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Non-invasive Imaging and Assessment of Pavements

by

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16. Abstract

Currently, there are over 3.96 million public centerline road miles in the U.S. and of this, 2.50 million miles (or about 63 percent) are paved (FHWA, 2002). Pavement deterioration is a significant problem that must be addressed to preserve highway infrastructure investments in highways in United State and around the world. Accurately evaluating condition of pavement and sub-pavement soil/rock over time and using this information to choose appropriate maintenance techniques is critical in terms of the responsible maintenance of roadways. In order to demonstrate the utility and cost-effectiveness of using geophysical tools to assess roadway and sub-roadway conditions, I propose to acquire geophysical control along total of eight segments of roadway in central Missouri (Figure 1) to assess the condition of pavement, base and native soil all the way down to the top of bedrock. Each segment of road way will be approximately 1000 ft. long. Geophysical data will be acquired at these different locations using; Electrical Resistivity Tomography, Multi-Channel Analysis of Surface Wave, Ground Penetrating Radar using both 1.5 GHz and 400 MHz, Portable Seismic Property Analyzer and Ohm Mapper methods. Core control (surface to native soil) and falling weight deflect meter control will be acquired along the test segments in order to constrain the interpretation of the acquired geophysical data. Data will be collected under different weather conditions (wet, dry, warm and cold) to assess the impact of these climatic conditions on the data quality and interpretability. The test sites will be selected so, data will be acquired in different geological environments and with very different pavement condition (including asphalt over concrete, asphalt reinforces concrete, thick asphalt, thin asphalt, good asphalt and poor asphalt). The reason of using these geophysical techniques is because the utility and cost-effectiveness of these techniques has not been demonstrated yet because they are not routinely applied to the investigation of roadways and the use of these geophysical techniques could result in decreased cost and time and increased safety. The tools to be tested will generate reliable information about pavement thickness, pavement/base/sub-grade elastic moduli, base and sub-grade moisture content, base thickness, sub-grade clay content, depth to top of rock. Information can also be generated about the thickness, elastic moduli, clay content and moisture content of the soil. A secondary objective is to assess the accuracy of the interpretations and the various factors that affect the reliability of the interpretations

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Pavements, concrete, asphalt, ground penetrating radar, surface

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1. Project Summary

Currently, there are over 3.96 million public centerline road miles in the U.S. and of this, 2.50 million miles (or about 63 percent) are paved (FHWA, 2002). Pavement deterioration is a significant problem that must be addressed to preserve highway infrastructure investments in highways in United State and around the world. Accurately evaluating condition of pavement and sub-pavement soil/rock over time and using this information to choose appropriate maintenance techniques is critical in terms of the responsible maintenance of roadways. In order to demonstrate the utility and cost-effectiveness of using geophysical tools to assess roadway and sub-roadway conditions, I propose to acquire geophysical control along total of eight segments of roadway in central Missouri (Figure 1) to assess the condition of pavement, base and native soil all the way down to the top of bedrock. Each segment of road way will be approximately 1000 ft. long. Geophysical data will be acquired at these different locations using; Electrical Resistivity Tomography, Multi-Channel Analysis of Surface Wave, Ground Penetrating Radar using both 1.5 GHz and 400 MHz, Portable Seismic Property Analyzer and Ohm Mapper methods. Core control (surface to native soil) and falling weight deflect meter control will be acquired along the test segments in order to constrain the interpretation of the acquired geophysical data. Data will be collected under different weather conditions (wet, dry, warm and cold) to assess the impact of these climatic conditions on the data quality and interpretability. The test sites will be selected so, data will be acquired in different geological environments and with very different pavement condition (including asphalt over concrete, asphalt reinforces concrete, thick asphalt, thin asphalt, good asphalt and poor asphalt). The reason of using these geophysical techniques is because the utility and cost-effectiveness of these techniques has not been demonstrated yet because they are not routinely applied to the investigation of roadways and the use of these geophysical techniques could result in decreased cost and time and increased safety. The tools to be tested will generate reliable information about pavement thickness, pavement/base/sub-grade elastic moduli, base and sub-grade moisture content, base thickness, sub-grade clay content, depth to top of rock. Information can also be generated about the thickness, elastic moduli, clay content and moisture content of the soil. A secondary objective is to assess the accuracy of the interpretations and the various factors that affect the reliability of the interpretations.

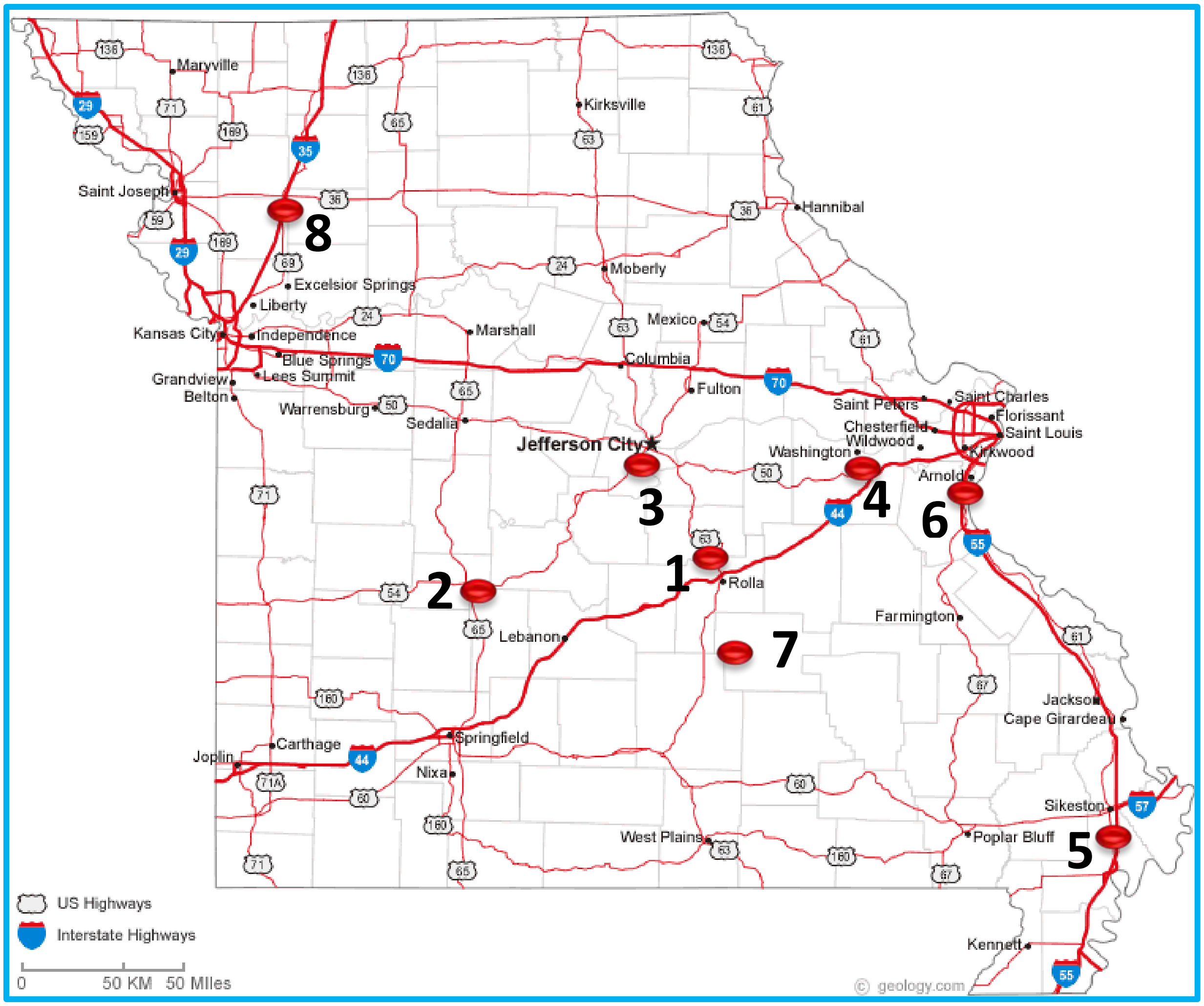


Figure 1. Study site locations (eight segments of road way, these segments are project level. Each segment of road is approximately 1000 ft.). (1) US 63 North of Rolla; (2) US 54 Camden County; (3) MO 179 Jefferson City; (4) HWY AT Franklin County; (5) I-55 Pemiscot County; (6) I-55_MM137_NB_PerryCounty; (7) HWY U Dent County; (8) I-35 Daviees County.

2. Overview of Pavement

2.1 Pavement Structures

‘Pavement’ is defined as an engineered structure was designed to transport vehicles load (differentiated from a ‘footway’ which is built for walkers only) and the importance of well built and maintained pavement structures has been recognized for many years. Mostly, pavements comprise of several layers of materials placed over the natural ground (‘subgrade’), as showed in (Figure 2).

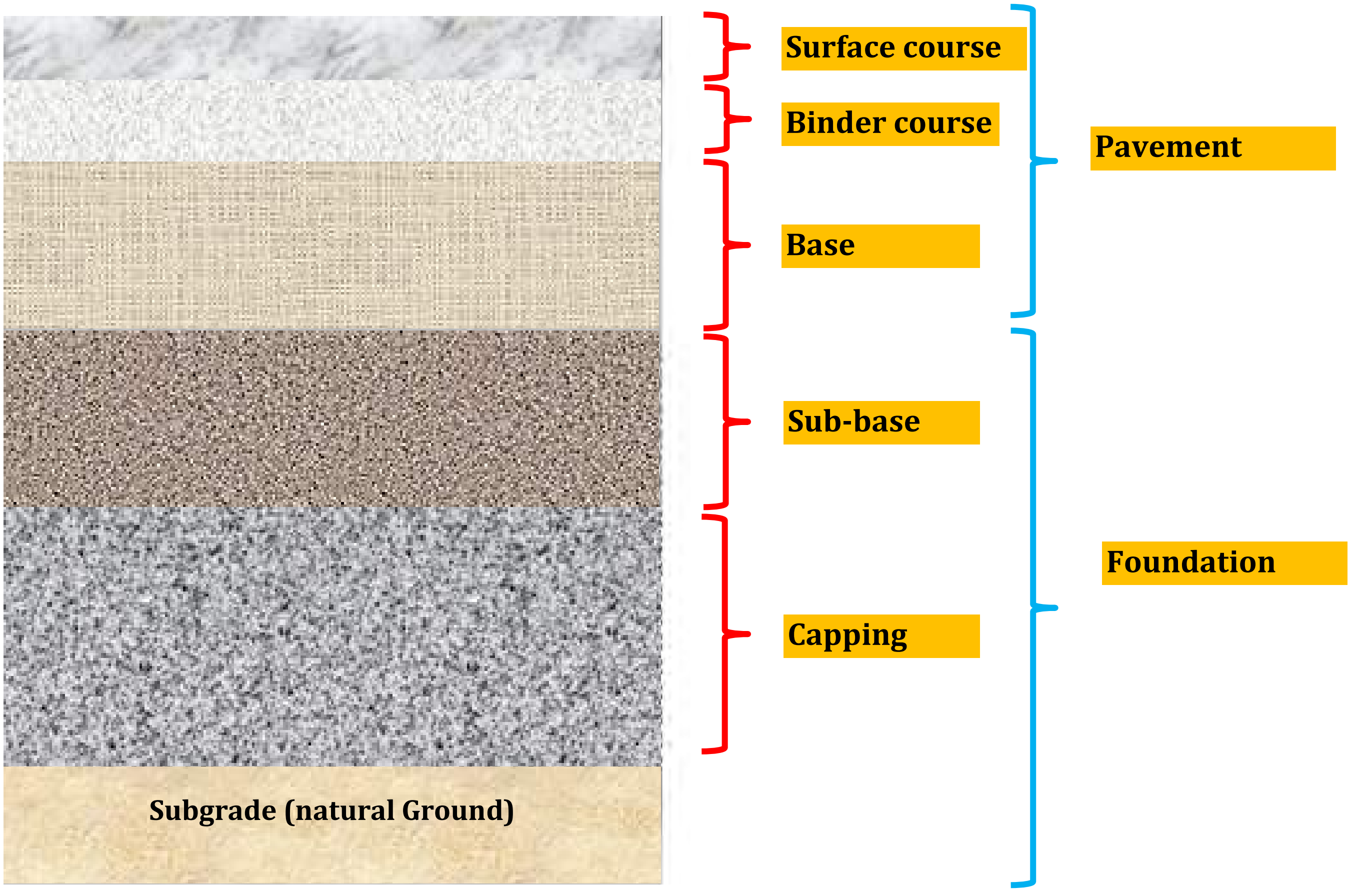


Figure 2. Typical layers in a pavement structure.

Above the subgrade will be ‘sub-base’ which is mostly a layer of un-bound compacted aggregate to save the subgrade from the action of weather changes and to provide a platform for construction of the upper layers of pavement. (Occasionally a ‘capping’ layer is also included below the sub-base, comprising of lower grade compacted unbound aggregate). The tow base layers including capping (if there is) are together considered to be the foundation of the pavement structure. Above the sub-base the main structural layer of the pavement, known as the ‘base’ (or ‘road base’), is constructed. This usually comprises of a chosen crushed rock material bound together with bitumen to form an asphalt layer, or cement to form cement bound material (CBM) layer. After that comes the base layer is the pavement surfacing that is often provided in two bound material layers, known as the ‘binder course’ and the ‘surface course’. When bitumen bound material (asphalt) only is used in the pavement, each layer comprises of a small different mix of aggregate and bitumen greatest suited to implement the function necessary, but after the pavement is constructed from CBM only, the function of all the bound layers (surface course, binder course and base) is provided by a single concrete slab (which sometimes may has steel reinforcement). The material used for high strength pavement slabs is often referred to as pavement quality concrete (PQC). Pavements that comprise only of asphalt material are known as ‘flexible’ pavements, and other that with CBM only are termed ‘rigid’ pavements (Figure 3 A and B). Likewise, several pavements are designed with a CBM base layer and asphalt surfacing, and these are called ‘composite’ pavements.

