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Imaging Voids Beneath Bridge Bent Using Electrical Resistivity Tomography

by

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A National University Transportation Center
at Missouri University of Science and Technology

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16. Abstract

Five electrical resistivity tomography (ERT) profiles and borehole control were acquired beneath two bridges on the bank of the Gasconade River in order to determine extension of the underground water-filled openings in rock encountered during a drilling program, to locate other possible water-filled rock openings, and to map variations in rock quality in immediate proximity to the bridge foundations.

The geophysical program was successful. Two east-northeast trending fracture zones were identified. Competent rock was differentiated from fractured rock. Extend of the water-filled rock opening was mapped based on the geophysical, borehole and grout data. A conceptual model of the development of the water-filled opening was proposed.

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ABSTRACT

Five electrical resistivity tomography (ERT) profiles and borehole control were acquired beneath two bridges on the bank of the Gasconade River in order to determine extension of the underground water-filled openings in rock encountered during a drilling program, to locate other possible water-filled rock openings, and to map variations in rock quality in immediate proximity to the bridge foundations.

The geophysical program was successful. Two east-northeast trending fracture zones were identified. Competent rock was differentiated from fractured rock. Extend of the water-filled rock opening was mapped based on the geophysical, borehole and grout data. A conceptual model of the development of the water-filled opening was proposed.

INTRODUCTION

The westbound lane bridge was constructed in 1955, it carries west-bound traffic on the interstate over the Gasconade River in Laclede County, Missouri (Figure 6.1). The construction conducted in 2011 included building a temporary substructure north of the existing bridge to support a new replacement bridge deck. After the new deck was completed and the old deck removed, the new deck was transferred into place – on the existing bridge foundations, supporting the new bridge deck.

During the construction of a drilled shaft for the temporary substructure north of the westbound lane bridge, water-filled rock openings were noted beneath a 2-foot-thick layer of dolomite at a depth of 19 to 20 ft. The foundation of Westbound Lane Bridge was designed to be spread footings bearing on rock, and concerns arose for the integrity of the rock beneath the existing bridge foundation.

Figure 6.1. Aerial photograph of the Gasconade River study site.

Subsequent borings and ERT data confirmed the presence of rock openings adjacent to or at the foundation bearing level of the northern and central Westbound Lane Bridge footings (Figure 6.2).

GEOLOGY AND STRATIGRAPHY

The study area is located in the Salem Plateau region, known also as the Salem Plateau Groundwater Province (Miller and Vandike, 1997) (Figure 6.3), north and east of the Springfield Plateau, and is separated from it by an abrupt drop. The Salem Plateau is often underlain by dolomite or dolostone. The study area is underlain by generally flat-lying sedimentary strata of Ordovician age. The project site was located near the contact between the Gasconade Dolomite and the overlying Roubidoux Sandstone.

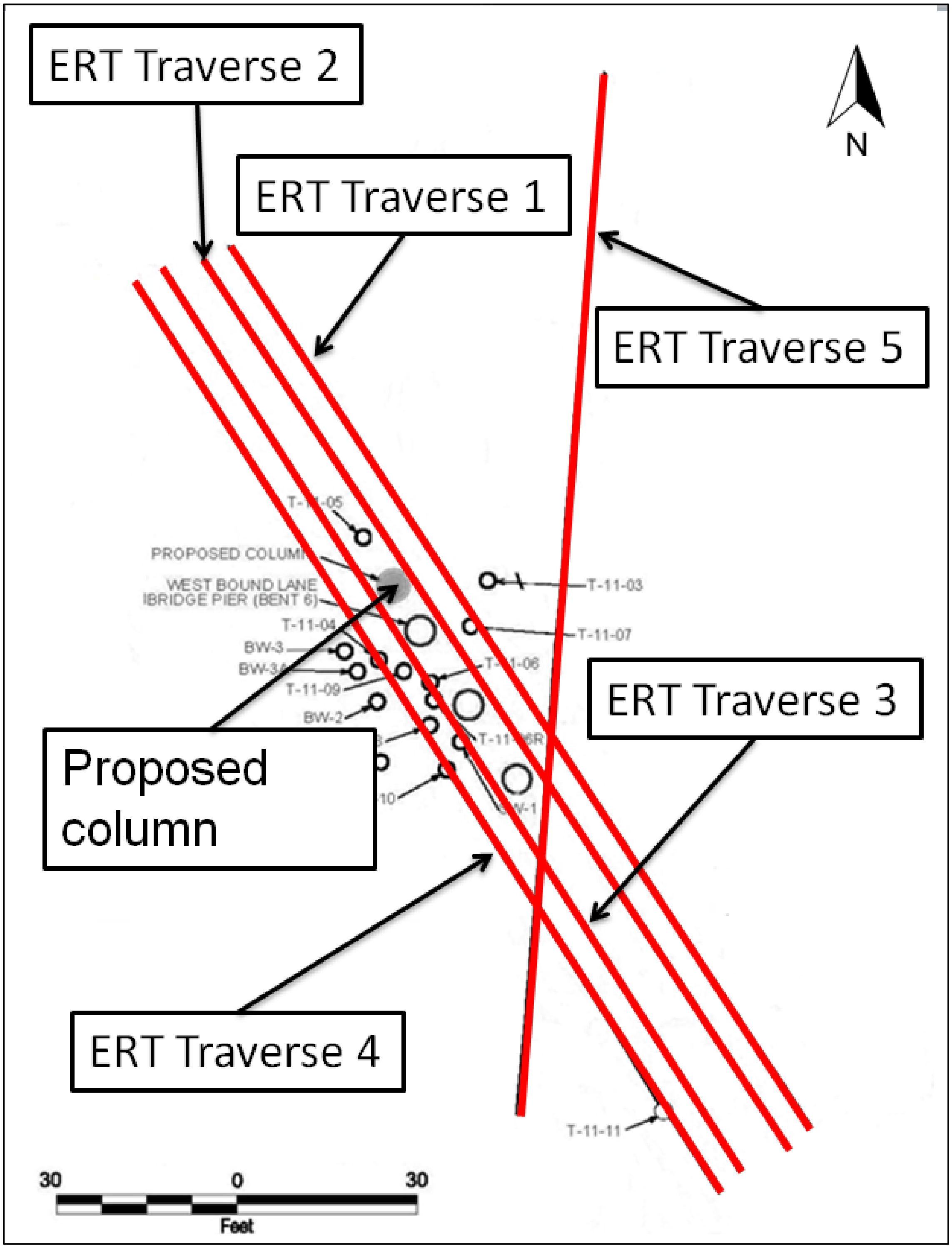

Figure 6.2. ERT traverses and borehole locations.

Five ERT profiles were acquired in an effort to map extension of the noted underground water-filled rock openings during the drilling program and any other potential water-filled or air-filled rock openings and to characterize rock beneath the existing foundations.

The sloping valley floor first intercepts the Gasconade Dolomite directly upstream of the project site, and cuts deeper into the Gasconade as it progresses downstream. The Gasconade Dolomite is represented mostly by a light brownish-gray, cherty dolomite, and is highly weathered in the study area (Figure 6.4). The Roubidoux Formation, overlying the Gasconade, outcrops on the valley slopes in the vicinity of the project site.

The Roubidoux consists of dolomite, cherty dolomite, sandy dolomite, dolomitic sandstone, and sandstone. The Jefferson City Dolomite, is also present and caps the uplands in the study area, it primarily consists of medium- to finely crystalline dolomite.

