Profile SP-7.

Sinkhole Feature A appears to represent an elliptical or elongate, north-northwest trending sinkhole. This topographic low was selected for the 1993 placement of the nearby golf course irrigation lake (Deer Lake). Feature A is identified on Seismic Lines SP-1, SP-2, SP-4 and SP-5 (Figures 6, 7, 9 and 10, respectively). The interpretation of Seismic Line SP-2 suggests that the underlying sinkhole extends southward beneath the Interstate (Figures 5 and 7). Sinkhole A appears to have been reactivated by leakage from nearby Deer Lake. Evidence of such leakage is shown by recent (April, 1997) collapse near the southeastern margin of the golf course lake. Catastrophic drainage of the lake should be studied in more detail, to ascertain if it constitutes a long-term threat (re: highway stability).

Subsurface sinkhole B is imaged only on Seismic Line SP-2 (reflection seismic control was not acquired either to the north or south of this feature). Sinkhole B should be studied in more detail, to determine if it constitutes a potential long-term threat (re: highway stability).

Sinkholes C and D are manifested as recent collapse features (mapped in field studies), and are imaged on Seismic SP-6 and SP-7, respectively (Figures 11 and 12). Neither sinkhole is sufficiently close to the highway to warrant further investigation. The shear zone systems along which these sinkholes developed probably extend beneath the Interstate. However, unless subsidence has been noted in these areas, further investigations may not be warranted at this time.

Sinkhole E is imaged only on Seismic SP- 5 (Figure 9). Sinkhole E does not appear to extend beneath the Interstate, and further investigation of this sinkhole probably is not warranted at this time.

Two additional anomalous subsurface features (in addition to Sinkholes A and B) are identified on Seismic SP- 2 (Features F and G; Figures 7). These anomalous features may be the images of the dissolution-widened joint systems through which much of the fine-grained fill material has been removed. These features should be examined to ensure that they do not represent developing cavities, fed from roadway runoff.

GROUND-PENETRATING RADAR EQUIPMENT AND FIELD ACQUISITION PARAMETERS

In May of 1997 (Survey 1B), 30 GPR profiles were acquired along paved sections of Interstate 44, in places immediately adjacent to recent subsidence features (lines 1-30; Figures 4, 13, 14 and 15). The intent was to image the shallow subsurface to a depth of about 4 m, to detect possible voids. In October of 1997, the study site was revisited (Survey 2) and a duplicate set of 30 GPR profiles and 25 additional GPR profiles were acquired (lines 31-55; Figure 4). The duplicate set of 30 profiles was acquired to determine the effectiveness of the grouting program and determining if any new voids have 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). All of these GPR data were processed at UMR, and interpreted by UMR researchers, in consultation with MoDOT personnel Newton and Goessmann.

A GSSI SIR-8 GPR unit equipped with a 500 MHz monostatic antenna was used to acquire the Survey 1B and Survey 2 GPR data (Figure4). The sampling interval was 50 scans/m. The trace length was 50 ns, providing for depth penetration on the order of 4 m.

GROUND-PENETRATING RADAR DATA PROCESSING

The GPR data were processed 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 GROUND-PENETRATING DATA

Two sets of GPR data (Survey 1B and Survey 2) were acquired at site, along Interstate 44, Springfield Missouri. In Survey 1B (May 1997), 30 profiles were acquired along paved sections of Interstate 44 , in places immediately adjacent to recent subsidence features (lines 1-30; Figures 4, 13, 14 and 15). Survey 1B was successful, from the interpretation of these data, MoDOT personnel were able locate voids that had developed beneath the pavement (as a result of the washout of fine- grained material), and devise an effective grouting plan. The validity of the GPR interpretations, and the utility of the GPR method was established during the grouting program. All of the areas designated as anomalous on the GPR profiles accepted grout (Figures 13, 14, and 15).

In October of 1997, geophysical Survey 2 was conducted. A duplicate set of 30 ground-penetrating radar profiles and 25 additional GPR lines were acquired. The duplicate set of 30 GPR profiles was acquired with a view to determining the effectiveness of the grouting program and determining if any new voids had developed since the May survey (Survey 1B). The 25 additional lines (lines 31-55; Figure 4) were acquired to extend GPR control into previously untested areas, with a view to identifying any voids. Survey 2 was also successful. The interpretation of these ground-penetrating radar data suggests that the grouting program effectively stabilized 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).

Three example duplicate GPR profiles (1, 2 and 3) are shown as Figures 16, 17 and 18, respectively. Areas designated as anomalous on the GPR profiles have been highlighted on Figures 13, 14, and 15. These anomalous zones are characterized on the GPR profiles by high amplitude diffractions (Figures 16, 17, and 18).