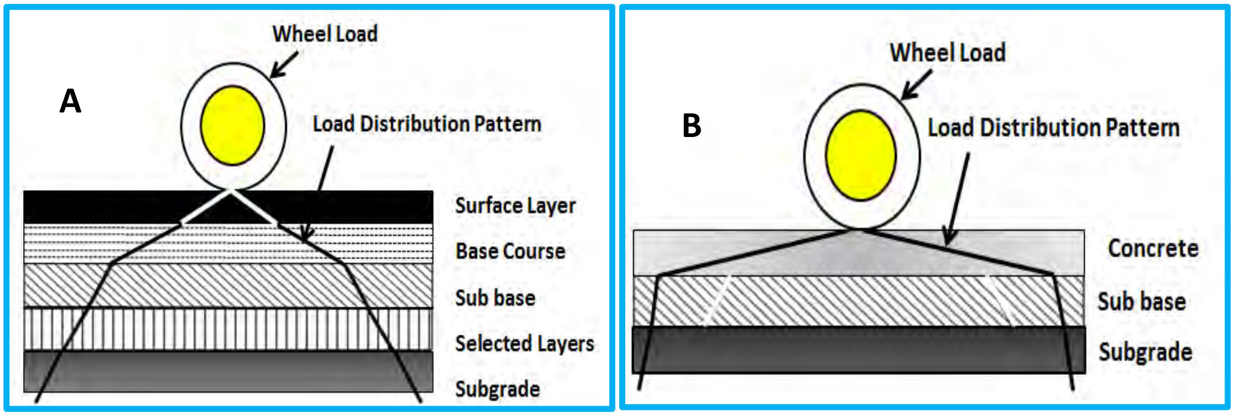


Figure 3. Shows both pavement types and the distribution load patterns on both kinds (A) Flexible pavements (B) Rigid pavements.

Even though CBM is still a commonly known description, recently the term ‘hydraulically bound mixture’ (HBM) has entered use, which is used as a generic term for pavement material comprising of aggregate bound with any binder that needs the presence of water (which includes cement, but also lime, slag, fly ash and others). Thus, as CBM is a type of HBM, the use of the term HBM to refer to cement bound materials is becoming more general (Thom 2008 and Highways Agency, 2008).

The Missouri state highway system covers of about 71,357 lane-miles of pavement. It has only three different types of pavement. The types include, portland cement concrete (PCC), asphalt concrete (AC) overlaid PCC, full-depth AC, and AC overlaid AC. The types of roadway vary from low-volume rural collectors to multi-lane, high-volume urban Interstates. And also it divides into three functional categories addressed in the Missouri Long Range Transportation Direction (LRTD): the National Highway System (NHS), remaining arterials and collectors. These groups represent different levels of functional importance that need different levels of rehabilitation and maintenance effort. (MoDOT. 2002) (Figure 3).

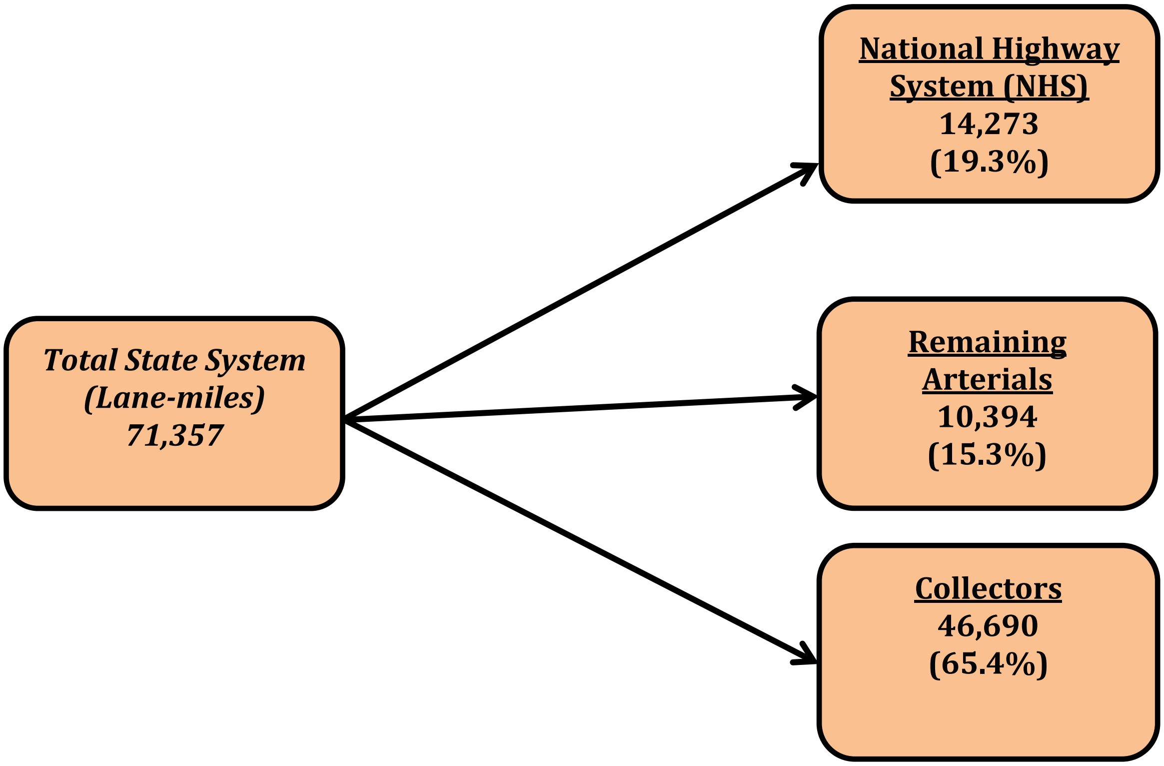
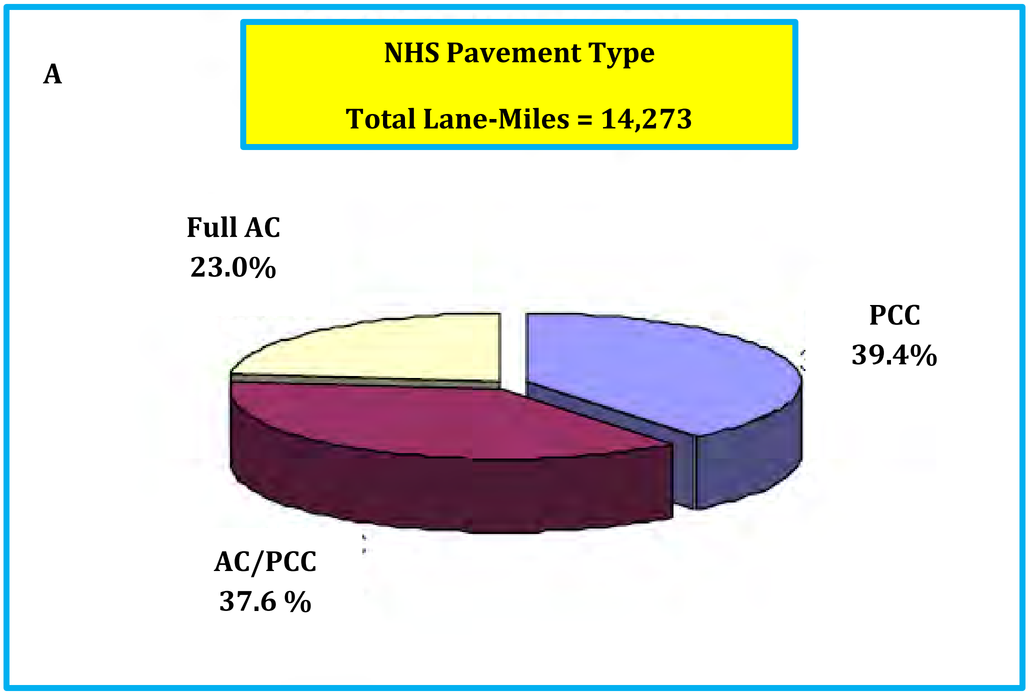
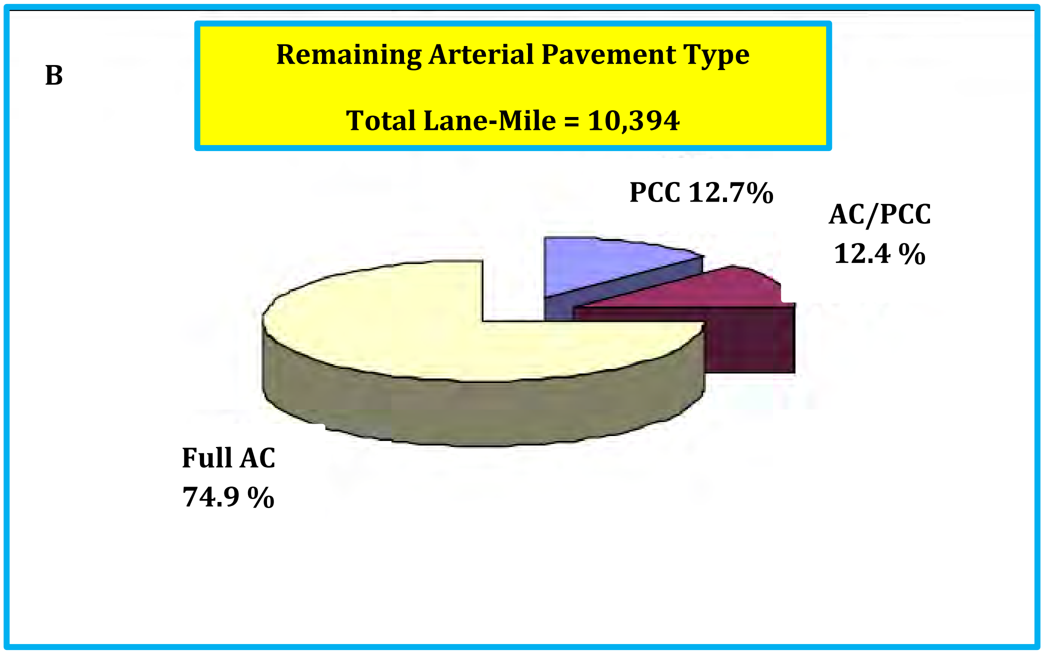


Figure 3. Sketch shows what makes up the Missouri state highway system.

Missouri's NHS occupied around 14,273 miles total of the Missouri highway system. It is mostly portland cement concrete (PCC) or PCC overlaid with asphalt concrete (AC) (MoDOT 2002). The percentage of AC/PCC may actually be higher and full-depth AC lower because of uncertainty about the historical records for some full-depth AC pavements. The whole Interstate system was initially paved with PCC, except for few short stretches on I-44 (Figure 4 A). However the remaining arterials are about 10,394 miles of the Missouri highway system. It comprises about 75 percent of full-depth AC. The rest is evenly split between bare and overlaid PCC. The percentage of AC/PCC may actually be higher and full-depth AC lower because of uncertainty about the historical records for some full-depth AC pavements (Figure 4 B) while collectors that serve smaller towns and traffic generators that are not on arterial routes occupied around 46,690 miles, and these routes are predominantly AC (Figure 4 C). (MoDOT 2002).





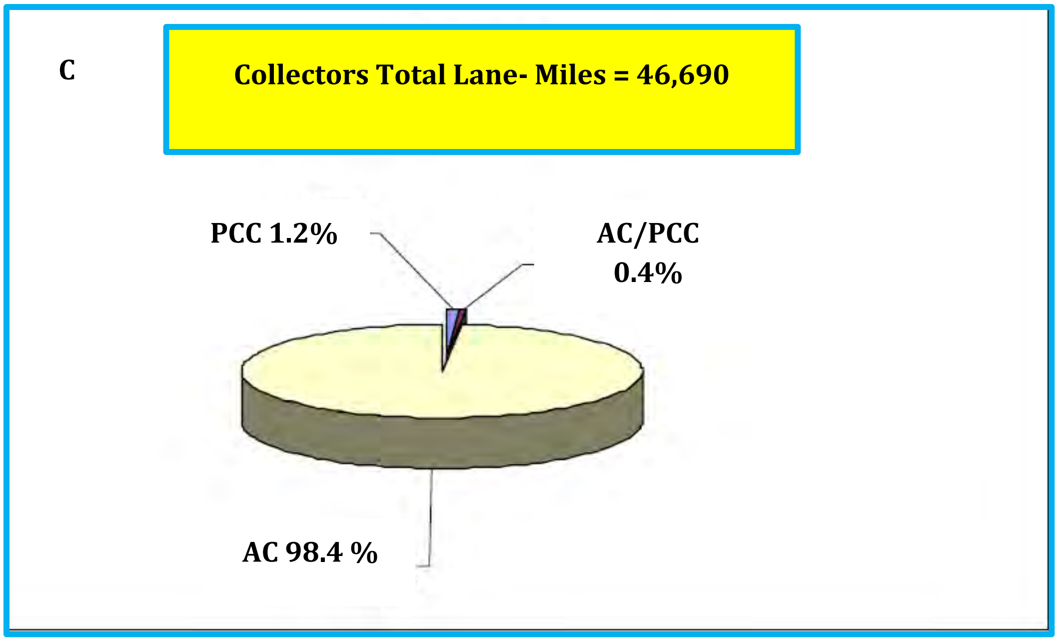


Figure 4. Total mileage and percentage for the different pavements types across Missouri State a) NHS pavement, type total lane-miles = 14,273 b) Remaining arterial pavement type, total Lane-Mile = 10,394 C) Collectors, total lane- miles = 46,690.