Structurally there are two known faults trending northwest-southeast south of the study area but no known faults extend thru the project site (Figure 6.5). Topographic lineaments do not suggest that a major bedrock joint set (sets) runs thru the project site. It is common for the Gasconade Dolomite have karst development, but no major karst features such as sinkholes or swallow holes are known to occur in the vicinity of the project. The only known sinkhole, located approximately 3.5 miles away, is shown in Figure 3.3.5. Three springs are shown to surface within 3 miles of the project site; two within the Roubidoux Formation and one at the Roubidoux-Gasconade contact. The Gasconade River is a gaining stream in the vicinity of the project site.

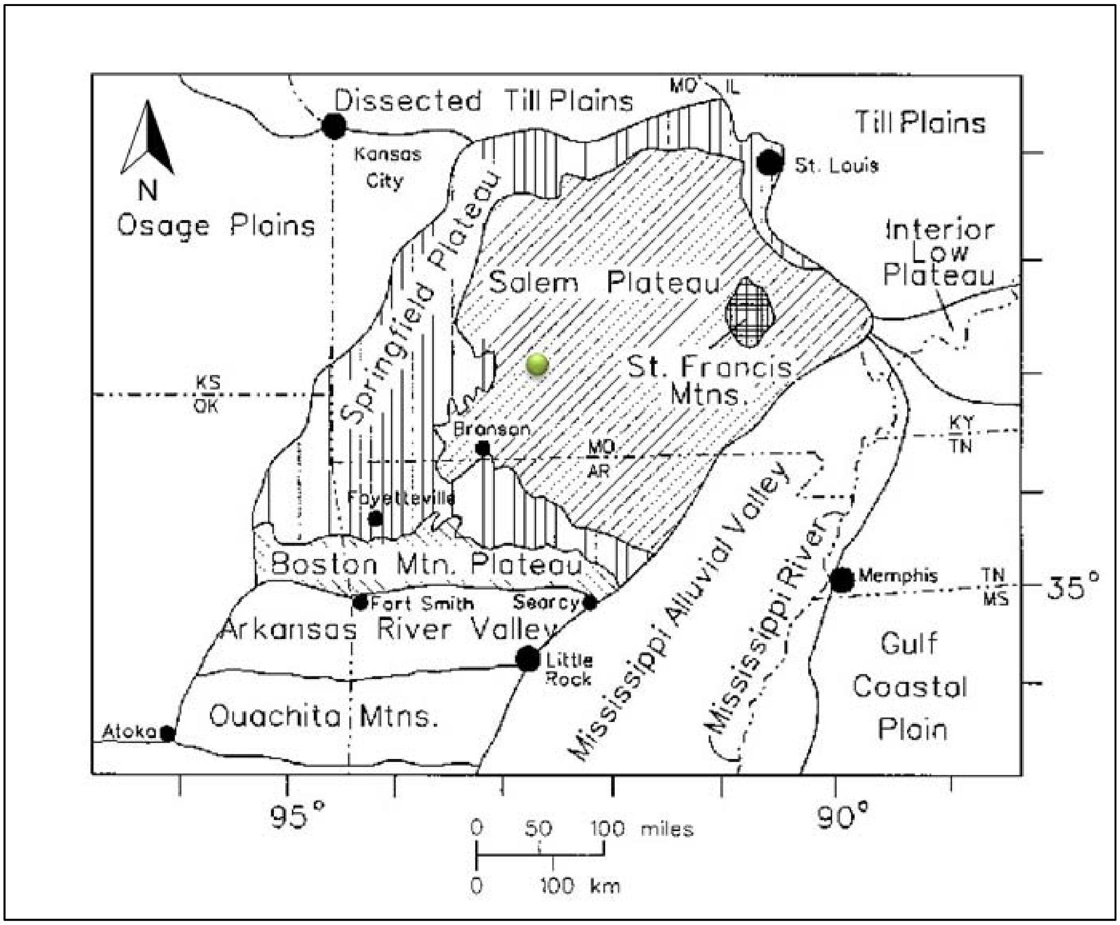

Figure 6.3. Geologic map of the Ozark Plateau (http://www.encyclopediaofarkansas.net/).

Fugure 6.4. Highly weathered, cherty Gasconade Dolomite from borehole T-11-06.

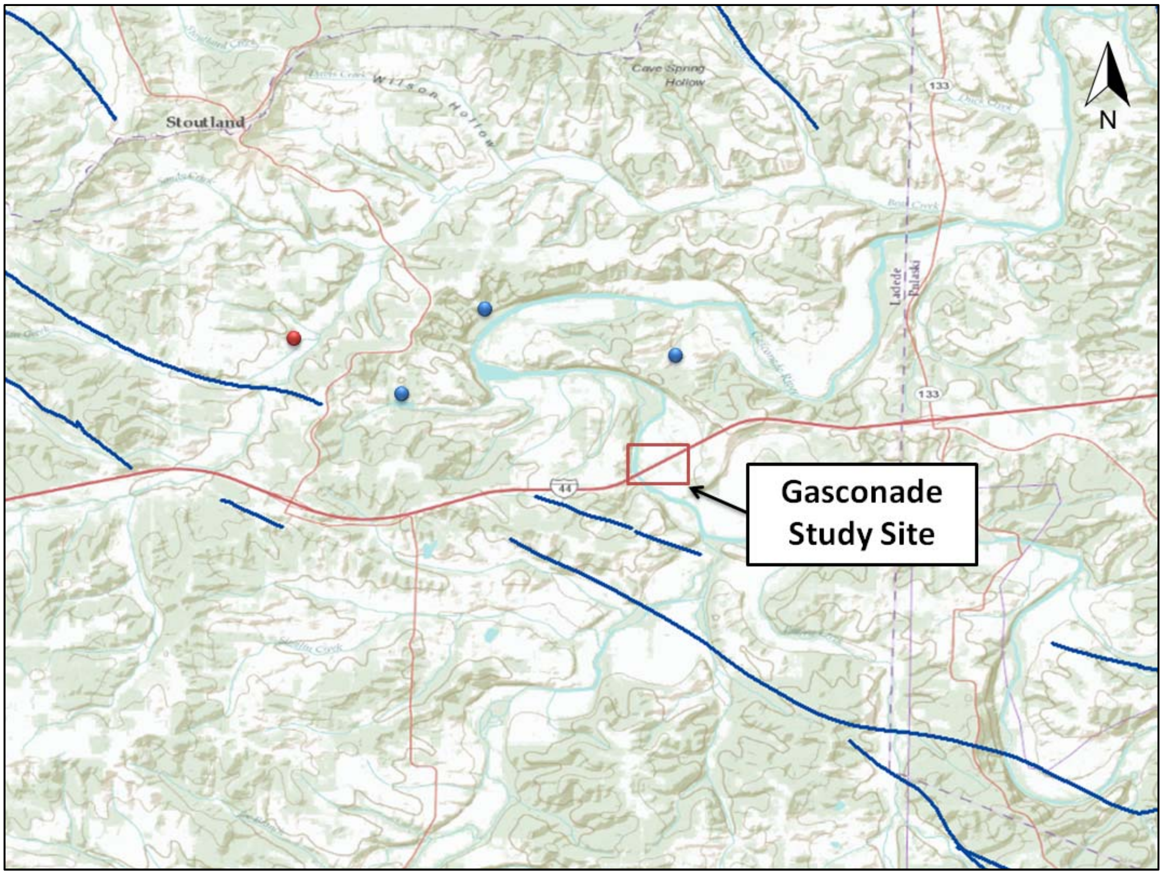

Figure 6.5. Faults, springs and sinkholes in the study area. The study site is marked as red rectangular. The sinkhole is marked as red dot. Springs are marked as blue dots. The mapped faults and lineaments are marked as blue lines (ArcGIS, 2012).