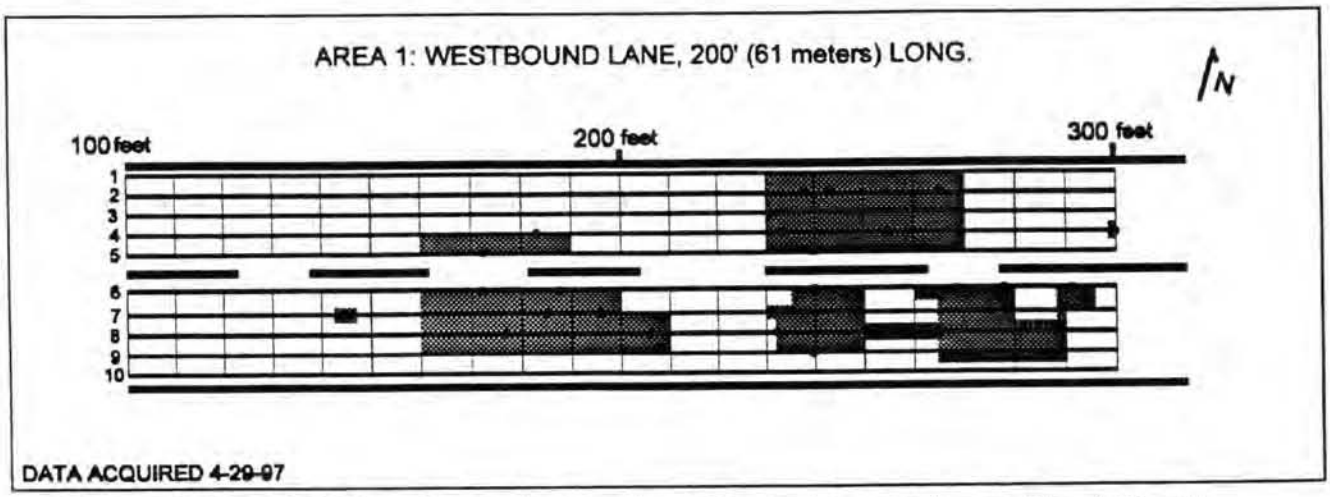


Figure 13: Map of GPR study area 1. Locations of ground-penetrating profiles 1-10, with associated GPR anomalies.

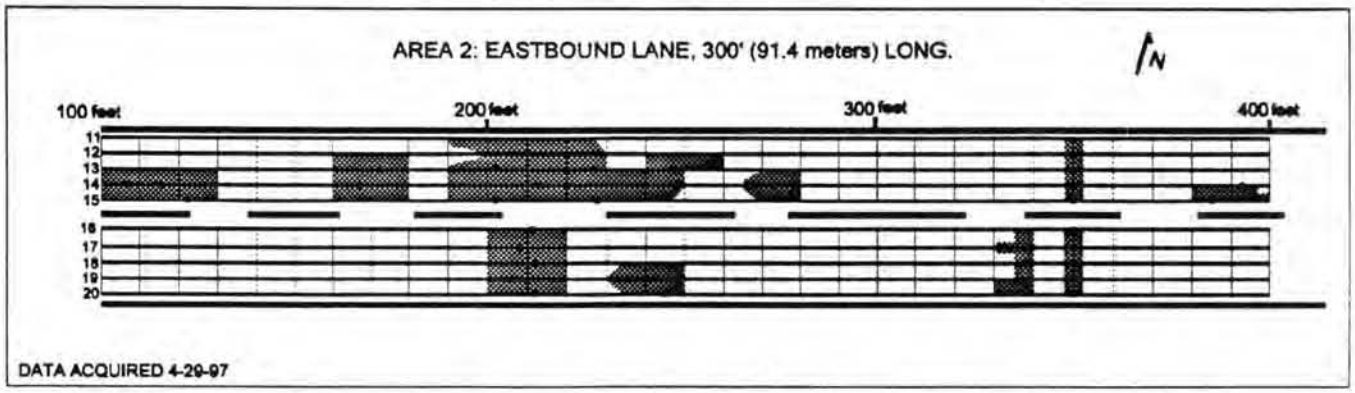


Figure 14: Map of GPR study area 2. Locations of ground-penetrating profiles 11-20, with associated GPR anomalies.

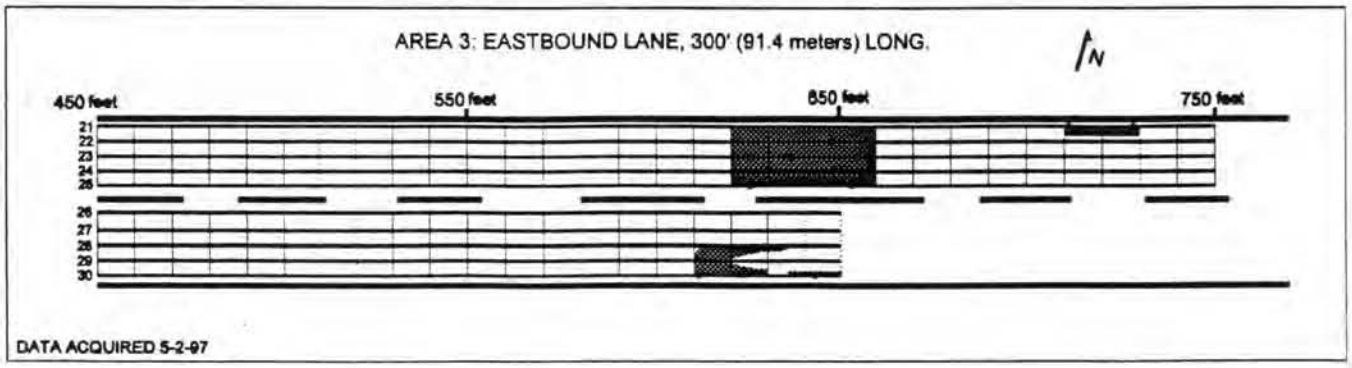


Figure 15: Map of GPR study area 3. Locations of ground-penetrating profiles 21-30, with associated GPR anomalies.