As it was mentioned the Missouri state highway system covers of about 71,357 lane-miles of pavement. It has three different types of pavement. These types include, portland cement concrete (PCC), asphalt concrete (AC) overlaid PCC, full-depth AC, and AC overlaid AC.

Portland Cement Concrete (PCC). PCC pavements are subject to several distress mechanisms nevertheless in Missouri the main culprits have been; faulting and cracked slabs at joints and cracks, spalling and blowups at joints, D-cracking, and loss of load transfer (Figure 7).

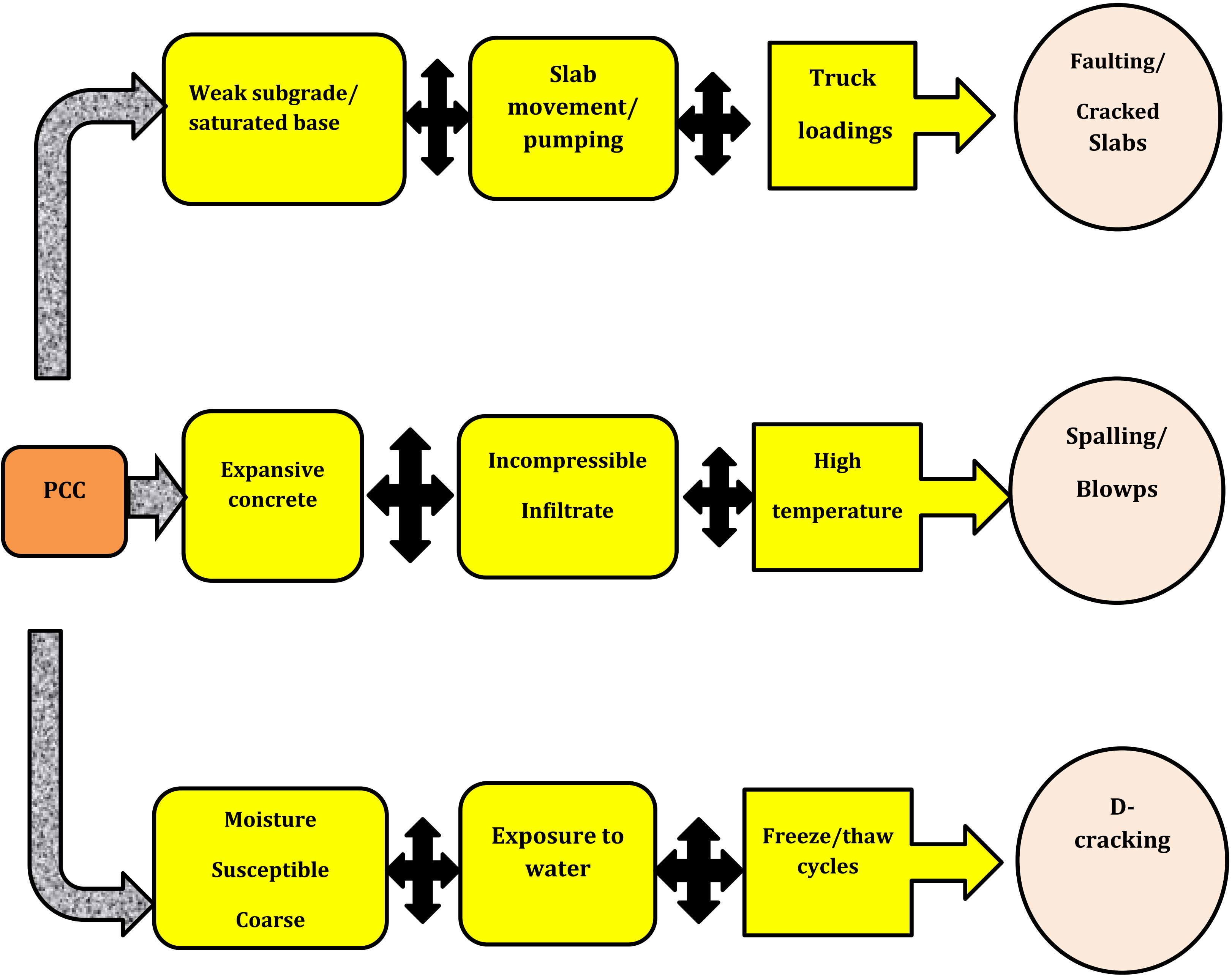


Figure 7. Sketch examines the performance of Missouri's different PCC designs.

Asphalt Concrete Overlay Portland Cement Concrete (AC/PCC pavements). Very few pavements in Missouri were originally designed as composites with asphalt over concrete. AC/PCC pavements have become a predominant pavement type on high volume roads. AC overlays were put on many old PCC pavements to add structural capacity, provide smoothness and mitigate distresses. These overlays were prone to several distress mechanisms: rutting, raveling, reflective cracking and block cracking (Figure 8).

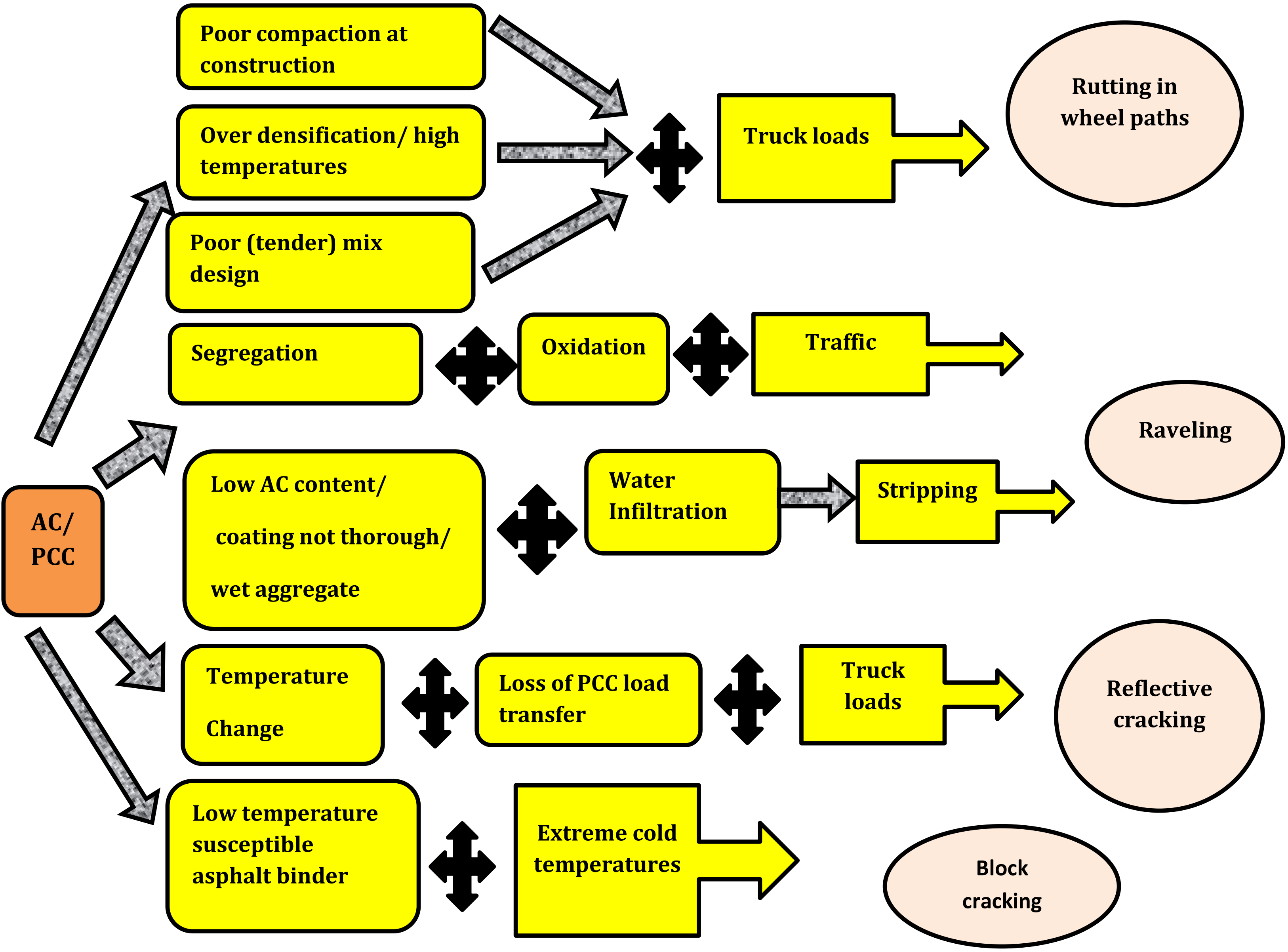


Figure 8. Sketch examined the effects of multiple overlays, overlay thickness and traffic levels on AC overlay performance.

Full-depth AC Pavements. Full-depth AC pavements, like AC overlays, are prone to rutting distress. Nevertheless, in addition to mix problems, they can also rut because of a weak base and/or subgrade. As with AC overlays, rutting has come under better control in recent years with the advent of stone matrix asphalt (SMA) wearing courses and super pave mix design.

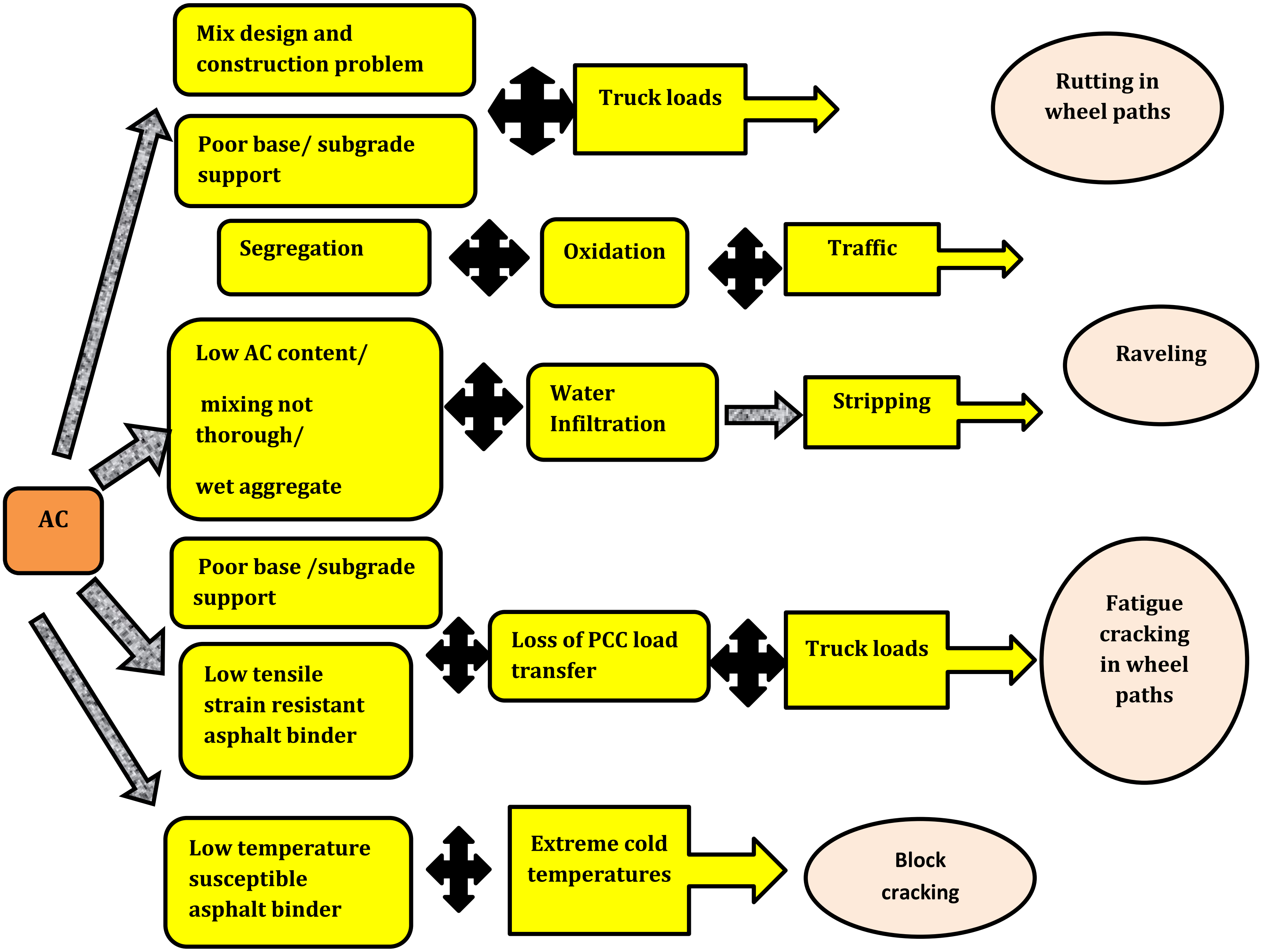


Figure 9. Sketch examined the effects of Missouri's different AC designs.