Surficial materials. Bedrock in the study area is overlain by unconsolidated surficial materials consisting of silt, sand, gravel, and boulders. The soil encountered in the borings at the study site consisted of lean clay and silty alluvium with varying amounts of sand and gravel. In general in the study area the surficial materials are mostly residuum, which is the insoluble material left from in situ weathering of the bedrock. Residuum, formed from weathering of the Roubidoux Formation, typically contains more gravel and larger chert fragments and has less clay content than residuum derived from the Jefferson City Dolomite (Vandike, 1992). Residuum at the study site ranges from 14 to 26 feet thick, with the average thickness of 20 ft.

BOREHOLE DATA

Total nine boreholes were drilled at the study site. Boreholes T-11-03 and T-11-07 were near ERT Traverse 1; borehole T-11-05 was located between ERT Traverses 2 and 3; borehole T-11-06 was on ERT Traverse 3; borehole T-11-09 was located between ERT Traverses 3 and 4; boreholes T-11-04, T-11-08, T-11-10 and T-11-11 were located near or on ERT Traverse 4 (Figure 6.6).

Weathered and vuggy rock was encountered at the depth of 18.5 to 23 ft (Table 6.1). The ovelaying soil consisted of soft brown lean clay and gray silty clay, with gravel fragments.

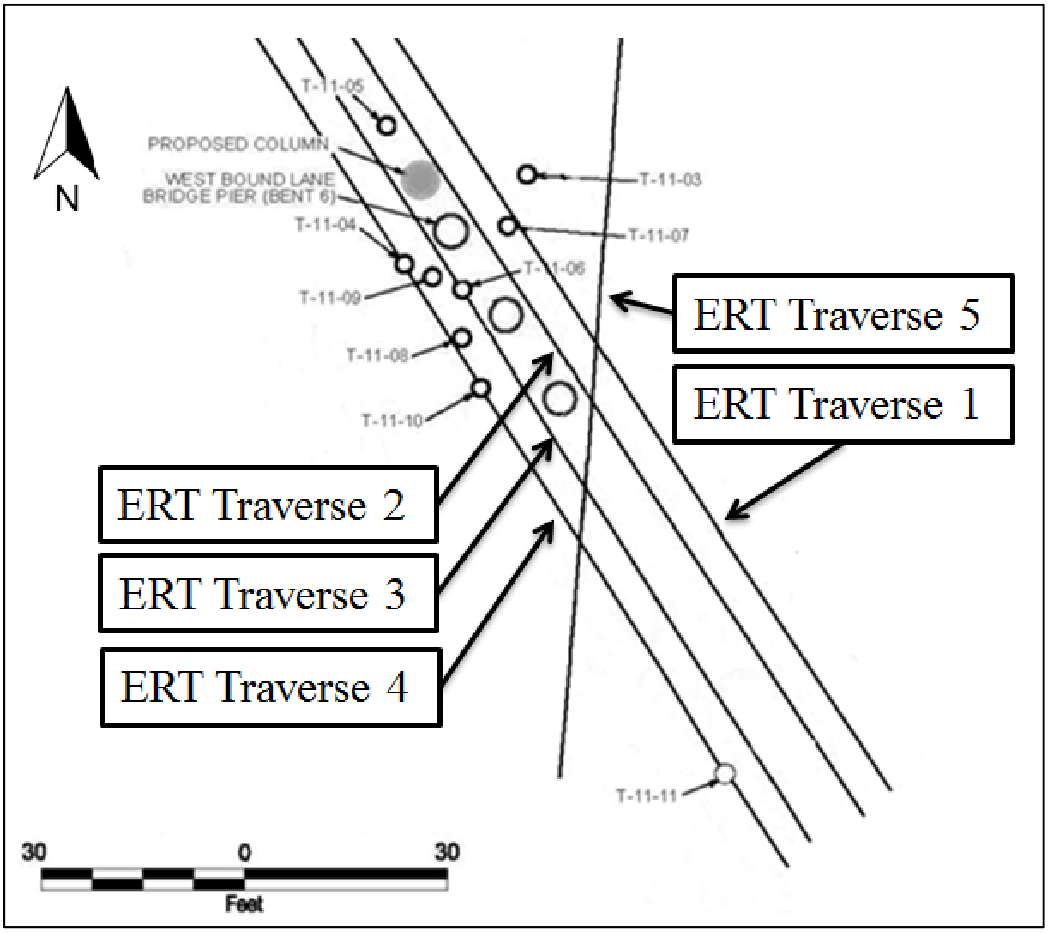

Figure 6.6. Boreholes locations.

During the drilling program competent rock was encountered in the boreholes adjacent to the East Bound Lane Bridge. Water-filled rock openings were encountered in borehole T-11-04 at the depth of 21.2 to 27.7 ft; in borehole T-11-06 at the depth 20.7 to 20.9 ft and 23.4 to 27.0 ft; in borehole T-11-08 at the depth of 22.8 to 27.4 ft; and in borehole T-11-09, immediately adjacent to Bent 6 Bridge L-0698, at the depth of 22.0 to 27.4 ft.

Table 6.1. Boring summary (per driller’s log).

T-11-03	0-20.5’ Soil	20.5-21.3’ Weathered Rock	21.3-33.0’ Hard Rock				
T-11-04	0-20.6’ Soil	20.6-21.2’ Weathered Rock	21.2-27.7’ Void	28.0-28.5’ Rock			
T-11-05	0-18.5’ Soil	18.5-28.0’ Vuggy Rock					
T-11-06	0-18.5’ Soil	18.5-19.0’ Weathered Rock	19.0-20.7’ Vuggy Rock	20.7-20.9 Void	20.9-23.4’ Vuggy Rock	23.4-27.0’ Void	27.0-4.2’ Vuggy Rock
T-11-07	0-19.2’ Soil	19.2-28.4’ Vuggy Rock					
T-11-08	0-22.3’ Soil	22.3-22.9’ Weathered Rock	22.9-27.4’ Void	27.4-34.0 Vuggy Rock			
T-11-09	0-20.5’ Soil	20.5-22.0’ Weathered Rock	22.0-27.4’ Void	27.4-34.2 Vuggy Rock			
T-11-10	0-23.0’ Soil	23.0-25.2’ Weathered Rock	25.2-34.2’ Vuggy Rock				
T-11-11	0-20.8’ Soil	20.8-31.6’ Vuggy Rock					

ELECTRICAL RESISTIVITY TOMOGRAPHY DATA

6.5.1. Acquisition of ERT Data. Electrical resistivity profiles were acquired along five traverses (Traverses 1, 2, 3, 4 and 5, Figure 6.2) in an effort to determine extension of the encountered underground openings in rock during the drilling program and any other rock openings, if present, and map variations in rock quality in immediate proximity to the bridge foundations.

The ERT data were acquired using an AGI SuperSting R8/IP resistivity unit equipped with a dipole-dipole array consisting of 72 electrodes (Figure 6.7). Typical depth of investigation is 20 percent of the length of the electrical resistivity array. With 72 available electrodes and the required depth of investigation 35 ft, a 2.5 ft spacing between the electrodes was chosen for this ERT survey. The ERT data were acquired in February, after two days of rain.

Figure 6.7. Photograph of the study site (looking southeast). ERT data are being acquired on Traverse 3.