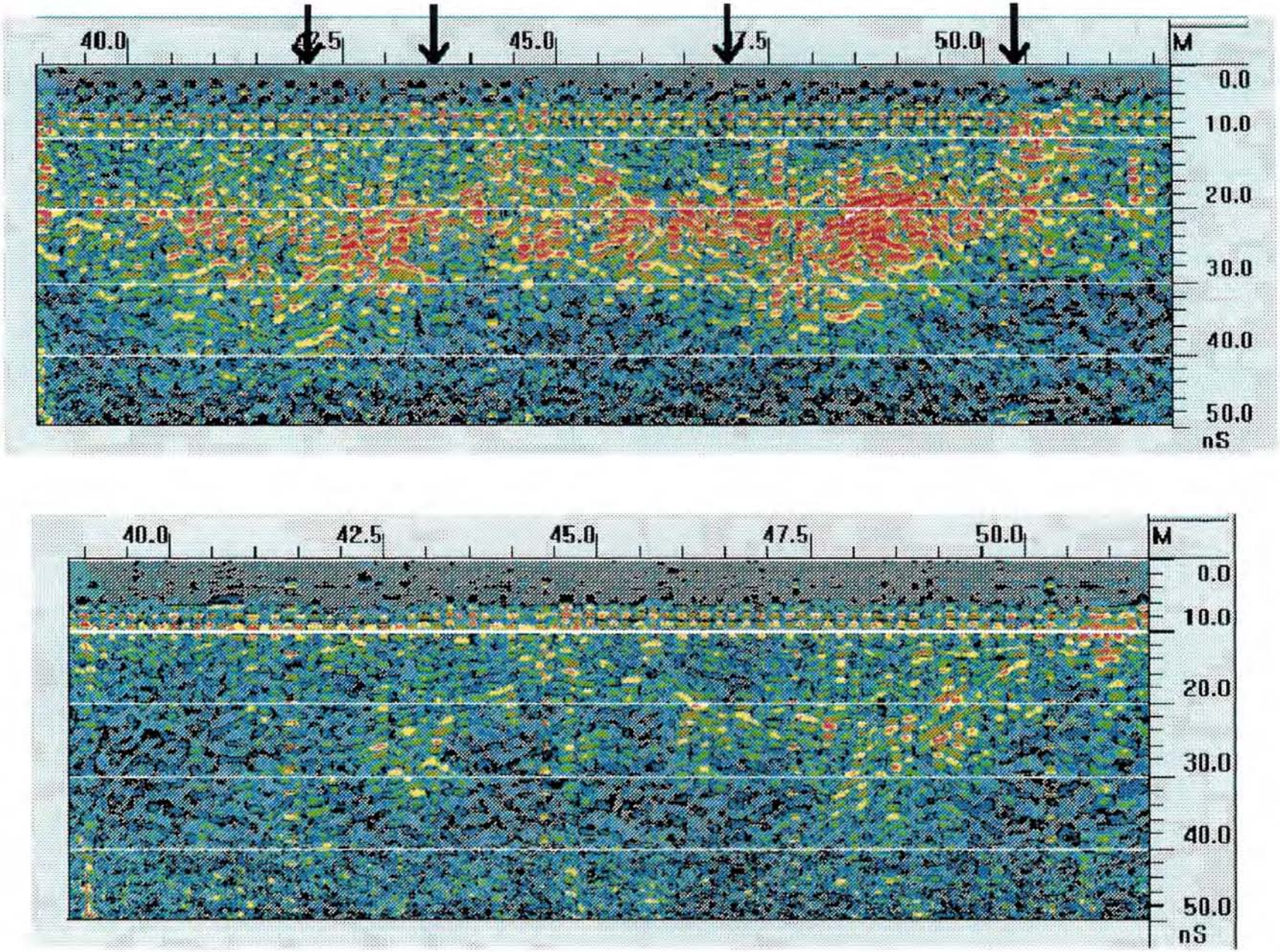


Figure 16: May and October versions of ground-penetrating radar profile 2 (Area 1: Figure 12). The upper GPR profile was acquired in May, the lower profile in October. Grout application borehole locations are shown.