AC pavements do not exhibit reflective cracking, because there are no rigid layer discontinuities below. They will, however, produce fatigue or alligator cracking in the wheel paths from heavy loads. They also are subject to the same segregation, oxidation, raveling, stripping and block cracking problems which plague AC overlays (Figure 9).

Over time pavement becomes more porous for a variety of reasons, including loading temperature stresses, vibration, and frequent alternation of freezing and thawing. Those reasons cause to pavement to deteriorate. Deterioration can result in loss of strength and unsafe conditions. Therefore it is important to have an understanding of the vulnerabilities of pavement structures in order to help minimize long-term repair and maintenance costs. For the past five years, MoDOT's construction program has averaged $1.25 billion each year. For the next five years, it will be $500 million per year, an annual reduction of 60 percent. MoDOT became focused on preserving the existing system assets and must find effective ways to maintain Missouri's road and bridges. (MoDOT 2010). For that purpose, Missouri S&T by collaboration with MoDOT propose to use combination of geophysical techniques in order to demonstrate the utility and cost effectiveness of these technologies to solve high related problems. The most common highway problems included; deterioration of concrete deterioration of asphalt, subsidence, and slope stability.

2.2 Deterioration of Asphalt and Concrete and

Deterioration has two common reasons: environmental because of weathering and aging and structural due to repeated traffic loadings. Clearly, almost pavement deterioration results from both environmental and structural causes. However, it is necessary to attempt to differentiate between the two in order to choice the best effective rehabilitation techniques. The rate at which pavement deteriorates depends on its environment, traffic loading conditions, original construction quality, and interim maintenance procedures. Poor quality materials or poor construction procedures can significantly reduce the life of a pavement. As a result, two pavements constructed at the same time might have significantly different lives, or certain portions of a pavement might deteriorate more rapidly than others. On the other hand, timely and effective maintenance can extend a pavement's life (UWM 2002). Missouri has a different geological environments and different weather (wet, dry, warm and cold). These weathering and environmental changes and repeated traffic loadings as well cause pavements deterioration in Missouri.

Figure 5. An example of asphalt & concrete deterioration.

Figure 6. Steel corrosion and delamination (left) and spalling (right). Gucunski N. (2009).

2.3 Slope Stability

Slope stability is defined as the resistance of inclined surface of rock or soil mass to failure by both sliding and collapsing (Figure 10).

Figure 10. Missouri rock cuts with contrasting degrees of hazard (Highway 63) (Maerz and Youssef, 2010).

Slope either occur naturally (natural slopes), such as cliffs and valleys or engineered by humans (human-made slopes), such as embankments, cut slopes, and retaining walls open pit (Kliche, 1999). Slope failures and landslides constitute significant hazards to all types of both public and private infrastructure throughout the world and around U.S. as well and contribute to economic and casualty losses. According to the Department of Highway in Washington State a significant number of accidents and nearly a half dozen fatalities have occurred because of rockfalls in the last 30 years …and…. 45 % of all unstable slope problems are rockfall related (Badger et. al 1992). In Canada almost 13 people died because of rockfall in the last 87 years, most of them on British Columbia highways **(**Hungr et. al 1989). Total direct costs for maintenance and repair of landslides involving major U.S. highways alone (roughly 20 percent of all U.S. highways and roads) were recently estimated to exceed $100 million annually (MoDOT 2007). In the same study, indirect costs attributed to loss of revenue, use, or access to facilities as a result of landslides was conservatively estimated to equal or exceed direct costs (MoDOT 2007). Based on TRB study estimated that the costs for repair of minor slides equal or exceed costs associated with repair of major landslides. This estimate is supported by the Missouri Department of Transportation's (MoDOT) experience with surficial slide problems, which are estimated to cost on the order of $1 million per year on average. Many other state departments of transportation have similar problems with similarly high, or even higher annual costs. All available evidence clearly indicates that the cumulative costs for repair of many surficial slides can become very large, in spite of the fact that costs for repair of individual slides are generally low. In addition, minor failures often constitute significant hazards to infrastructure users (e.g. from damage to guard rails, shoulders, or portions of road surface) and, if not properly maintained, often progress into more serious problems requiring more extensive and costly repairs.

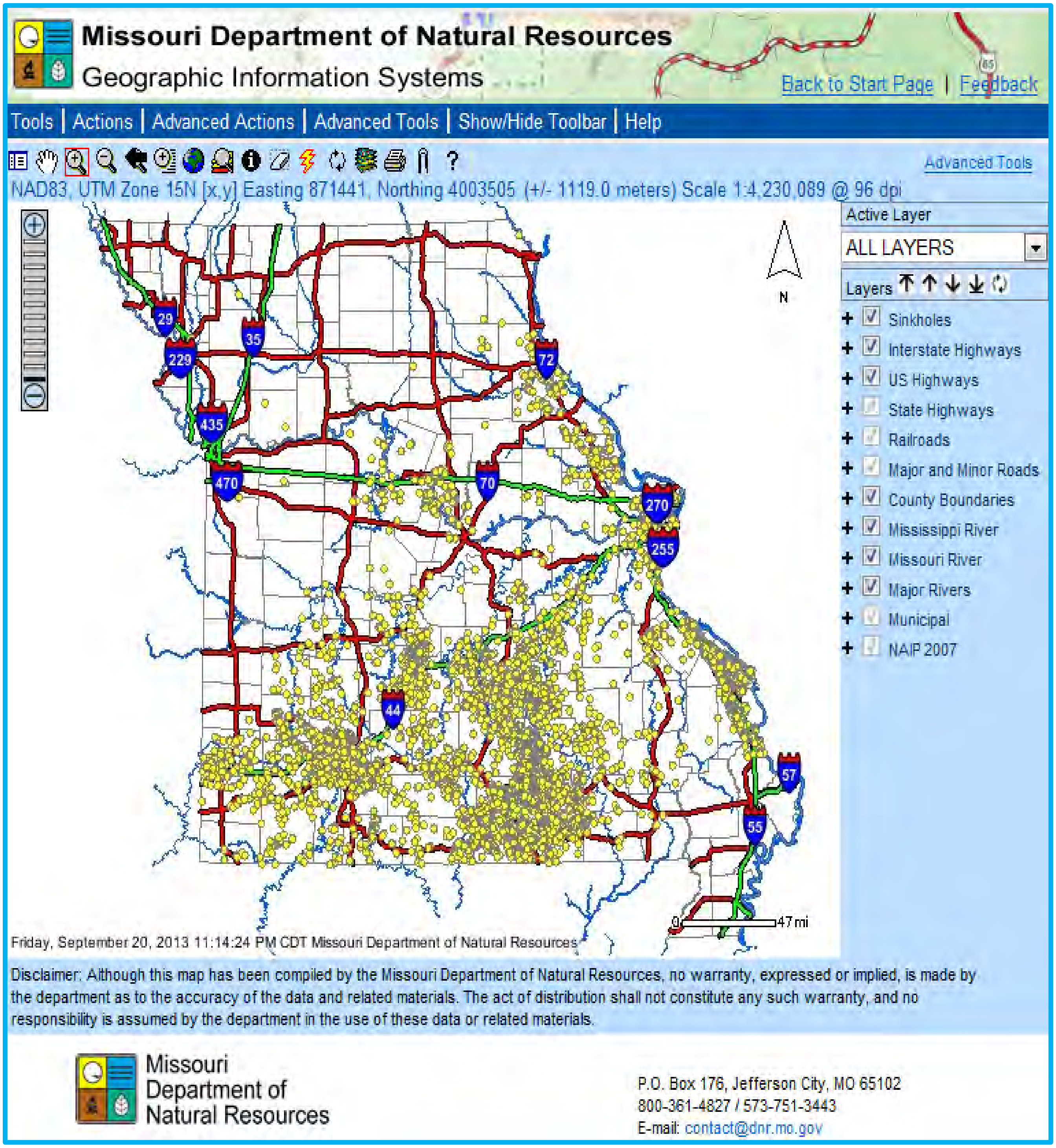
Overall, repairing rockfall or landslides after collapse is expensive and requires specialized knowledge. Determining slope stability issues must be addressed first, or the repair may prove to be only temporary.

2.4 Subsidence

Subsidence is a lowering or collapse of the ground. It can be caused by man-made disturbance such mining exploration, ground water exploration, and extraction of natural gas or naturally such dissolution of limestone, faulting induced, earthquake, and Isostatic subsidence or seasonal effects (British Geological Survey). Ground subsidence is a global problem and can be concern to geologists, geotechnical engineers and surveyors (Subsidence). In the United States, more than 17,000 square miles in 45 States have been directly affected by subsidence (USGS). It commonly causes major problems in karst terrains, where dissolution of limestone by fluid flow in the subsurface causes the creation of voids (Figure 11). This type of subsidence can result in sinkholes which can be many hundreds of meters deep (Subsidence). Most of the karst features in Missouri are developed in limestone and dolomite rocks in the Springfield and Salem plateaus. However there are also karst features north of the Missouri River. According to the Missouri Department of Natural Resources there are over 5,500 caves and more than 2,800 springs recorded in the state of Missouri. Sinkholes were not inventoried in most of the state, however more than 2,500 sinkholes are recorded in Greene County and over 7,000 sinkholes are registered in Perry County (Vandike, 1997). Losing streams are also not inventoried statewide, but hundreds of streams and segments of streams are known to be losing streams. All these numerous karst features show how karst is widely developed in Missouri and can create complex subsurface conditions. Major karst areas in Missouri occur in the Mississippian rocks of St. Louis, Ste. Genevieve, Cooper, Greene, Boone, and Christian counties, and in Ordovician rocks of Perry, Phelps, Pulaski, and Howell counties. A complex assortment of caves, tunnels, bridges, and arches in a relatively small area is a result of karst development. Famous karst complexes include the Grand Gulf in Oregon County and the Ha Ha Tonka in Camden County along a southern arm of the Lake of the

Ozarks. Missouri map shows the distribution of sinkholes among Missouri State from Missouri Department of Natural Resource (Figure 11).

Figure 11. Big sinkhole growing larger in South County, St. Louis County, MO (KSDK).



NAD83, UTM Zone 15N [x,y] Easting 871441, Northing 4003505 (+/- 1119.0 meters) Scale 1:4,230,089 @ 96 dpi

- ☑ Sinkholes
- ☑ Interstate Highways
- ☑ US Highways
- ☐ State Highways
- ☐ Railroads
- ☐ Major and Minor Roads
- ☑ County Boundaries
- ☑ Mississippi River
- ☑ Missouri River
- ☑ Major Rivers
- ☐ Municipal
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Figure 12. Sinkhole (data from Missouri Department of Natural Resource, 2013)

3. Previous Geophysical Studies Investigations of Pavements

In the last few decades the applications of geophysical techniques (Non-Distractive Techniques NDT) methods have been increasing in site characterization and geotechnical investigations by state highway agencies to solve transportation related problems. Also, depending on specific site-conditions for example geology, target dimensions, cultural interface, and the engineering problem to be investigated, a combination of methods or techniques may be used in a given investigation. In other words there is no one, unique interpretation to a set of geophysical data. Also several methods may be used to solve a particular engineering problem. A considerable amount of research has been published regarding the use of (MASW, ERT, GPR and PSPA) methods in pavement investigation. These techniques highlighted both the strengths and the weaknesses of using these methods singly and in combination.

Electrical resistivity tomography (ERT)

(Buettner et al. 1997) conducted (ERT) to image spatial moisture distribution and movement in pavement sections during an infiltration test. The ERT data were inverted, and the resulting images show 1) the basic structure of the pavement section and 2) the movement of water through the image planes as a function of time during infiltration. An interesting result is that the water does not appear to drain from the section toward the shoulder as had been expected based on the design. It was concluded that in spite of the difficulties, is appears that ERT can be used to delineate moisture movement in pavement structures. (Painter 2000) and Ishankuliev 2007) conducted resistivity imaging surveys in order to map abandoned coal mines in southeast Ohio. (Painter 2000) stated that mine workings appeared as resistivity anomalies, and saturation has a pronounced effect on the resistivity images. While mined coal seams were reliably detected. (Ishankuliev 2007) compared resistivity to borehole data to have cross-checks and was able to list locations of potential voids in the study area with their inferred saturation state. It was concluded that dipole-dipole resistivity is a suitable tool for subsurface void detection and should be verified by additional geophysical methods.

(Youssef et al. 2012) collected geophysical data at Umm er Radhuma area about 200 km north east of Ar Riyad city in Saudi Arabia using (ERT) with different electrode spacing to delineate buried sinkholes and associated subsurface cavities. Their findings indicated that the dipole–dipole method using an electrode spacing of 1 m was successful in detecting a known subsurface sinkhole. The dimensions of sinkholes are; depth ranges from 2 to 4 m, its height ranges from 2 to 4 m, and its width ranges from 5 to 7 m. The authors summarized that the ERT was successful in detecting and mapping a known sinkhole in the study area that is characterized by limestone and dolomite and covered by calcareous sandstone of the Ajfar formation. They end up with that spaced ERT profiles managed to show the dimensions and lateral extensions of the air-filled cavity which will enable the geotechnical engineers to determine the volume of the appropriate materials to fill it to avoid any unexpected collapse, subsidence or any geological and environmental hazard especially if these sinkholes are located in a critical areas such as along highways and/or urban areas. (MARTI´NEZ-LO´PEZ et al. 2013) have conducted electrical resistivity tomography in order to analyze the geoelectric response produced by three cavities cut into different geological substrata of granite, phyllite, and sandstone. The varying geoelectric response in the area under investigation enables users to obtain 2D profiles and 3D images of the distribution of the resistivity under the ground, which makes it a very effective, non-destructive tool for analyzing and characterizing possible discontinuities in the subsoil (Sasaki, 1992; Store et al., 2000). The authors then conclude electrical resistivity tomography is a viable geophysical tool for the detection and monitoring of mining voids and other subsurface cavities.