ERT Profiles 1, 2, 3 and 4 were acquired on parallel to the bridge bents Traverses 1, 2, 3 and 4, spaced at 5 ft. ERT 5 was acquired along Traverse 5, crossing the Traverses 1, 2, 3 and 4. All the ERT traverses were 177.5 ft long (Figure 6.8). The acquired ERT field data were good quality and were processed using RES2DINV software.

6.5.2. Data Interpretation. Five electrical resistivity profiles were acquired at the study site. ERT profiles 1 to 4 were oriented parallel to the bridge bents (Figures 6.8-6.11); the axis of the fifth ERT profile was oblique to the bridge bent (Figure 6.12). Foundation of Westbound Lane Bridge (I-44 West Bound Lane) was the primary target; foundation of Eastbound Lane Bridge was a secondary target.

All electrical resistivity field data sets were transformed into contoured two-dimensional resistivity images. The contoured values on each ERT profile show distribution of the resistivities in the subsurface along the respective traverses. The depth of investigation extends to a depth of approximately 35 ft in the middle portion of the profiles and decreases toward the ends of the profiles to 0 ft.

Bedrock beneath Westbound Lane Bridge foundation (central part of the ERT profiles 1-4, Figures 6.9 – 6.13), the primary exploration target, was generally characterized by resistivity values 300 ohm-m or less, except on the ERT profile 3 in immediate proximity to the bridge foundations, where resistivity values were up to 1,000 ohm-m, which can be explained by injected grout during the original bridge construction in 1955. The relatively low resistivity of bedrock on the ERT profiles 1 (Figure 6.9), 2 (Figure 6.10) and 4 (Figure 6.12) was most likely related to its high degree of weathering and water saturation. This interpretation was consistent with the borehole data. Water-filled rock openings were encountered in boreholes T-11-04, T-11-06, T-11-08, and T-11-09. Also water-saturated vuggy dolomite, encountered at the study site, could have contributed to low resistivity values of the bedrock.

Top of rock beneath the foundation of westbound lane bridge (location marked as C3 and C4 on the 75-ft mark and 90-ft mark accordingly in Figures 6.14 and 6.15) could not be confidently imaged on all four ERT profiles because the interpreted weathered, vuggy rock most likely filled with highly saturated clays, in places, was characterized by resistivity values similar to the values of the overlying soil. The interpreted top of rock was mapped at a depth of about 20 ft in the northwestern part of the ERT profiles 1 to 4

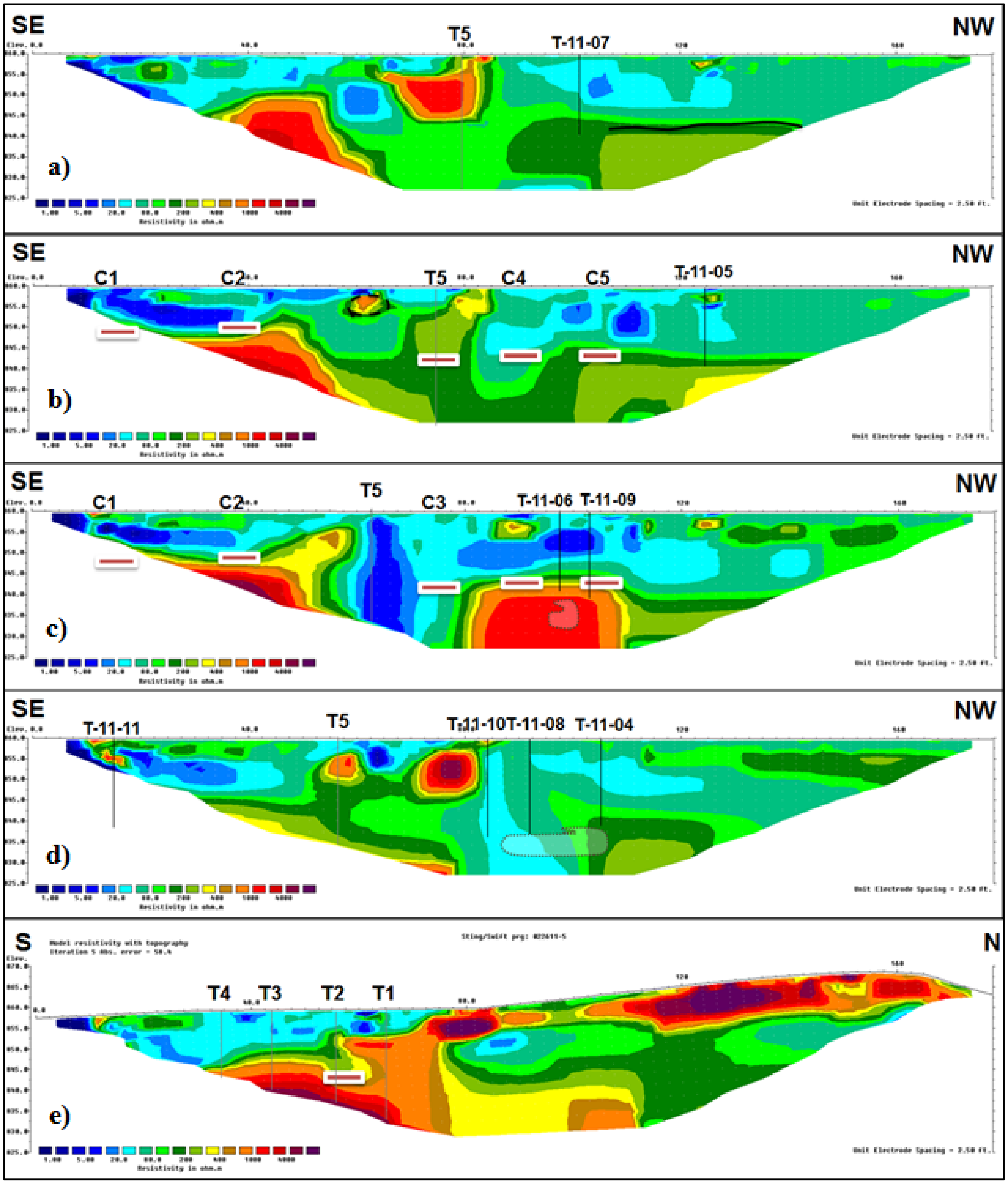

Figure 6.8. Uninterpreted ERT Profiles acquired along Traverses 1-5 accordingly (Figure 6.2): Profile 1 (a), Profile 2 (b), Profile 3 (c), Profile 4 (d), Profile 5 (e). Crossing location of Traverse 5 marked as T5. Foundation (Columns 1 and 2) of eastbound lane bridge marked as C1 and C2. Foundations (Columns 3, 4 and 5) of westbound lane bridge marked as C3, C4 and C5. Rock opening, marked as a dashed polygon, encountered at a depth of approximately 22 to 27 ft in Boreholes T-11-04 and T-11-08, and at a depth of approximately 23 to 27 ft in Boreholes T-11-06 and T-11-09 (Borehole T-11-09 was located between ERT Profiles 2 and 3).

and was consistent with the borehole control. Mapped top of rock in the central part of the ERT profiles 1 to 4 (approximately 55-ft to 85-ft mark, marked as dashed line) could also be gravel from construction of the bridge foundation. No borehole control was available at that location. Rock in central part of the ERT profiles 1 to 4 was interpreted as highly weathered with resistivity values ranging between 120 and 300 ohm-m.