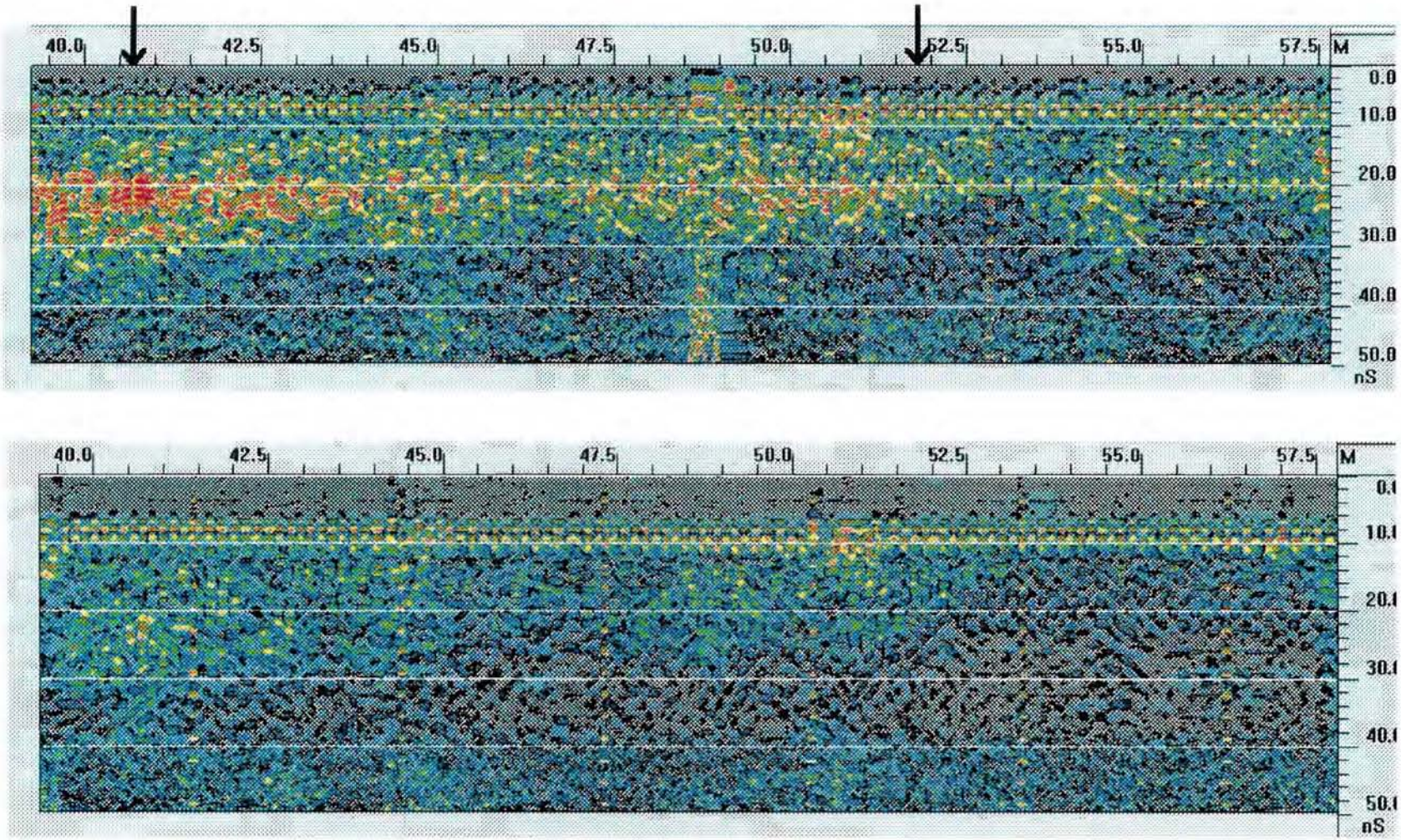


Figure 17: May and October versions of ground-penetrating radar profile 4 (Area 1: Figure 12). The upper GPR profile was acquired in May, the lower profile in October. Grout application borehole locations are shown.