Multi – channel analysis of surface wave (MASW)

(Miller et al. 1999) reported accurate mapping of the bedrock surface and identification of potential fracture zones within bedrock using surface-wave methods. The study was designed to target an area near a building where hazardous fluids used to manufacture electronic components were stored. (Sheehan 2002) conducted a seismic hazard mapping project in Ohio, using surface-wave methods (MASW). Several study sites in the Cleveland South Quadrangle area and three sites in western Ohio were chosen to compare the Multi-channel Analysis of Surface-waves method to preexisting shear-wave information from drilling logs. It was concluded that MASW was able to detect both high and low velocity layers and has successfully profiled shear-wave velocities down to an adequate depth at all study sites. (Xu and Butt 2006) evaluated the potential of using surface-wave techniques to image steeply dipping cavities in laterally inhomogenous geological terrain in a historical gold mining area in Nova Scotia. Overall the velocity images were in agreement with the presence of steep openings at the locations indicated by historical mapping and current subsidence. Furthermore, the velocity sections were consistent with the thickness of the overburden at each site and the possible weakening of crown pillars.

(Ismail and Anderson 2007) acquired shear wave velocity utilizing multichannel analysis of surface wave (MASW) method to map bedrock surface and relief, and to reflect soil rigidity within the upper 50 ft. (16 m) soil thickness. The results were compared to down hole seismic shear wave data acquired at two shallow boreholes and boring information for calibration purpose. On the basis of the comparison of MASW-estimated bedrock depths, proximal ground truth (boring information) and soil type\rigidity, it is concluded that the interpretation of the 2-D MASW shear wave velocity profiles are reasonably reliable. (Seshunarayana and Sundararajan 2012) reported accurate mapping of the shallow sub surface layers to estimate the bedrock depth and the corresponding shear wave velocities (Vs) of various layers in a complex geological environ over granites in Hyderabad, India using MASW techniques. The researchers then concluded that the MASW technique is not only reliable for accurate and detailed characterization of a small area but also for quick detection of underground anomalous zone from a reconnaissance survey over a large area. Also, liquefaction of low velocity layers and stiffness of soil can be well established through MASW.

Ground Penetrating Radar (GPR).

(Missouri S&T and MoDOT) acquired 2-D ground penetrating radar (GPR) profiles across selected streams and drainage ditches at ten bridge sites in southeast and central Missouri to determine if GPR is an effective tool for monitoring bridge scour, and estimating the depths and breadths of in-filled (paleo) scour features (Anderson et al. 2000). They ended up with that GPR tool can be used to accurately estimate water depths in shallow fluvial environments (maximum depths in study areas were less than 20 feet). The tool can also be used to monitor fluctuations in water depths over time, and to study depositional and erosional patterns. GPR has certain advantages over alternate methods for estimating water depths. GPR can provide essentially continuous 2-D and/or 3-D images of the stream channel and the sub-water bottom sediment. Perhaps the most significant disadvantage of GPR is that the tool does not work well in “clayey” sedimentary environments. GPR survey was conducted along Interstate I-70 across the state of Missouri in order to determine asphalt and concrete layer thickness every tenth mile and update history information related to types of pavements that make up I-70 across Missouri (Hickman 2001).The results of this study show that GPR data can be a good tool for quality control in road construction and repair.

(GDOT) purchased a (GPR) unit in order to enhance their scientific investigation of archaeological sites (James 2004). GPR data was acquired by (GDOT) to increase the effectiveness and accuracy of testing and mitigation phase archaeological projects by being able to precisely locate data-rich archaeological features prior to subsurface excavation. After two years GDOT has successfully been able to utilize GPR on a number of archaeological site types in diverse environments. (Kim et al. 2007) conducted ground penetrating radar (GPR) survey to inspect Bridge A-2138 in Franklin County, Missouri to determine whether the non-destructive, non-invasive GPR tool is an effective method for identifying and mapping zones of deterioration (corroded rebar and delaminations) within bridge decks. The data were collected under different weather conditions (wet, dry, warm and cold) to assess the impact of these climatic conditions on the data quality and interpretability. The study results confirm that the GPR tool cannot be used to directly resolve delaminations and/or corroded rebar within concrete bridge decks. However, the GPR tool can be successfully used to detect and map zones of relatively high dielectric constant (low EM velocity) and high attenuation. These low-velocity/high-attenuation zones are typically zones of delamination (characterized by anomalously high moisture content and chloride ion concentration). The authors concluded that weather conditions did not significantly affect the overall utility of the GPR tool.

(Han et al. 2012) conducted a nondestructive test on typical roadway supports of a mine via drilling core and ground penetrating radar in order to investigate the influence of the unfavorable geologic environment on supporting concrete and evaluate the real performance of roadway supports of a mine. For that purpose, seventeen typical projects were chosen and the strength of supporting concrete was detected by nondestructive drilling core method. The result shows that the strength is widely less than the design value. Furthermore, four projects of them were investigated by the ground penetrating radar (GPR) in order to evaluate the feasibility of GPR in the performance investigation of the roadway supports of a mine. They end up with that ground penetrating radar is capable of measuring the thickness of the support, the distribution of rebars and the defects of the surrounding rock.

Combinations of Geophysical Technologies

(Anderson et al. 2000) conducted three geophysical surveys for the Missouri Department of Transportation (MoDOT) along and adjacent to the study section of I-44 in an effort to establish the probable cause of ongoing subsidence and to locate undetected sub-pavement voids. The GPR technique proved useful tool in locating sub-pavement voids. Recently, proposed highway expansion in Missouri has necessitated identifying the location of the underground fuel storage tanks to aid in the demolition of the gas station structures (Brady 2000). For that purpose, the geophysics group at the University of Missouri S&T was asked to acquire geophysical data at different sites to detect and delineate the underground fuel storage tanks and associated utility lines using cost effective two geophysical techniques (GPR&EM). The complementary use of the EM and GPR techniques was successful and cost effective in the detection and delineation of the underground fuel storage tanks and associated utility lines. (Anderson et al. 2001) conducted a reflection seismic and GPR survey for the (MoDOT) along segments of proposed interstate route 249, near Joplin, Missouri across ground previously mined for lead/zinc. The objective is to map Mississippian bedrock, locate and identify paleo-sinkholes and abandoned mine features, and determines structural geologic trends in the study area. The results of both techniques matched well and also were successful in meeting MoDOT goals. Several different geophysical techniques including seismic refraction, gravity, PR, 2D resistivity imaging and spectral analysis of surface waves have been tested in an Ohio Department of Transportation study of coal mine collapse hazards under roadways in southeastern Ohio (Wolfe et al., 2002). After testing these different geophysical methods while considering cost-effectiveness and some restrictions in resistivity methods caused by metallic conductors in some highway sections, buried steel pipes, fences etc., (Wolfe et al., 2002) concluded that seismic refraction, 2D resistivity imaging and surface-wave profiling are the most appropriate methods for mine void detection surveys in southeastern Ohio.

Several different geophysical techniques including seismic refraction, gravity, GPR, 2D resistivity imaging and spectral analysis of surface waves have been tested in an Ohio Department of Transportation study of coal mine collapse hazards under road ways in southeastern Ohio (Wolfe et al., 2002). They found that GPR survey was not successful due to a shallow clay layer absorbing the radar energy and reducing the effective penetration depth and gravity was not a suitable method either. After testing several different geophysical methods while considering cost-effectiveness and some restrictions in resistivity methods caused by metallic conductors in some highway sections, buried steel pipes, fences etc., (Wolfe et al., 2002) concluded that seismic refraction, 2D resistivity imaging and surface-wave profiling are the most appropriate methods for mine void detection surveys in southeastern Ohio. Three different geophysical techniques (radar, 2D resistivity, seismic refraction) were applied in bedrock detection survey in the Alps of Germany and Austria by (Sass 2007). The three techniques coincided well as long as the setting was relatively straightforward (e.g., debris overlying bedrock). When additional sediment units like till, wet or compacted debris were present, the methods deviated to some degree. The crosscheck of several methods was extremely valuable to validate and underpin the GPR and ERT results, especially in areas where no drilling was performed.

The Iowa DOT conducted a geological survey and (MASW, ERT and GPR) surveys on the Avenue of the Saints corridor in Iowa, specifically a portion of US 18 in Cerro Gordo County. These investigations were prompted by the formation of sinkholes or sinkhole like features that occurred on the shoulders, in a roadway ditch, at the edge of the right of way, and in adjacent farm fields. Both survey investigations were conducted to Investigate: 1) the subsurface nature of the underlying bedrock; 2) if any voids were present under the pavement or within the road embankment; and 3) if there were any large voids in the subsurface that could be attributed to the sinkhole surface expression. (Matthew Trainum 2004 and 2005). The GPR Survey in 2004 using 250 MHz antenna identified the sinkholes that formed on the shoulders and were filled prior to the investigation but did not identify any voids immediately under the pavement that would cause a loss of subgrade or pavement support. In contrast, the GPR Survey in 2005 identified numerous anomalies within the first two meters. The authors then concluded that the GPR Surveys proved to be useful only in determining the possible existence of voids directly beneath the road or within the upper few meters of the road embankment. After testing three different geophysical methods and doing the geological investigations while considering cost-effectiveness, (Trainum M., 2004 and 2005) concluded that 2D resistivity imaging and surface-wave profiling are the most appropriate methods for highway sinkhole detection surveys along the Avenue of the Saints corridor (US 18) in Cerro Gordo County, Iowa.

(Anderson et al. 2007) in collaboration with the Missouri Department of Transportation (MoDOT) evaluated and compared four field methods on the basis of the interpretation of processed field data acquired at two test sites within the Mississippi Embayment in the Poplar Bluff area, southeast Missouri in order to determine and classify the shear wave velocity of the soils to depths of 30 m (as per NEHRP recommendations). This comparative analysis of the available shear wave technologies was conducted because MoDOT wanted to ensure that their geotechnical site investigations in the Mississippi Embayment area are efficient and cost-effective. The methods included seismic cone penetrometer (SCPT) and (cross hole: CH; multichannel analysis of surface waves: MASW; and refraction micro tremor: ReMi). (Anderson et al. 2007) then concluded that, on the basis of the comparative analyses of the corresponding shear wave velocity profiles, MASW data are generally more reliable than SCPT data, comparable to quality ReMi data and only slightly less accurate than CH data. However, MASW's other advantages generally make it a superior choice over the CH, SCPT and ReMi methods for general soil classification purposes to depths of 30 m (as per NEHRP recommendations) Table (1).

Considerations	**MASW**	**ReMi**	**CH**	**SCPT**
Accuracy	**2**	**3**	**1**	**4**
Functionality (acquisition)	**1**	**2**	**3**	**4**
Functionality (processing)	**1**	**2**	**3**	**4**
Other considerations	**3**	**3**	**1**	**2**
Cost	**2**	**1**	**4**	**2**
Overall utility	**1**	**2**	**4**	**2**

Table 1. Ranking of MASW, CH, SCPT and ReMi methods.

(Sudha et al. 2009) conducted Electrical Resistivity Tomography (ERT) in association with Standard Penetration Test (SPT) and Dynamic Cone Penetration Test (DCPT) for geotechnical investigations at two sites having different soil matrix for soil characterization, proposed for thermal power plants and are located in Aligarh and Jhansi in Uttar Pradesh (UP), India. Borehole data were used for calibration and correlation of resistivity values to the subsurface soil. (Sudha et al. 2008) then concluded that the determination of soil strength using ERT is economic, fast and efficient in comparison to the direct in situ methods used to determine the soil strength for civil engineering purposes and, thus, is very useful in geotechnical investigations. Integrated geophysical methods involving vertical electrical sounding (VES) and electrical resistivity tomography (ERT) were carried out by (Ayolabi et al. 2012) in order to map subsurface hydrocarbon contamination in city of Baruwa, Nigeria. Self-Potential (SP) and Induced Polarization (IP) data were also acquired to constrain the results obtained by ERT and

VES and also to assist in differentiating geologic layers that may probably give the same resistivity signatures because of their fluid contents. (Ayolabi et al. 2012) then marked out the hydrocarbon contaminated layers beneath each VES point by high resistivity ranging between 943Ωm and 4749Ωm at a depth of 1 to 35.44m below the surface. Likewise, the ERT result shows that the subsurface soil around the investigated area has been contaminated at a shallow depth of about 2m downward with resistivity value above 1000Ωm.

4. Work Plan

This work is funded by Missouri Department of Transportation (MODOT). The data will be processed and analyzed by applying the best geophysical techniques to get the most accurate results. Exactly eight segments of roadway (10000 ft. long) in central Missouri State will be investigated using combination of geophysical technologies. The project work will be completed in 27 months and will be divided into five phases: part 1 consists of background preparation and collection of data. Part 2 will involve processing, analysis, and interpretation of the data in the Geophysical Laboratory at Missouri S&T [The lab is well equipped with all facilities necessary to complete all tasks on time]. Part 3 will be the actual writing of the dissertation. Finally, part 4 will prepare for the defense of the thesis.