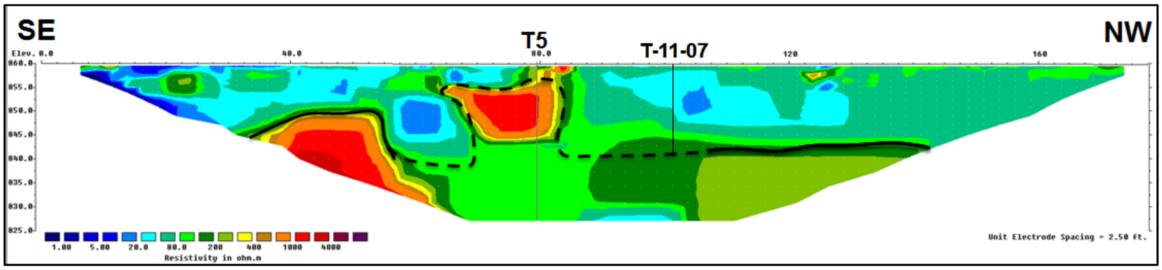

Figure 6.9. Interpreted ERT Profile 1, acquired along Traverse 1 (Figure 6.2). Solid black line represents interpreted top of bedrock, dashed black line shows estimated depth to top of rock. Crossing location of Traverse 5 marked as T5. Vuggy dolomite was encountered at a depth 19.2 ft in Borehole T-11-07.

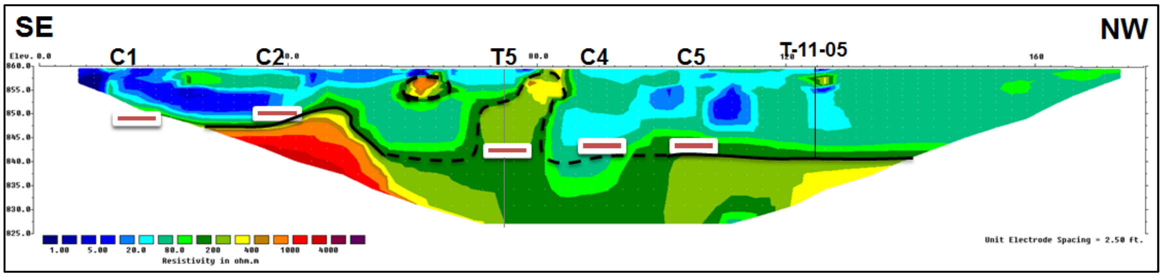

Figure 6.10. Interpreted ERT Profile 2, acquired along Traverse 2 (Figure 6.2). Solid black line represents interpreted top of bedrock, dashed black line shows estimated depth to top of rock. Crossing location of Traverse 5 marked as T5. Foundations (Columns 1 and 2) of eastbound lane bridge marked as C1 and C2. Foundations (Columns 3, 4 and 5) of westbound lane bridge marked as C3, C4 and C5. Vuggy dolomite encountered at a depth 18.5 ft in Borehole T-11-05.

Top of rock in proximity to the foundation of the eastbound lane bridge (location marked as C1 and C2 in Figures 6.10 and 6.11) was interpreted at a depth of approximately 10 ft immediately to the east of the structure (Figure 6.10), to 16 ft immediately to the west of the structure (Figure 6.11). Top of rock in proximity to the foundation of the eastbound lane bridge (location marked as C1 and C2 in Figures 6.10 and 6.11) was interpreted at a depth of approximately 10 ft immediately to the east of the structure (Figure 6.14), to 16 ft immediately to the west of the structure (Figure 6.11). Bedrock beneath the eastbound lane bridge foundation was characterized by resistivity values of 300 ohm-m and higher and was interpreted as competent rock. The interpretation was consistent with limited borehole control (borehole T-11-11). The overlying soil was characterized by resistivity values of less than 300 ohm-m, except where shallow gravels appeared to be present.

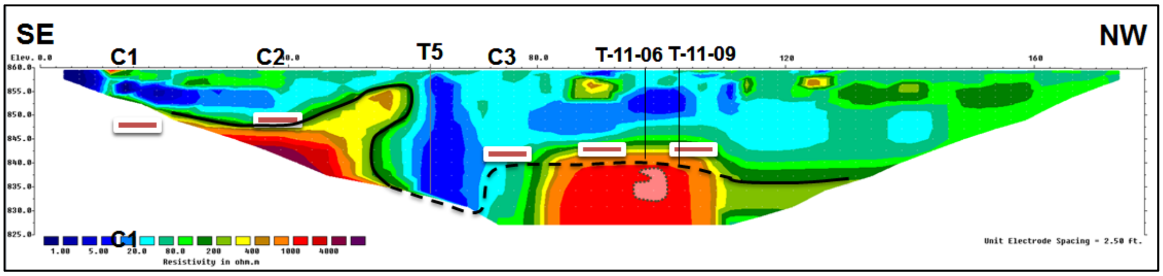

Figure 6.11. Interpreted ERT Profile 3, acquired along Traverse 3 (Figure 6.2). Solid black line represents interpreted top of bedrock, dashed black line shows estimated depth to top of rock. Crossing location of Traverse 5 marked as T5. Foundations (Columns 1 and 2) of eastbound lane bridge marked as C1 and C2. Foundations (Columns 3, 4 and 5) of westbound lane bridge marked as C3, C4 and C5. Weathered rock encountered at a depth 18.5 ft in Borehole T-11-06 and at a depth 20.5 ft in Borehole T-11-09. Rock openings, marked as dashed polygon, encountered at a depth of approximately 23 to 27 ft in Boreholes T-11-06 and T-11-09 (Borehole T-11-09 was located between the ERT profiles 2 and 3).

Side-by-side comparison of the ERT profiles 1-4 is shown in Figure 6.14. A linear geological feature was observed on all five ERT profiles (Figure 6.14 and 6.15). This feature was interpreted as a set of solution-widened joints with clay infill, trending southwest-northeast (Figure 6.16). Solution-widened joint is a typical feature for karst landform. An example of solution-widened joints with vuggy dolomite is shown in Figure 6.17.

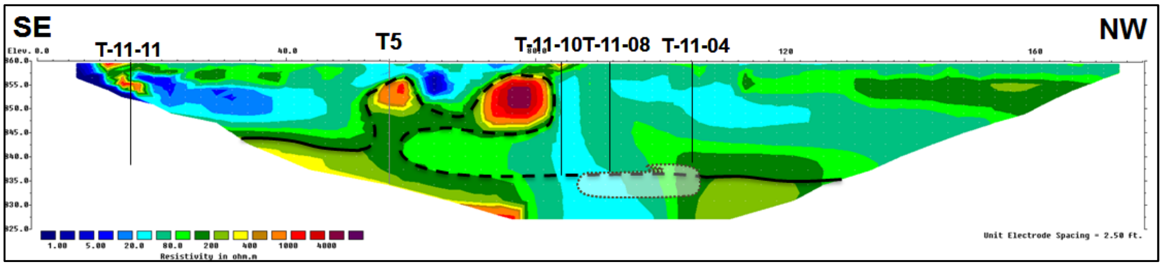

Figure 6.12. Interpreted ERT Profile 4, acquired along Traverse 4 (Figure 6.2). Solid black line represents interpreted top of bedrock, dashed black line shows estimated depth to top of rock. Crossing location of Traverse 5 marked as T5. Vuggy dolomite encountered at a depth of 20.8 ft in Borehole T-11-11; weathered rock encountered at a depth of 23 ft in Borehole T-11-10, 22.3 ft in Borehole T-11-08, and 20.6 ft in Borehole T-11-04. Rock opening, marked as a dashed polygon, encountered at a depth of approximately 22 to 27 ft in Boreholes T-11-04 and T-11-08.