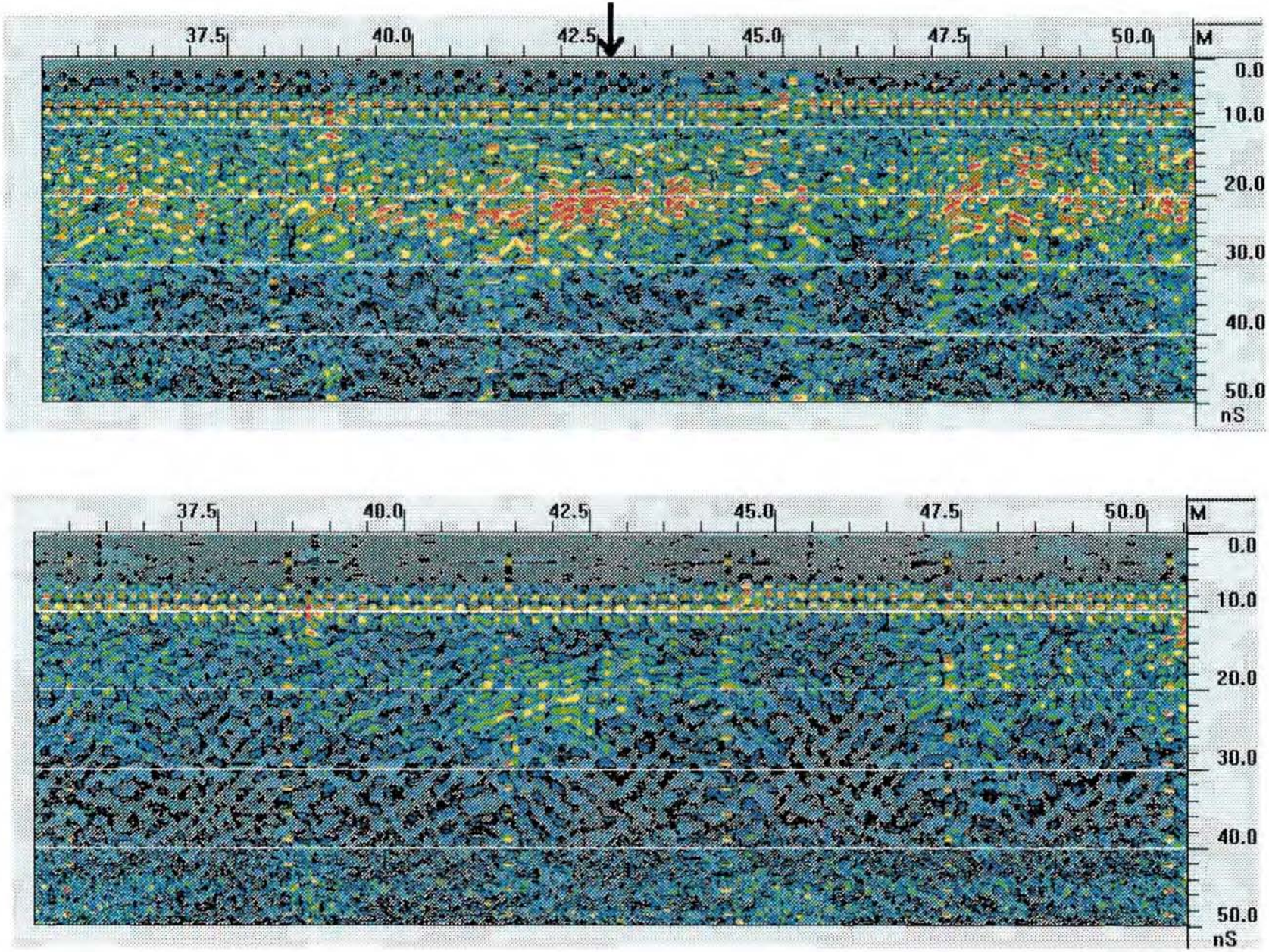


Figure 18: May and October versions of ground-penetrating radar profile 5 (Area 1: Figure 12). The upper GPR profile was acquired in May, the lower profile in October. Grout application borehole locations are shown.

UNIVERSITY RESEARCH CONCLUSIONS

The engineering geophysical surveys

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 active sinkholes. Although there is no evidence that catastrophic collapse is imminent anywhere along the tested section of Interstate, we recommend that these two sinkholes are investigated further. If these sinkholes are determined to be structurally stable, the tested segment of Interstate is not "high risk" for catastrophic collapse. 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. However, fine- grained sediment will continue to be "washed out" as long as substantial volumes of water flow into the sinkholes. Pavement subsidence will be a reoccurring and long term problem, until drainage problems are mitigated.

Utility of the Reflection Seismic Method

The reflection seismic profiles (Figures 6-12) establish that high-resolution reflection seismic data can effectively image the shallow subsurface in the study area, and can be used to identify and map bedrock structure and sinkholes. These data demonstrate that the high-resolution seismic technique can be used effectively to image the shallow subsurface between depths of 3 and 60 meters. The data also demonstrate just how critical parameters such as fold, geophone spacing, source type, and near-offset are to the successful acquisition of quality reflection seismic data in the study area.

On the basis of our experience in acquiring, processing and interpreting the seven reflection seismic lines, we have come up with a suite of recommendations for any additional seismic work. These are listed below under the headings: Data Coverage, Data Fold, Seismograph, Source, Geophones, Sampling Interval, Record Length, Spread Length, Near-offset, Elevation Control, Velocity Analysis, Processing, and other.

Optimal Reflection Seismic Survey Parameters

Data Coverage: Subsurface coverage on the order of 1.5 m is necessary to image significant lateral changes in shallow lithology and structure. This translates into a surface geophone spacing of 3 m.

Data Fold: Nominally 12-fold CDP data is necessary to effectively image the shallowest subsurface as well as pre-bedrock reflectors. At lower folds, data redundancy both at shallow (<6 m) and greater (>45 m) depths are unacceptably reduced due to unacceptable NMO stretch, and ground roll contamination respectively.

Seismograph: A 24-channel (or greater) seismograph with roll-a-long capabilities is necessary to acquire the data in an efficient manner.

Source: Given the shallow depth of the primary target zone, a near surface source is required. This should consist of either a surface weight drop or a small explosive (shotgun shell for example) detonated in a shallow (1 m deep), filled 8 cm diameter drillhole. We recommend using a weight drop source, with multiple (6-8) impacts (to attenuate high frequency ground roll and airblast).

Geophones: Geophones with a natural resonant frequency of 40 Hz (or more) should be used. These will effectively attenuate low frequency ground roll and yet allow for the recording of desired high-frequency reflection data. Although it is common practice to use single high-frequency geophones a closely clustered array would be preferable (assuming a multiple weight drop source). If single geophones are used, they should be buried at shallow depths (or covered with soil) to minimize noise from the wind and airblast.

Sampling Interval: A sampling interval of 0.5 ms is sufficient. Data with dominant frequencies between 50 and 100 Hz are expected.

Record Length: A record length of 500 ms is sufficient to image the subsurface to a depth of at least 300 m.

Spread Length and Near-offset: We recommend using an array of 24 geophones with a geophone spacing of about 3 m. We recommend using a near offset of 3 to 6 meters. This will result in nominal 12-fold data, with subsurface coverage at 1.5 m intervals.

Elevation Control: Source and receiver locations should be surveyed so that elevation corrections can be applied.

Velocity Analysis: Because of the variability in near-surface velocities, velocity analysis should be done for every tenth CMP gather, and more regularly where anomalous variations are noted.

Processing: Standard high-resolution processing routines should be followed. This would include the judicious muting of first breaks and excessive ground roll (or suitable F-K filtering), and the muting of excessively stretched NMO data.