Time Period	Task	Duration
06/2012 – 09/2013	Background Preparation	13 months
	Data acquisition& data Processing	
	Interpretation	
08/2013 – 12/2013	Paper composition	5 months
	Comprehensive exam	
12/2013 – 09/2014	Writing dissertation composition	9 months
	Defense	

Table 2. Project work plan.

5. Description of Geophysical Methods to be employed

5.1. Electrical Resistivity Tomography Technique (ERT).

The resistivity method is one of the oldest geophysical survey techniques (Loke 2011). ERT typically, current (I) is induced between paired electrodes (C1, C2). The potential difference (ΔV) between paired voltmeter electrodes P1 and P2 is measured. Apparent resistivity (Δa) is then calculated (based on I, ΔV, electrode spacing) **(**Figure 13). Depth of investigation depends on the biggest electrode spacing. Larger electrode spacing will provide for greater depth penetration. If the array is extended and moved along the surface, 2-D or 3-D resistivity–depth models will be created. If external constraints are existing, resistivity–depth models will be transformed into geologic models (Anderson et. al., 2008).

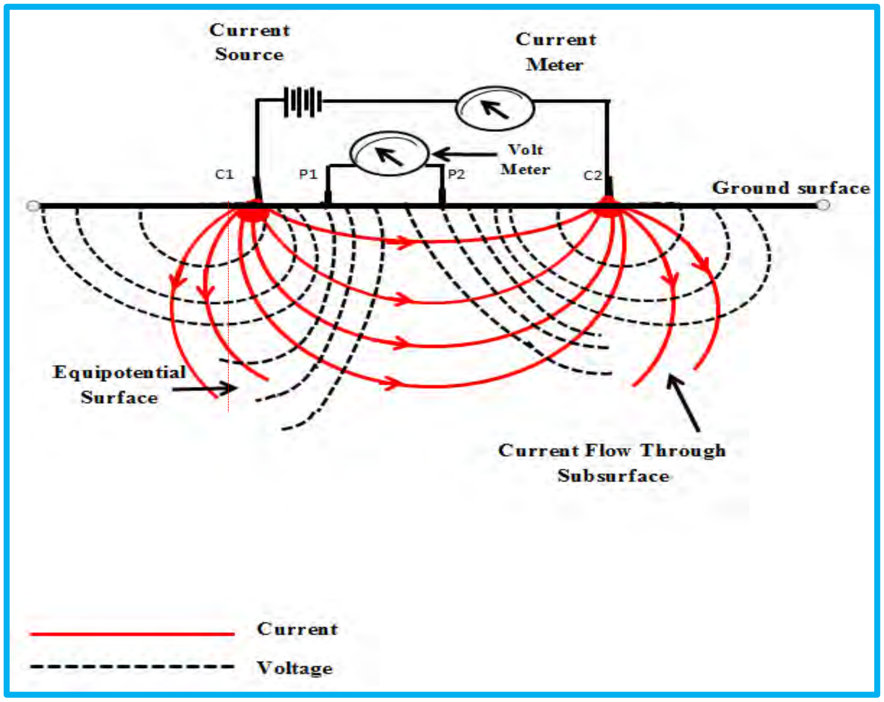

Figure 13. A conventional array with four electrodes to measure the subsurface resistivity.

Electrical Resistivity Tomography (ERT) technique is widely used in mapping subsurface electrical properties (David 2009). The purpose of electrical surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface will be estimated. The ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock. The figure below shows the resistivity of common rocks, soil, minerals materials and chemicals (Figure 14) (Loke el al. 2011).

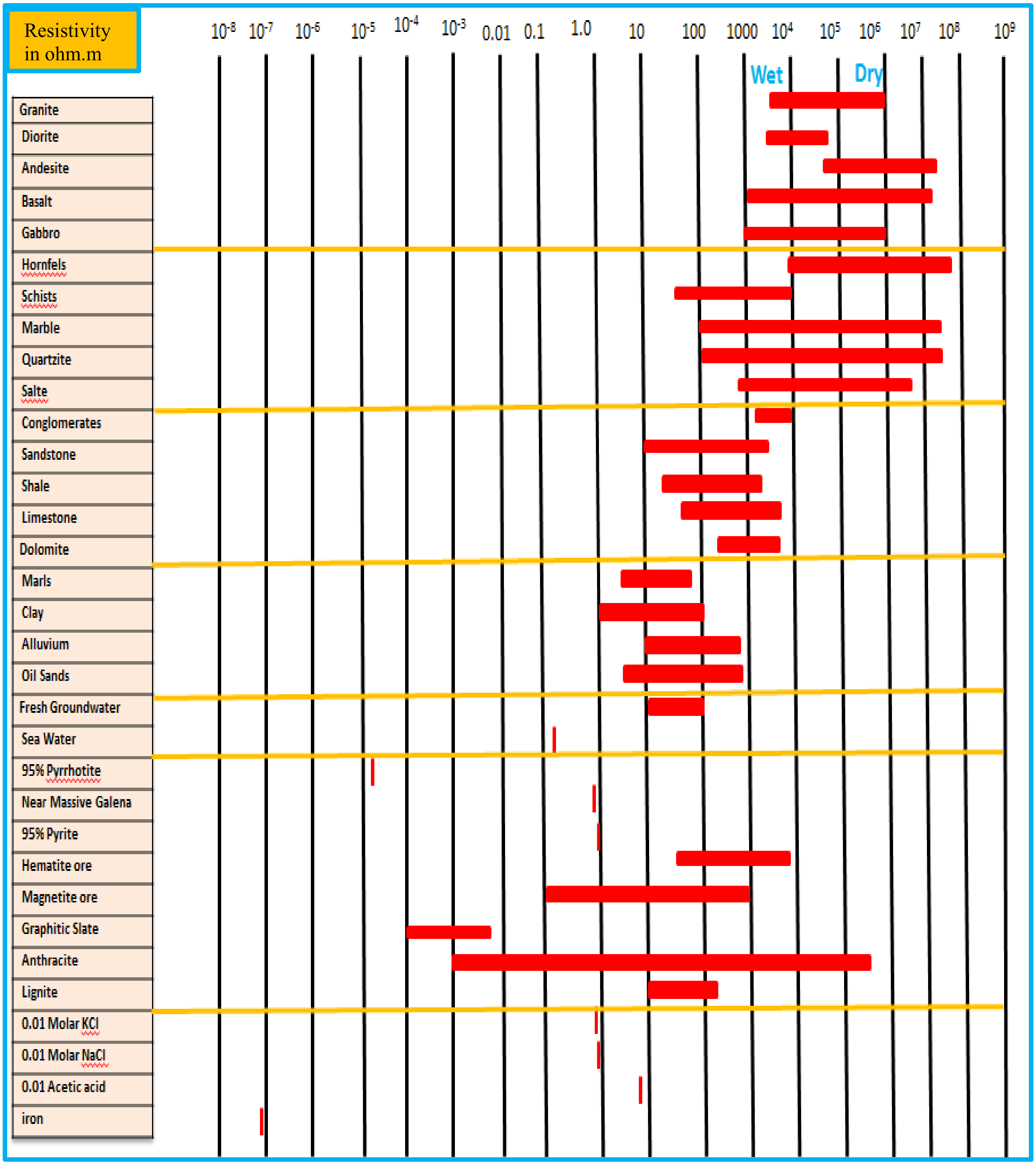

Figure 14. The resistivity of common rocks, soils and minerals (Keller and Frischknecht 1966, Daniels and Alberty 1966, Telford et al. 1990).

ERT has different applications. These applications include; locate voids, abandoned mines and tunnels, map variable depth to bedrock, mapping faults, fractures, weathered zones, mapping clay layers and lenses, mapping sand and gravels, mapping lithologic contacts, differentiate/map rock units, variable depth to water table, variations in porosity, variations in salinity, mapping contaminants. ERT applications that will be used in this research include; locating voids, information about moisture content and information about depth to the top of bedrock. Voids can be main cause of water drainage underneath pavement and they could also result in potentially dangerous collapse of roads or buildings that overlie the void. The electrical resistivity tomography will be used to detect voids because response of air- or water filled voids compared to the surrounding bedrock may allow electrical resistivity surveys to delineate areas underlain by such voids. The second application of ERT will be used to map variable depth to bedrock. Mapping of bedrock is considered important because it can help evaluate the lateral and vertical extend of the formation (David et. al 2009). And also ERT will be used to obtain information about moisture content because moisture content is considered to be one of the reasons for pavement degradation.

Acquisition of ERT Data. Three electrical resistivity profiles were acquired on the shoulder along three traverses at each segment of roadway around1000 ft. length (Figure 15&16 A, B, and C,). The ERT data were acquired using an AGI SuperSting R8/IP resistivity unit equipped with a dipole-dipole overlapping arrays consisting of 72 electrodes. Typical depth of investigation is 20 percent of the length of the electrical resistivity array. With (72 & 100) available electrodes and the required minimum depth of investigation of (80 & 100ft.) at 5 ft. spacing between the electrodes was chosen for this ERT survey. Data will be collected under different weather conditions, different geological environments and with very different pavement condition.

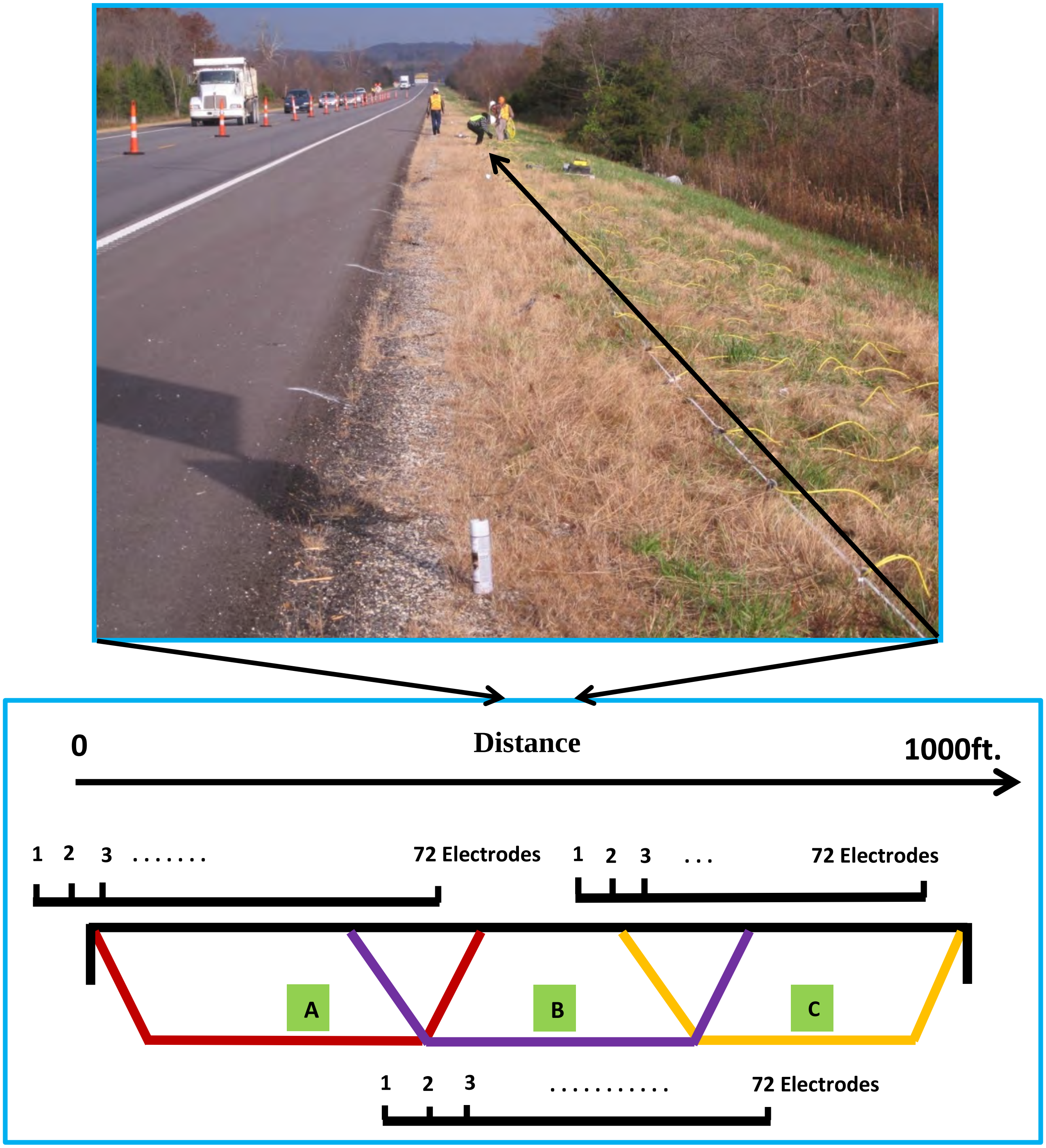

Figure 15. An example of how ERT data will be acquired using total of 72 electrodes (showing locations of three profiles).