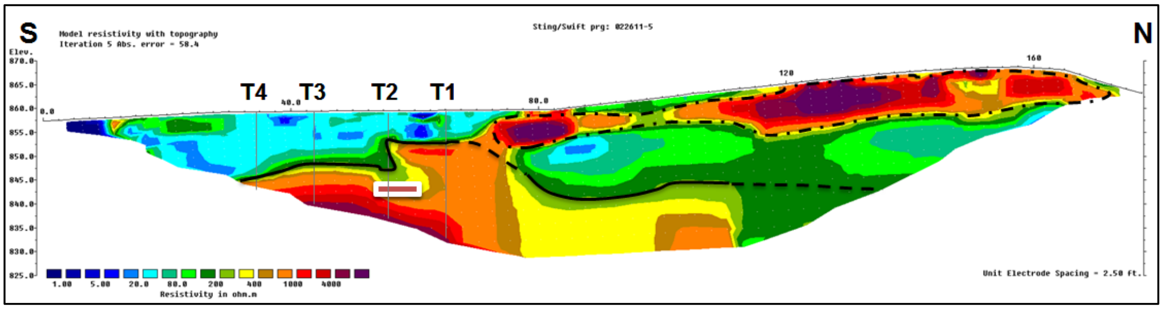

Figure 6.13. Interpreted ERT Profile 5, acquired along Traverse 5 (axis oblique to Profiles 1-4, Figure 6.2). Solid black line represents interpreted top of bedrock, dashed black line shows estimated depth to top of rock. Crossing location of Traverses 1, 2, 3 and 4 marked as T1, T2, T3 and T4 accordingly. Interpreted embankment fill (marked as dashed/dotted line) in the top part of the profile characterized by resistivity values of 400 ohm-m and higher. The central part of the profile (80-ft to 105-ft mark) has lower resistivities (400 ohm-m or less) compared to the surrounding rock with the values of 500 ohm-m or higher.

This prominent geologic feature is characterized by an approximately 25-ft wide low resistivity zone (compared to surrounding resistivity values at comparable depths in the study area), imaged on the ERT profiles 1-4 at about 85 to 100 ft mark (Figure 6.14) and on the ERT profile 5 at about 75 to 110 ft mark (Figure 6.15).

The interpreted set of solution-widened joints, trending southwest-northeast, was superposed on the ERT profiles location map (Figure 6.16) and on a map of known faults and lineaments with marked preferential surface flow path in the study area (Figure 6.18). The orientation of the interpreted set of solution-widened joints was consistent with the preferential surface path flow oriented southeast-northwest and perpendicular to the known faults and lineaments in the study area.

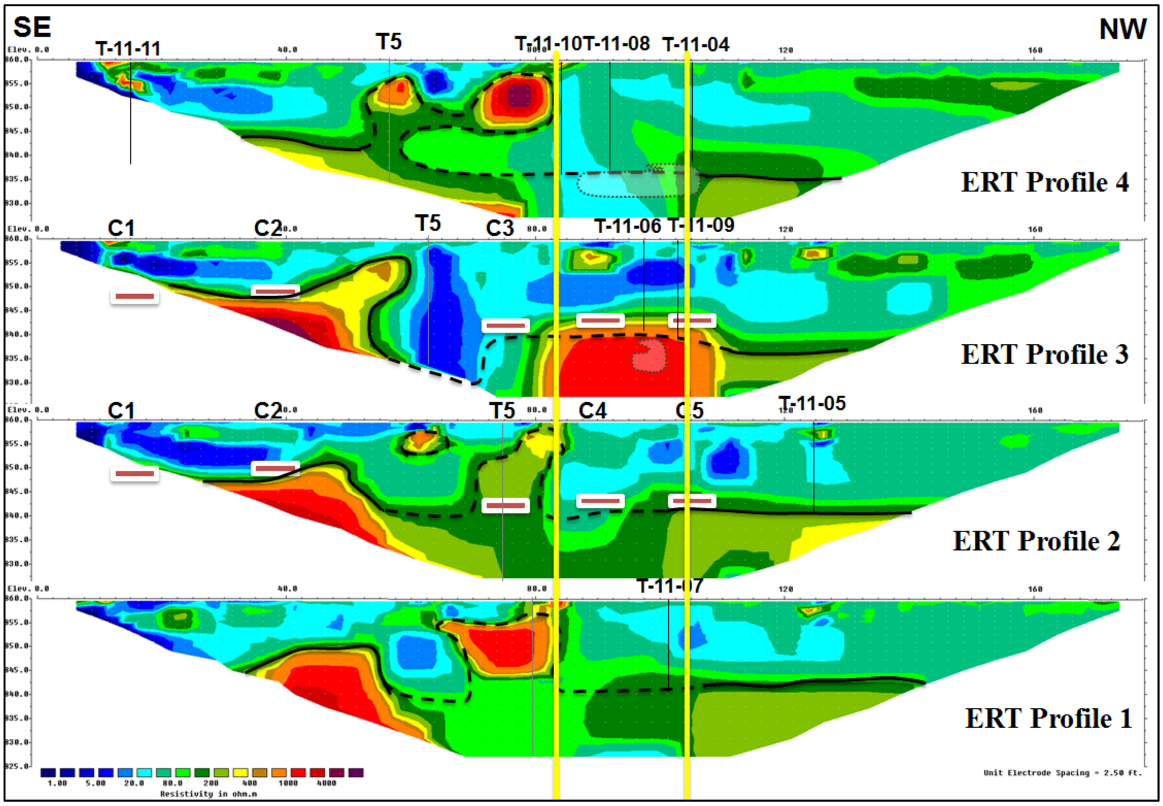

Figure 6.14. Side-by-side comparison of ERT Profiles 1-4 with mapped solution-widened joints. Anomalously low bedrock resistivity zone interpreted as a set of solution-widened joints with clay infill, trending southeast-northwest. This zone, with marked boundaries as yellow lines, extends from about 85 ft to 100 ft mark.

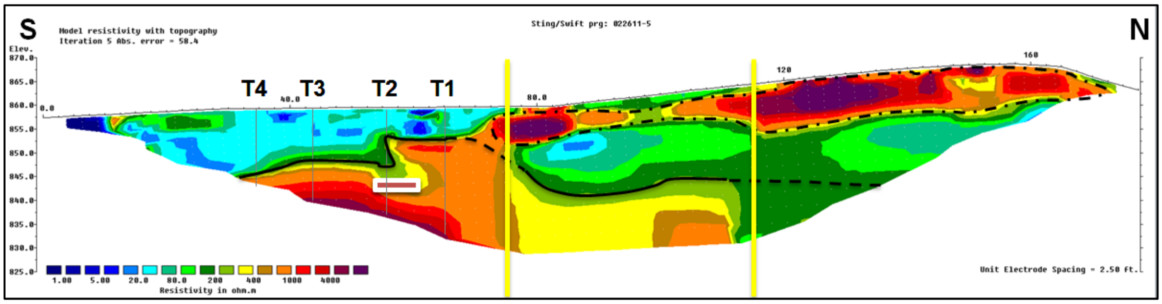

Figure 6.15. Interpreted ERT Profile 5 with mapped solution-widened joints. Anomalously low bedrock resistivity zone interpreted as a set of solution-widened joints with clay infill, trending southeast-northwest. This zone, with marked boundaries as yellow lines, extends from about 75 ft to 110 ft mark.