Utility of the Ground-penetrating Radar Method

The GPR profiles (Figures 16-18) demonstrate that sub-pavement voids can be located using the GPR tool. These data demonstrate that the GPR technique can be used effectively to image the shallow subsurface to depths of up to 4 m. The data also demonstrate just how critical parameters such as line spacing, antenna frequency, etc. are to the successful acquisition.

Optimal GPR Survey Parameters

Antenna Frequency: A 500 MHz antenna provided both the necessary depth penetration and vertical resolution to image shallow sub-pavement voids. A 900 MHz would provide better vertical resolution, but significantly less depth penetration. A 120 MHz antenna will provide slightly greater depth penetration, but substantially less vertical resolution (re: small voids).

Data Coverage: Subsurface coverage on the order of 2 cm is necessary to image the sub- pavement strata.

Sampling Interval: A sampling interval of 50 scans/m (or more) is sufficient.

Record Length: A record length of 50 ns is sufficient to image the subsurface to a depth of about 4 m.

Elevation Control: Elevation corrections should be applied.

Processing: Standard GPR processing routines should be followed.

University Research Recommendations (Additional Geophysical Work at Site)

On the basis of our interpretation of the geophysical data, we conclude that the tested section of Interstate overlies two reactivated sinkholes Although there is no evidence that catastrophic collapse is imminent anywhere along the tested section of Interstate, we recommend that these two sinkholes be investigated further. If these features do not constitute hazards (potential for catastrophic collapse), then our conclusion is that the tested segment of Interstate is not "high risk" for catastrophic collapse. 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 (May to October interval). However, fine-grained sediment will continue to be "washed out" as long as substantial volumes of groundwater flow into the sinkholes from the upgradient (north), and pavement subsidence will be a on going and long-term problem.

1. We recommend further investigation of the geophysical anomalies identified as Features A, B, F, and G. (Features A and B are interpreted sinkholes; Features F and G are interpreted fractures.) These are the most anomalous features on Seismic SP-2 (Figures 5 and 7).

2. We recommend remedial action to ensure that surface runoff seepage along this segment of Interstate is minimized. This (combined with grouting and long-term monitoring) will ensure that "washout" related subsidence is minimized.

3. We recommend the acquisition of GPR profiles at regular (6 month) intervals, until the surface run-off problem has been minimized and subsidence has effectively ceased. The profiles should cover both lanes of the Interstate, in the immediate vicinity of the subsidence features.