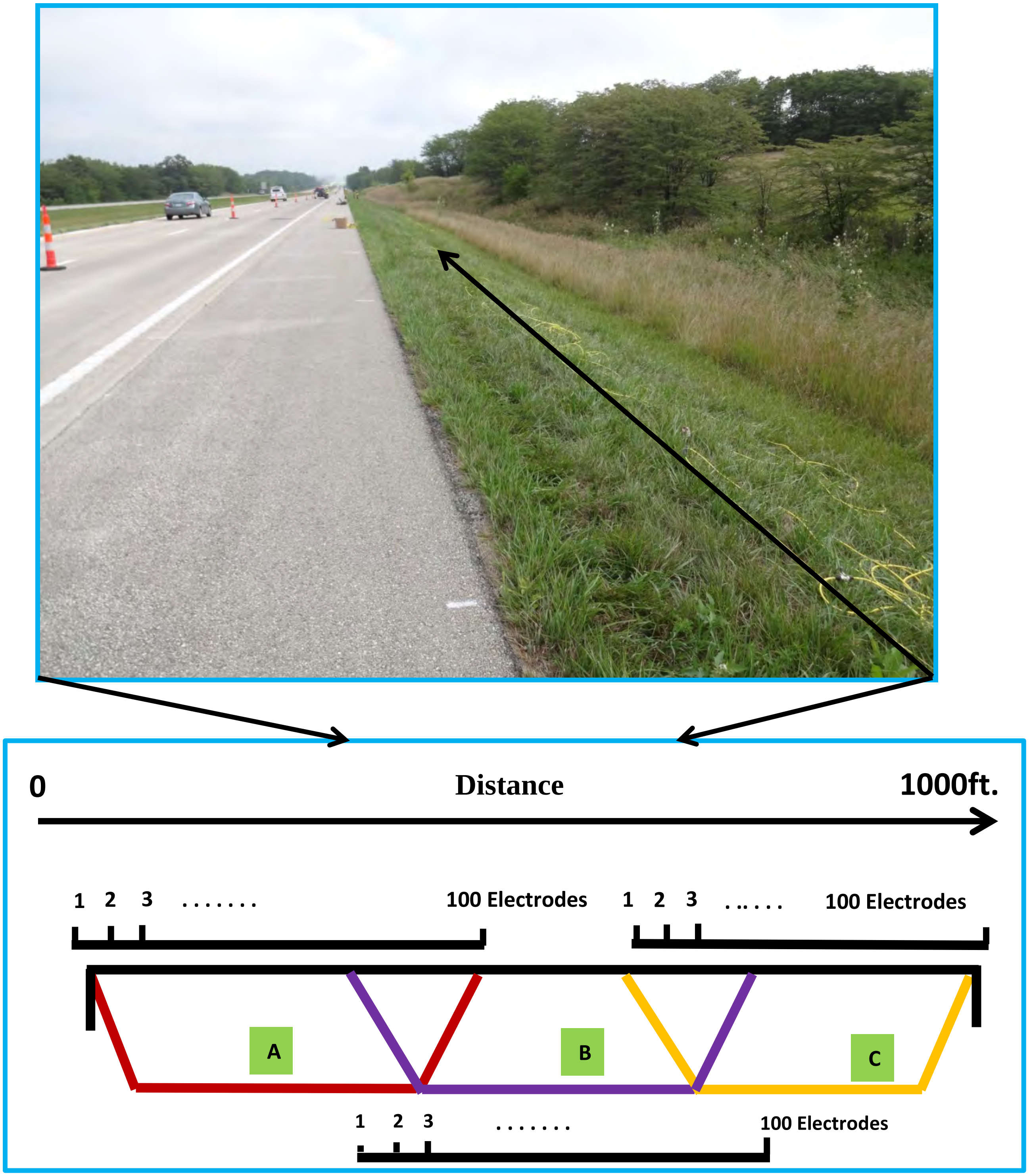

Figure 16. An example of how ERT data will be acquired using total of 100 electrodes (showing locations of three profiles).

Data processing. Data will be processed using RES2DINV software. Raw data are copied to the laptop for further processing. Processing time depends on several factors. The data can be processed fairy quick for a quick assessment: if the data quality is good and surveying control is not required, an ERT image can be generated on the site within 15 minutes. Generally, the output of a 2D survey is a 2-D pseudo-sections and a 2-D resistivity model of the subsurface.

5.2. Multi-Channel Analysis of Surface Wave (MASW).

The multichannel analysis of surface wave method (MASW) is a nondestructive seismic method. Surface waves typically, generated using acoustic source (sledge hammer) and recorded by multiple number of receivers (usually 24 or more) are deployed with even spacing along a linear survey line with receivers connected to a multichannel recording device (seismograph) (Figure 17). A dispersion curve (phase velocity versus frequency), generated from the acquired field data, is inverted and used to generate a 1-D shear wave velocity profile (generally tied to the physical center of the receiver array) (Anderson et al. 2008). MASW gives information in either 1D (depth) or 2D (depth and surface location) format. Two types of parameters are considered to be most important: the source offset (X_1) and the receiver spacing (dx) figure (5). The source offset (X_1) needs to change in proportion to the maximum investigation depth (Zmax). A rule of thumb is $X_1 \approx$ Z max. The receiver spacing (dx) may need to be slightly dependent on the average stiffness of near-surface materials (Geophysical Methods 2003). The maximum depth of investigation (Zmax) is usually in the range of 10 –30 m, but this can vary with the site and type of active source used. If additional MASW data sets are acquired at adjacent locations, 2-D or 3-D shear-wave velocity models can be created. If external constraints are available, the shear wave velocity models can be transformed into geologic models (Park 1999). MASW has several applications in geotechnical engineering. These applications included; variable depth to bedrock, depth to some sub-bedrock interfaces, mapping soil layers, void mapping, estimating shear-wave velocities with far greater precision than either reflection or refraction surveying, earthquake design data. MASW will be used to evaluate pavement thickness as well as to evaluate engineering properties of the soil or rock, and mapping variable depth to bed rock.

Acquisition of MASW Data. The acquisition of MASW data is relatively straightforward. Data will be acquired using twenty-four low-frequency (4.5 Hz) vertical geophones, spaced at 1.5 ft. at the stations placed at 25 ft. intervals along the (1000ft) of each segment of roadway (center of the bound lane) (Figure 17). Acoustic energy will be generated at an offset (distance to nearest geophone) of 10 ft. using a 20 lb. sledge hammer and metal plate. The generated data will be recorded using the 24-channel engineering seismograph.

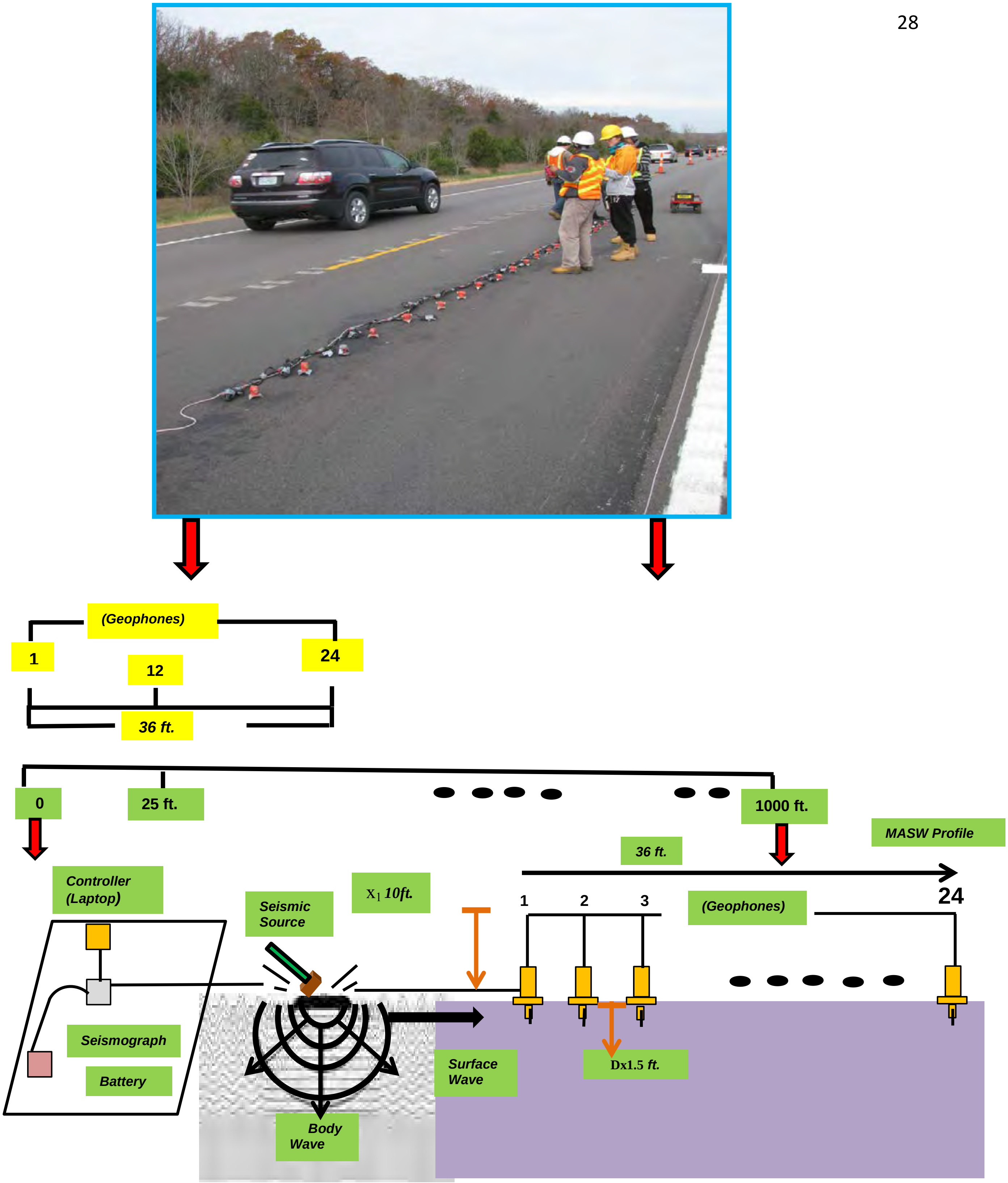

Figure 17. Acquisition of MASW field data.

Processing of MASW Data. The acquired data will be processed using the Kansas Geologic Survey (KGS) software package SURFSEIS. Each MASW field record is transformed into dispersion data (Rayleigh-wave velocity vs. frequency format; standard, established mathematical process that does not require any interactive input from the interpreter). The dispersion data are analyzed qualitatively and optimum phase velocities are selected (dispersion curve). The dispersion curve is usually inverted without any qualitative input from the interpreter. The output 1-D shear-wave velocity profile is the deliverable.

5.3. Ground Penetrating Radar (GPR).

GPR is an active geophysical technique, and it has been a common tool for identifying and defining subsurface geological features since the mid-1980s (Reynolds, 1997). The operational principals of GPR (similar to seismic reflection or sonar techniques) begin as pulsed electromagnetic (EM) into the ground at different frequencies (Lower frequencies provide greater depth penetration but lower resolution) from a transmitting antenna, and received by receiving antenna which records the electromagnetic energy or wave field reflections from the subsurface (Benson, 1995; and van der Kruk, et al., 1999) (Figure 18). Since its initial development during the mid-1920s, this technique has been utilized for a number of subsurface exploration applications, and has also proven to be a beneficial technique in appropriate near-surface geological settings as a way to quickly, cost-effectively, and un-intrusively analyze the shallow subsurface within engineering and environmental applications (Benson, 1995).

Although a versatile and proven method, GPR is only one of several geophysical survey tools that can be used to identify and define subsurface geological features (Chamberlain et al., 2000). (Reynolds 1997) refers to these subsurface features as geophysical anomaly-producing targets and lists trap structures for oil and gas, mineshafts, pipelines, ore lodes, cavities, groundwater, and buried rock valleys as specific examples. Subsurface cavities in areas of karst are often susceptible to ground surface subsidence which can pose a threat to new and existing development as well as the population that occupies the land (Doolittle and Collins, 1998). This technique can be used to locate depth to shallow bedrock, mapping lithology, bridge deck integrity studies, and archeological investigations. GPR technique will be used to assess integrity and thickness of pavement (asphalt & concrete). For concrete structures, GPR can be used to map the rebar and tendons as well as locate voids underneath slabs, or imaging all the way down into the native soil.