The interpreted electrical resistivity tomography data and borehole control did not indicate the presence of other than the encountered water-filled rock openings at the study site. However volume of injected grout (78 cubic yards) suggested the area of extension of the water-filled rock opening, assuming the rock opening height 5 ft, was up to approximately 32 ft by 17 ft (Figure 6.16). The ERT method was not able to map the water-filled rock opening due to the similar resistivity values of saturated weathered and vuggy rock and water-filled rock opening.

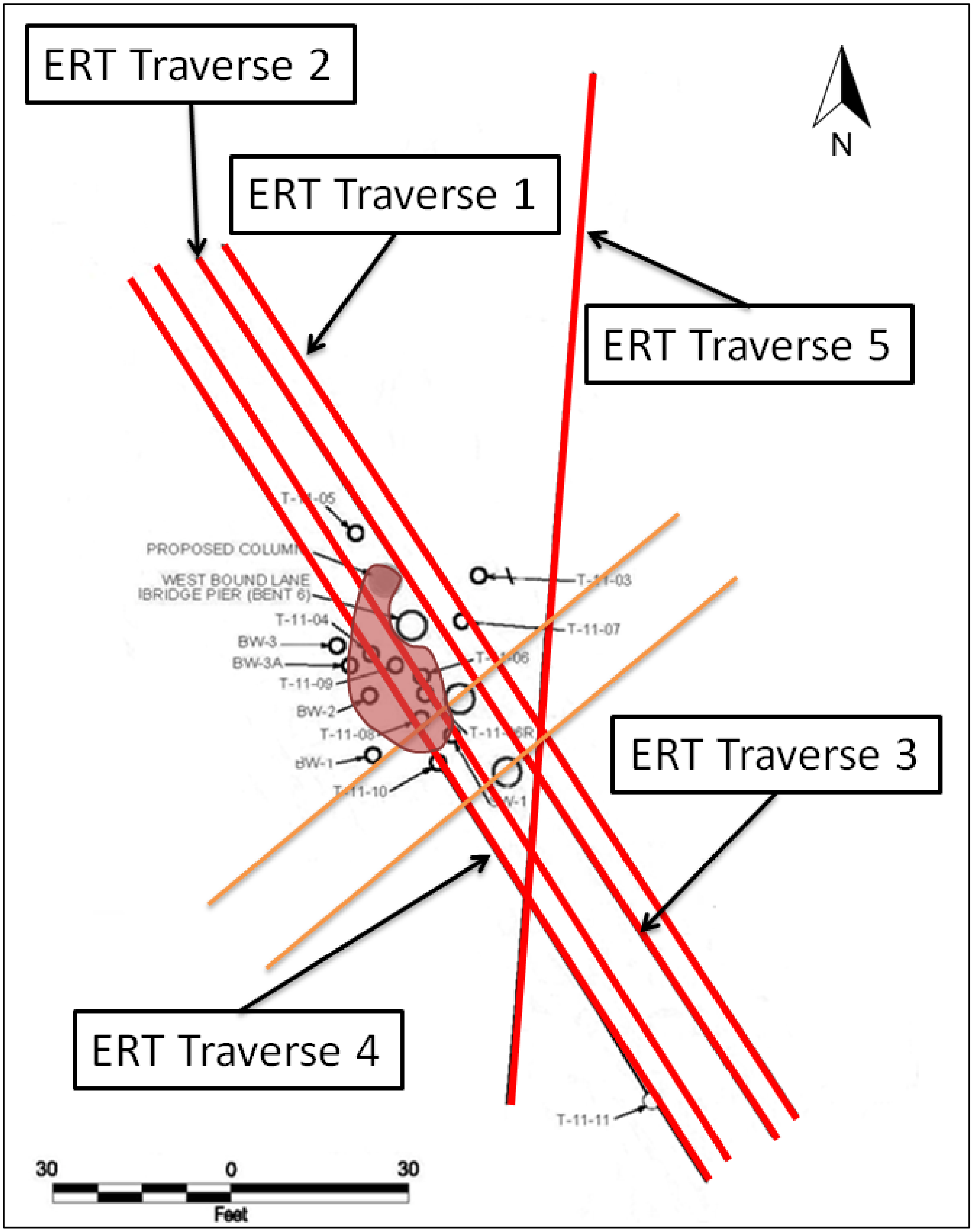

Figure 6.16. Interpreted set of solution-widened joints superposed on the ERT profiles and boreholes location map. Orange lines show mapped zone of solution-widened joints trending southwest-northeast. Red polygon shows estimated extension of the water-filled rock opening assuming with the assumed height 5 ft was over 400 square ft.

Figure 6.17. Premier example of karst landform features in Late Cambrian Eminence Dolomite in Ha Ha Tonkas State Park, Missouri: vugs (A), karst developed along bedding planes (B), vertical solution-widened joints (C).

Also according to the interpretation it was concluded that the east bound lane bridge foundation was founded on relatively more competent and shallower rock at a depth of 10 ft, the top of weathered, highly fractured and vuggy rock beneath the west bound lane foundation was at a depth of about 20 ft.

Rock opening development could be explained by a conceptual model (Figure 6.19): first the river bank is undercut by the meandering stream, and subsequently filled with sediments such as alluvium. After the bridge foundations were installed, traffic created vibrations in the rock. The vibrations caused subsidence of the sediments, piping effect of fine-grained sediments by the losing/gaining stream (Vandike, 1995) caused its removal and later created water-filled rock opening.