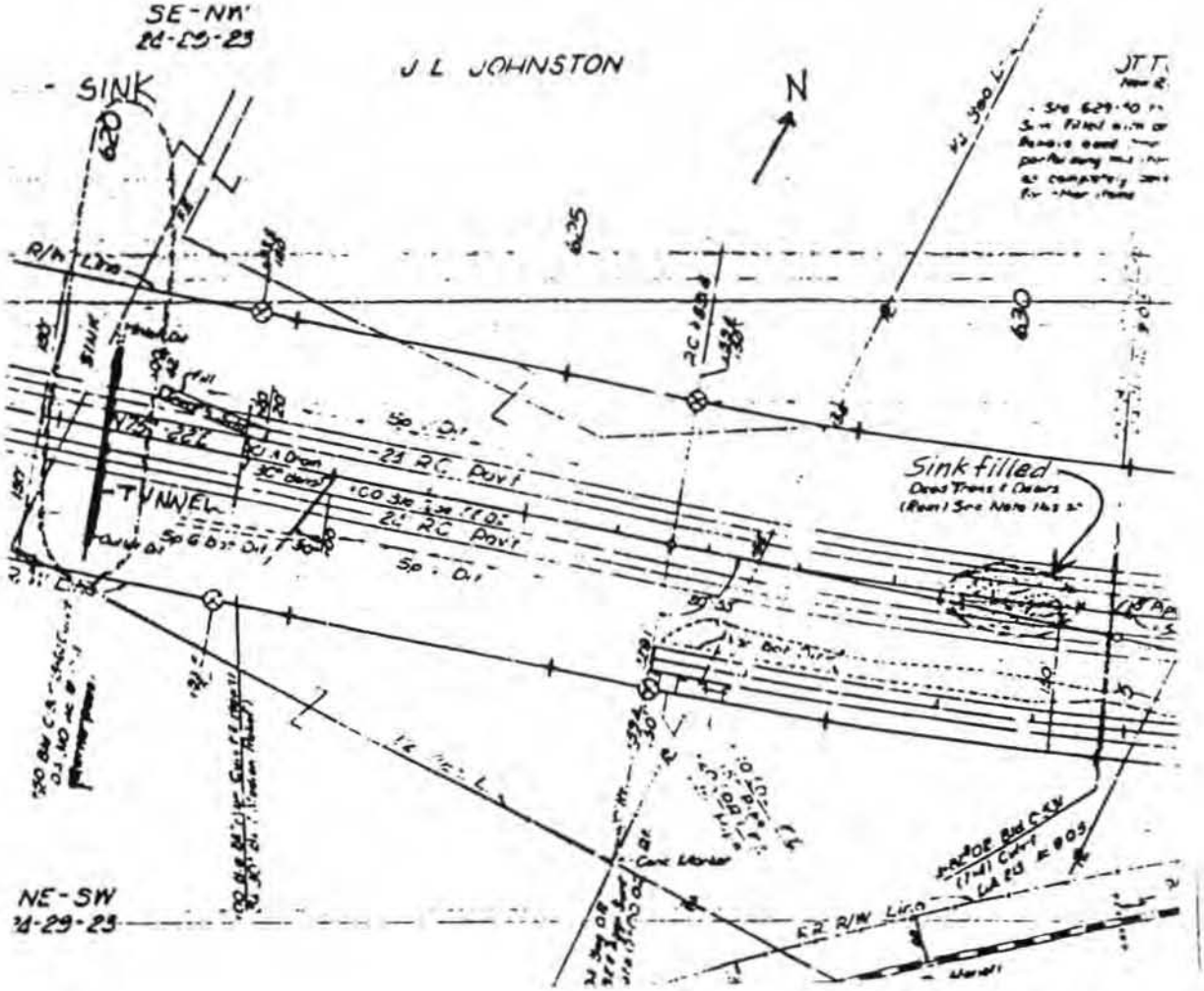


Figure 19: Burden of Proof - Pre-construction drawing of area found after the investigation showing the dashed outlines of the sinks that were confirmed with geophysics. Compare with Figure 5.

MoDOT CONCLUSIONS

The use of Ground Penetrating Radar (GPR) as an investigative tool reduced the time and cost of the project as compared to the traditional methodology of investigation and mitigation of karstic distress. Without GPR, subsurface information would be obtained by drilling auger holes through the highway pavement, shoulders, and median - a technique similar to finding a needle in the proverbial haystack. The impact of the numerous boreholes required would have a twofold effect on the stability of the roadway. The strength and integrity of the pavement bridging the subsurface voids would be greatly reduced, and secondly, the holes would act as conduits of stormwater, allowing water to flush additional soil downward and accelerate the growth of the voids.

Time wise, GPR allowed MoDOT to quickly assess the threat of roadway subsidence to the traveling public. This data contributed to the decision making process of keeping both lanes of the Interstate open. Processed GPR images were used to locate voids and unconsolidated material underlying the pavement. These features were marked on the pavement, drilled, and pumped full of cement grout to stabilize the subgrade. This process required 44 tons of cement grout to fill all the voids and only required the closure of one lane of traffic. The grout appears to have now stabilized the pavement and subsurface. A second application of GPR to the mitigated areas confirmed the voids had been adequately filled. The cost of materials and labor involved in the grouting / mitigation process was about $7,000.

Without GPR data, a typical mitigation of the areas suspected of possible collapse would be to tear out the overlying existing pavement, laying base rock, and re-paving the interstate roadway at an estimated cost of $45 per square yard, not including removal and excavation costs. New pavement would be 40 feet wide per east / west bound lanes. The high cost, amount of time required, and the associated long term traffic delays of this scenario make it an undesirable alternative. The problem would be exacerbated by the lack of an adequate bypass of the area and the consequent inference with business of the adjacent golf course.

This study has demonstrated the effectiveness of Ground Penetrating Radar and Reflection Seismic geophysical methods to investigate karst related threats to roadway pavements. The penetration of GPR is dependent on the conductivity of the soil, which varies considerably with geography. Reflection Seismic, which shows the underlying bedrock structure, is highly reliable but only necessary when the local geology and location of sinkholes and faults is unknown. MoDOT should integrate these geophysical tools into investigations where typical methods would be more costly and only provide limited information. More research is needed to determine the effectiveness of these tools in different subsurface soil and geology types throughout the state of Missouri.

IMPLEMENTATION / RECOMMENDATIONS

Any threatening roadway stability situation involving the shallow subsurface that requires quick assessment is a candidate for the application of the technologies described in this report. However, ground penetrating radar and reflection seismic are complex tools that require skilled technical persons to operate. MoDOT is currently conducting much research on the many applications of these nondestructive geophysical techniques. The results of these studies will be used to determine if the expenditure for equipment and its dedicated personnel is warranted. At this time it is recommended to establish qualified consultants that would be able to make their services available on short notice. Prior arrangements to expedite the mobilization and data collection should be made as well. This would be in the best interest of the traveling public, ensuring safety while minimizing disruption of traffic.

APPENDIX A

GEOLOGIC SITUATION LEADING TO THE PHENOMENON

GEOLOGIC SITUATION LEADING TO THE PHENOMENON

Site Area Geology

Site-area geology is complex from two important perspectives, which are 1) the abundant residual soil blanketing most of the bedrock and, 2) at least a dual and possible triple-decked system of karstic dissolution. We went into the project lacking the subtle distinction between vadose-zone karst dissolution features and those centered at a greater depth.

Pinnacles & Grikes

These features represent the prominent bedrock knobs displayed prominently along both sides of the depressed (cut) section of I-44 as it passes through the north side of Springfield. A few moments spent in reflection in this segment brings the viewer to the recognition that the karstic dissolution generally is bound to the uppermost 5 meters of bedrock and that most of the dissolution voids and gaps appear to terminate at a prominent bedding plane in the limestone and at a depth of about 5m.

"Grikes", the gaps, holidays, channels, and voids where limestone has been dissolved, are driven by original activity along the prominent vertical jointing system of most of the southwest Missouri limestone sequence. These grikes are by no means predictable, but we operate on a reference frame of about five (5) meters of lateral separation. Grikes normally are soil filled, by sloughing of silts and clay-sized particles furnished by gravity fall from the overlying residual clay soil.