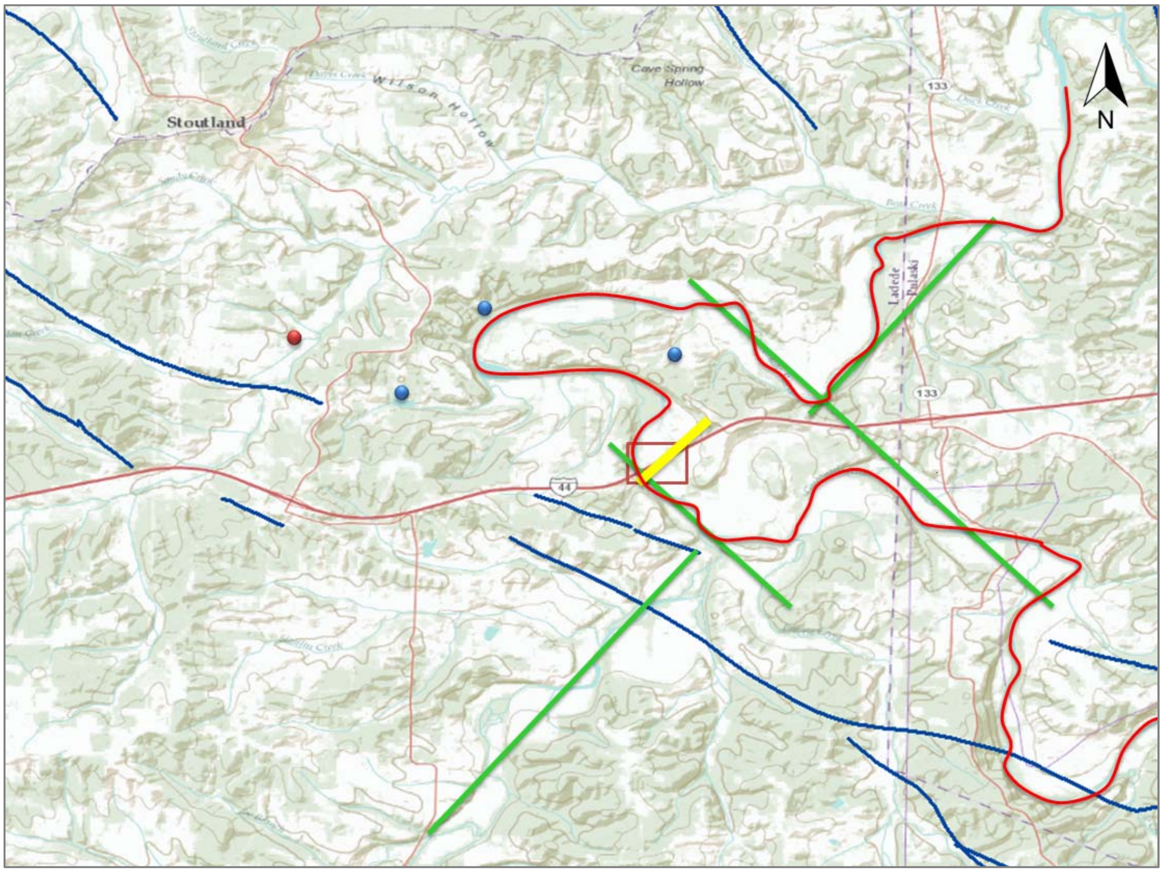

Figure 6.18. Interpreted set of solution-widened joints (not to scale) superposed on a map of known faults and structural lineaments in the study area. Study site is marked as red rectangular, known faults marked as blue lines (ArcGIS). The Gasconade River marked as red line, preferential surface water flow directions marked as green lines, yellow line represents orientation of the interpreted set of solution-widened joint, trending southwest-northeast.

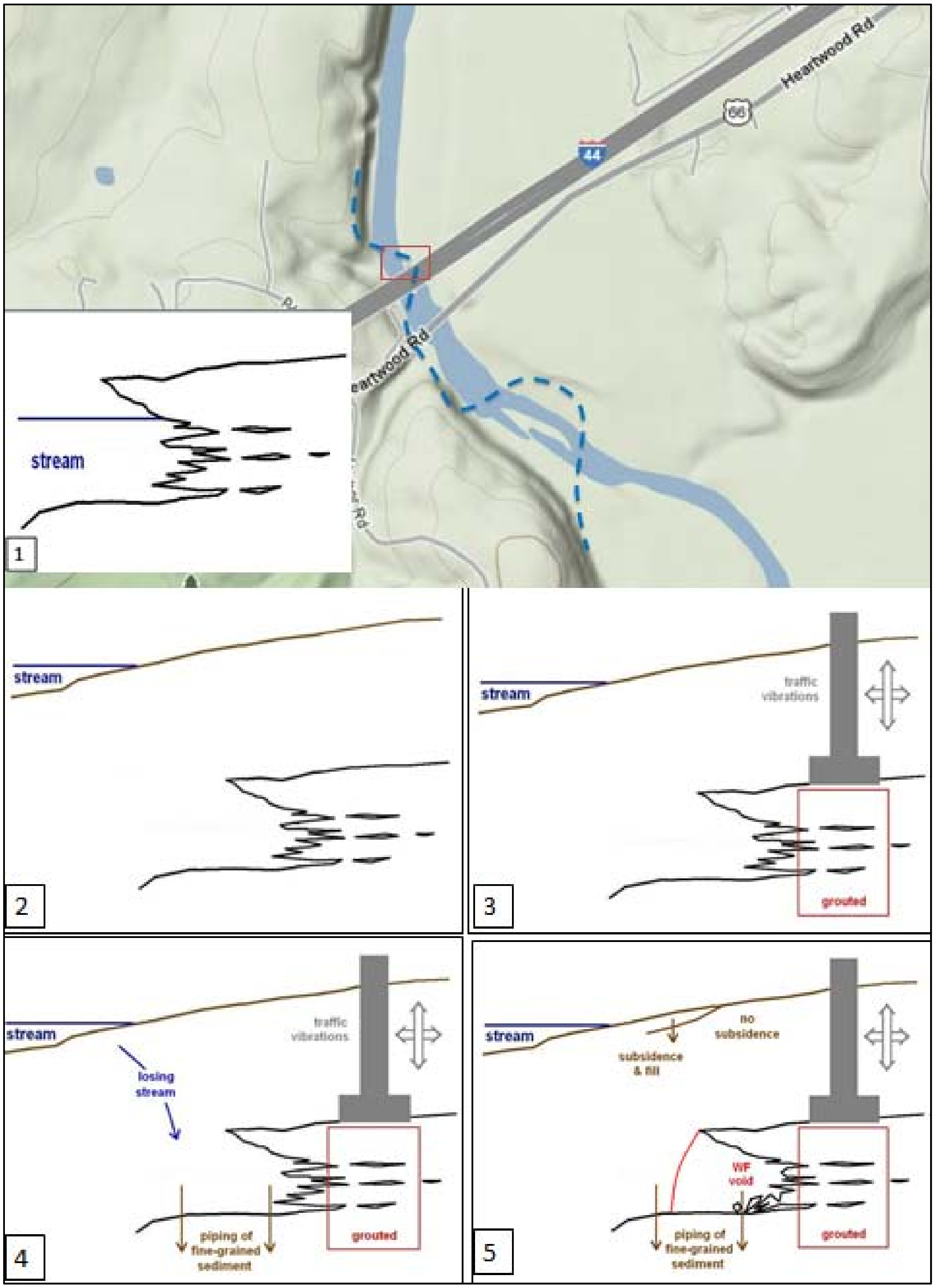

Figure 6.19. Five-stage conceptual model of water-filled rock opening developing at the study site. Stage 1 – river bank undercut by stream, 2 – stream channel is filled with sediment, 3 – bridge foundations installed on top of grouted rock, traffic creates vibrations of rock, 4 – traffic vibrations cause subsidence of sediment covered by overhanging layer of dolomite, and losing/gaining stream by piping effect of fine-grained sediments creates water-filled rock opening adjacent to the overhanging layer of dolomite.

6.6. CONCLUSION

Interpretation and analyses of the electrical resistivity tomography data and borehole control did not indicate any water-filled or air-filled rock openings except the encountered one were present at the study site. The rock opening encountered during the drilling program, was water-filled and most likely developed by a combination of factors such as meandering stream activity, traffic vibration and piping effect of a losing/gaining stream. Based on the injected grout volume of 78 cubic yards and the electrical resistivity tomography data with borehole control it was estimated that encountered water-filled rock opening was up to 6 ft high and could have an area extension of over 400 square ft.

This water-filled rock opening had resistivity values similar to surrounding vuggy and weathered rock high in water content. Due to these geological conditions it was difficult to differentiate the rock openings from the surrounding weathered and vuggy saturated rock. Also in some places it was impossible to differentiate soil overlaying rock based only on the ERT data. Based on the ERT and the borehole data it was concluded that the foundations of the eastbound lane bridge were found on shallower and competent rock. Westbound lane bridge foundations were found on fractured and weathered rock, which was grouted prior to an initial bridge construction in the 1950-s.

A set of solution-widened joints, trending southwest-northeast was mapped based on the interpretation of the ERT data. Analyses of the known faults and structural lineaments, trending south-east and southeast-east-northwest-west, supported the interpretation that a solution-widened fracture zone, trending southwest-northeast, runs thru the study site. The solution-widened fracture zone also follows the orientation of the preferential surface water flow.