Creation of the pinnacle-and-grike system of irregularity of the bedrock top-of-rock surface has occurred over literally millions of years. During this time it responded to slow infiltration of precipitation, with movement of this water typically downward in the uppermost 5-meter vertical zone, then laterally, toward breakout points furnished by nearby topographic irregularities, probably more so in the past than is presently apparent. This would have naturally occurred earlier than later (present time), over the entire period of a few millions of years, during which time the topography has become smooth and subdued, erasing the evidence of side-hill breakout.

We do not mean to imply, within the context of this report, that the appearance of irrigation waters, in the perched water system, are believed to have caused dissolution of rock. Theoretically this is not possible over a period of only a few years. The waters, however, are believed to have piped-away existing soil infilling in the near-surface bedrock karstic voids.

Deeper Karst

Karstic features of a deep (or "deeper") origin remain as "sinkholes" (AKA "dolines"), which dot the countryside of Greene County in an apparently random fashion. We believe that there are essentially two generic sets of sinkholes, one set driven by groundwater movement in the Uppermost Aquifer (limestone sequence lying at elevations above the Northview Shale Member) and the Second Aquifer (lying below the not-always-present Northview Shale).

Subsurface Water Flow

Surface-water flow normally would not have a considerable influence on the geotechnical stability of karstic ground in Greene County, except where considerable amounts of storm-water discharge inadvertently reach sinkholes. Conventional wisdom among civil engineers is to avoid discharging runoff or accumulated storm water into sinkholes, for the dual threats of washing out supporting debris and initiating collapses, and for actually extending the dissolution process with carbonate-dissolving "hungry" water with low TDS (Total Dissolved Solids) contents.

At the subject site, we believe that it has been an excess of surface water infiltration that has reactivated the karst process, mainly by erosion-removal of the silt and clay-sized grike fillings and also establishing hydraulic communication with the subsurface karst flow network incorporating perched water of the vadose zone with flow of ground water in at least the Uppermost Aquifer. We had initially discounted participation of the Uppermost Aquifer until we learned that more than 100cm (cubic meters) of soil and rock backfill had been introduced by the Maintenance Crew into the median cracks and pits (typically smaller than one meter of surface-open area in a single location) over the 12-year period 1983-1995, and by our recent (beginning 5 May 1997) mitigation drilling support.

APPENDIX B

PHOTOGRAPHS

Photo No. 1

"Pinnacle and Grike" geology exposed in roadcut near research project
on Interstate 44, Springfield, Missouri

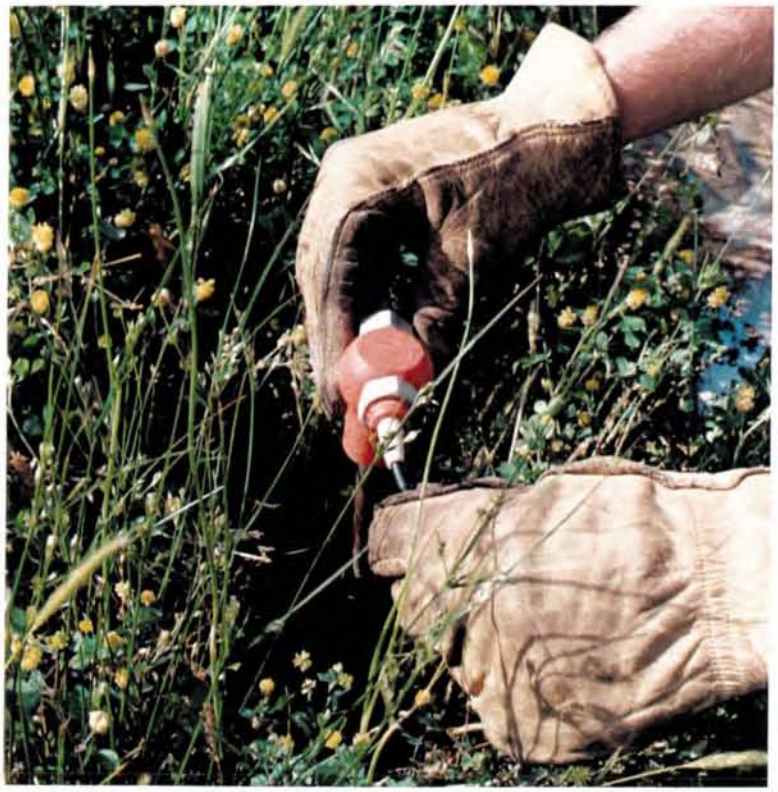
Photo No. 2

Collapse on shoulder signified the threat of future roadway subsidence.

Photo No. 3

University of Missouri-Rolla personnel collecting GPR data.
Red box being pulled is GPR antenna.

Photo No. 4



Geophone being placed in ground for reflection seismic data aquisition.

Photo No. 5

Truck mounted EWG seismic energy souirce "thumps" ground repeatedly to produce waves for reflection seismic data.

Photo No. 6

Pavement with GPR lines marked off. Interpreted data is being used to locate areas requiring mitigation.

Photo No. 7

Grouting operation in progress. Pavement is cored out with drill, then grout is pumped in to fill subsurface voids.

RD LIBRARY
RD0006568