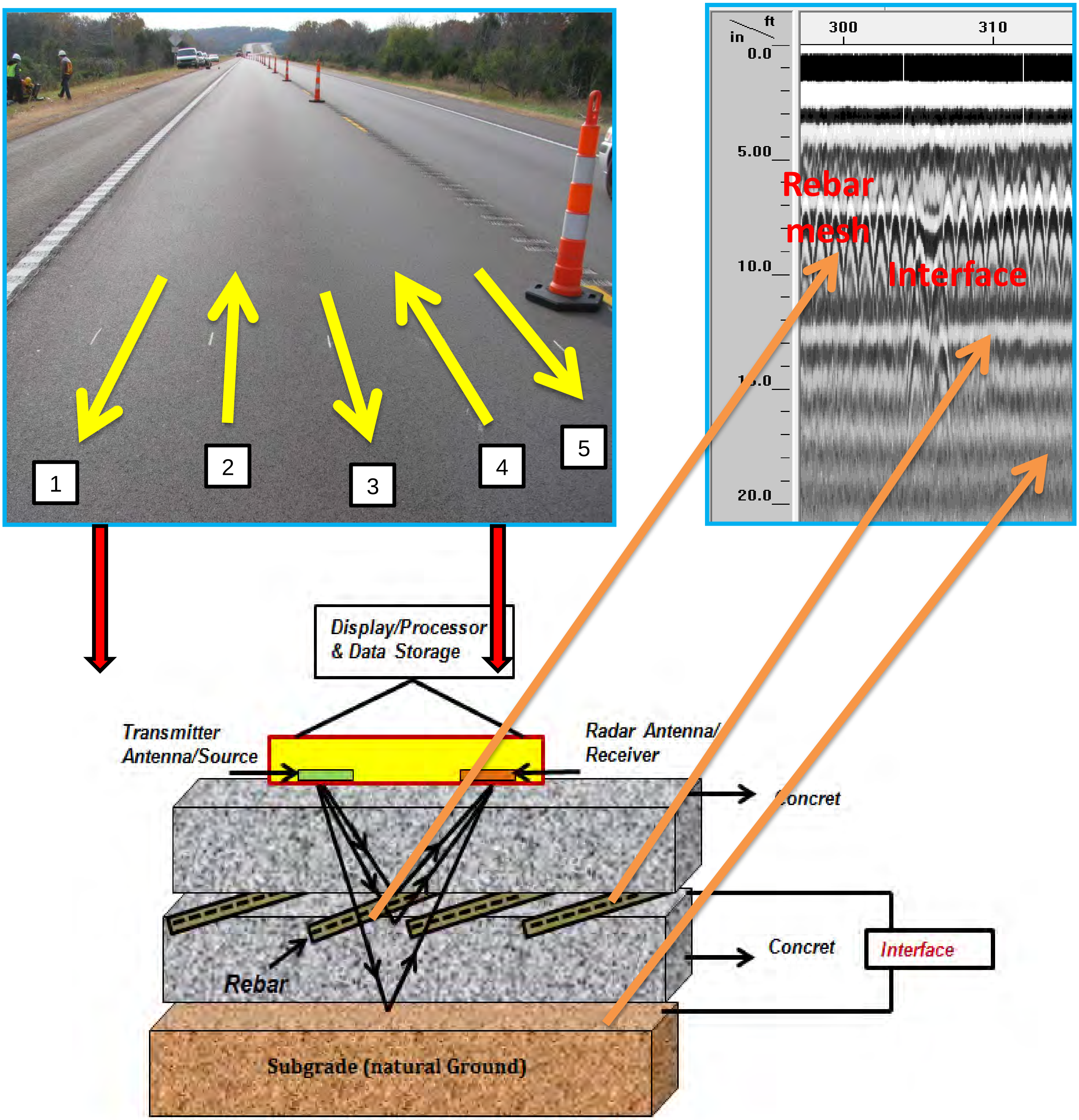

Figure 18. Simplified configuration of a GPR unit and operation and also showing location of GPR traverses on the site.

Acquisition of GPR Data. Data will be acquired using 1.5 GHz antenna along 5 traverses spaced at 2 ft. intervals (Figure 18) and using 400 MHz only along traverse number 3 at each segment of roadway.

Processing of GPR Data. Data will be processed using RADAN 6.5 software. Interfaces between layers (Asphalt overlay with asphalt, asphalt over concrete or concrete over concrete) will be mapped in all recorded GPR profiles of whole pavement sections in order to generate amplitude maps that help determination of deteriorated areas in pavement.

5.4. Portable Seismic Pavement Analyzer (PSPA).

The PSPA consists of two transducers and a source packaged into a hand-portable system, which can perform high frequency seismic tests. The source package is also equipped with a transducer for consistency in triggering and for some advanced analysis of the signals. The device is operable from a computer tethered to the hand-carried transducer unit through a cable that carries operational commands to the PSPA and returns the measured signals to the computer. The high-frequency source is activated four to six times. Pre-recording impacts of the source are used to adjust the gains of the amplifiers in a manner that optimizes the dynamic range of the electronics. The outputs of the three transducers from the final three impacts are saved and stacked. Typical voltage outputs of the three accelerometers are shown on the screen of the laptop.

The PSPA is used in detecting and locating defects within a material or at the interface of two adjacent materials. As a characterization tool, this method typically relies on determining the modulus of different materials by measuring either the compression or shear wave velocity. The PSPA can be utilized on both rigid and flexible pavements. When used on rigid pavements, the PSPA can provide information with respect to the quality and thickness of concrete, the existence and/or the location of voids or delamination within concrete, and the existence of voids or the loss of support underneath the slab. For flexible pavements, the PSPA provides information about the quality of the asphaltic-concrete layer. The PSPA will be used to obtain information about the integrity of asphalt and concrete. From the calculated modulus, the condition of the pavement can be estimated. High values are considered good condition, while low values are considered bad condition.

Acquisition of GPR Data. PSPA data were acquired at the stations spaced at 100 ft. along the 5 GPR traverses.

Processing of GPR Data. The PSPA data do not require processing. The operating principle of the PSPA is based on generating and detecting stress waves in a medium. The Ultrasonic Surface Wave (USW) interpretation method, which is implemented in the Spa Manager software in the PSPA computer, is used to determine the modulus of the material.

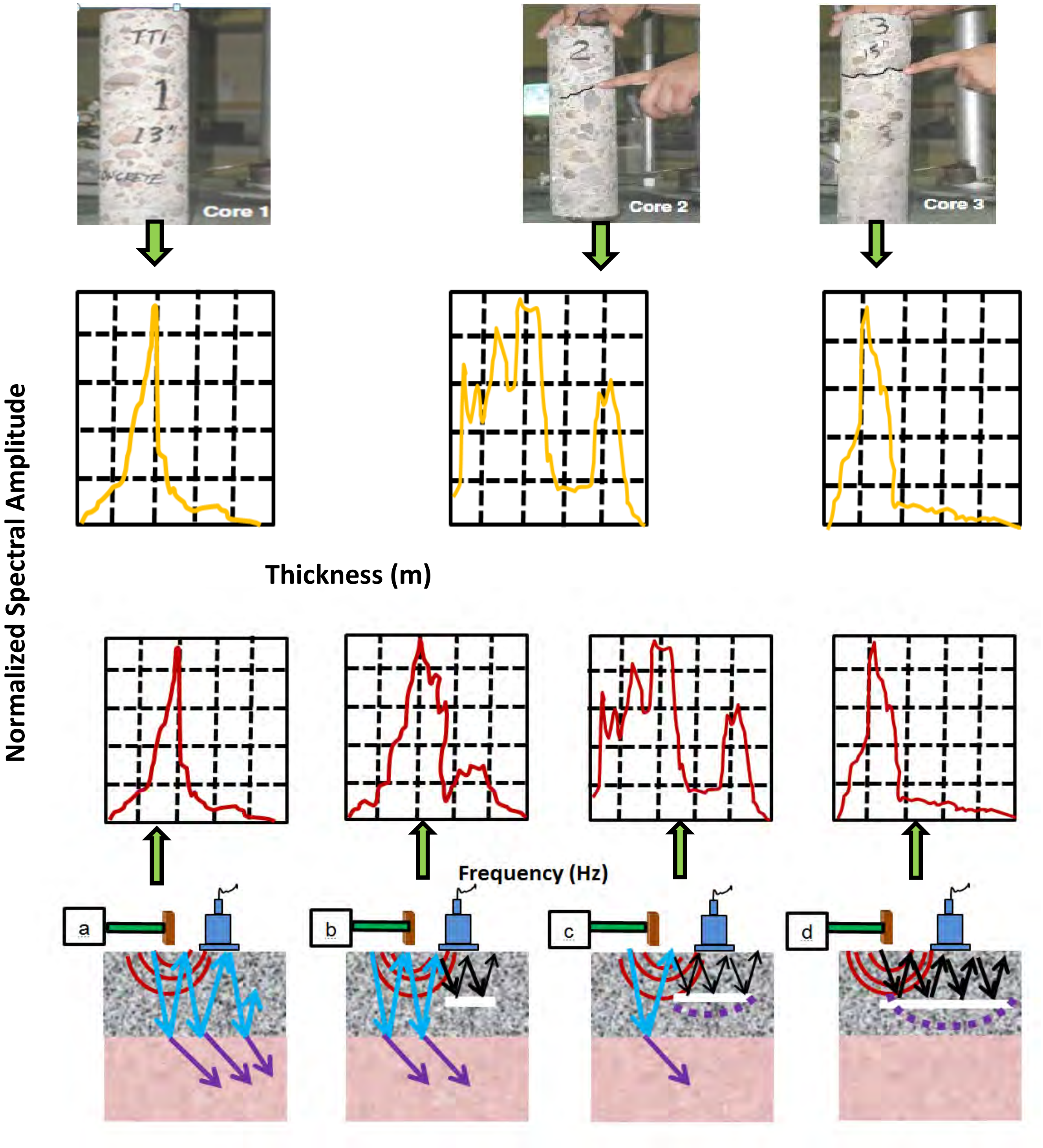

Figure 19. Typical normalized spectra representing (*a*) good (*b*) fair (*c*) poor and (*d*) severe.

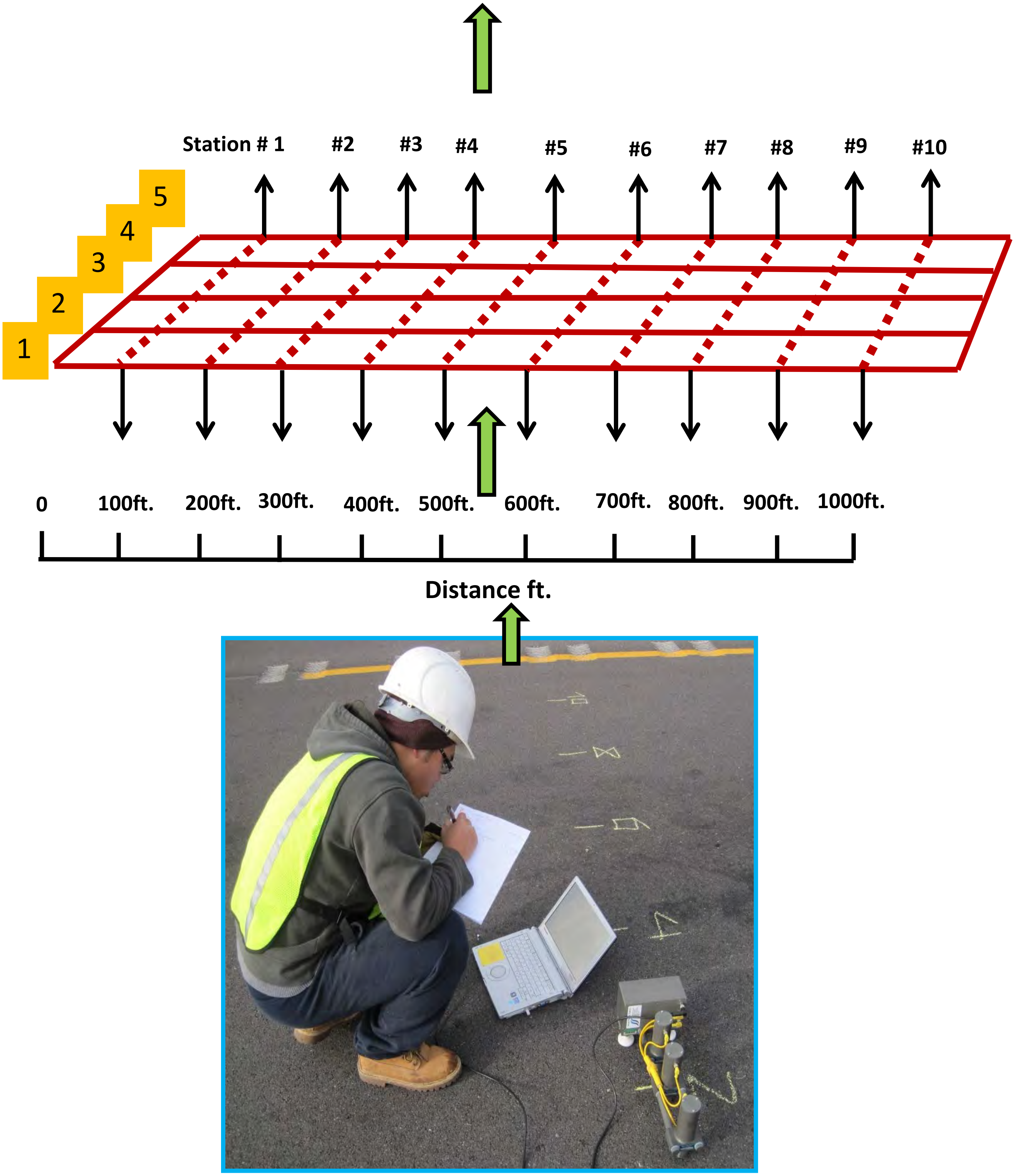

Figure 20. Portable seismic pavement analyzer data acquisition (PSPA).

6. Some Preliminary Results

Electrical Resistivity Tomography (ERT)

The ERT data were acquired in three segments (Figure 15 and 16) along the 1000-ft traverse and concatenated into a two-dimensional ERT profile (figure 21). A typical depth of investigation for the deployed resistivity dipole-dipole array with 72 electrodes and 5-ft spacing between the electrodes is typically 20% of the array length. Therefore the expected achievable depth of imaging in this site was approximately 80 ft. The acquired ERT field data were good quality and were processed using RES2DINV software. Black line represents depths to interpreted bedrock (dashed red line represents estimated depth to bedrock).

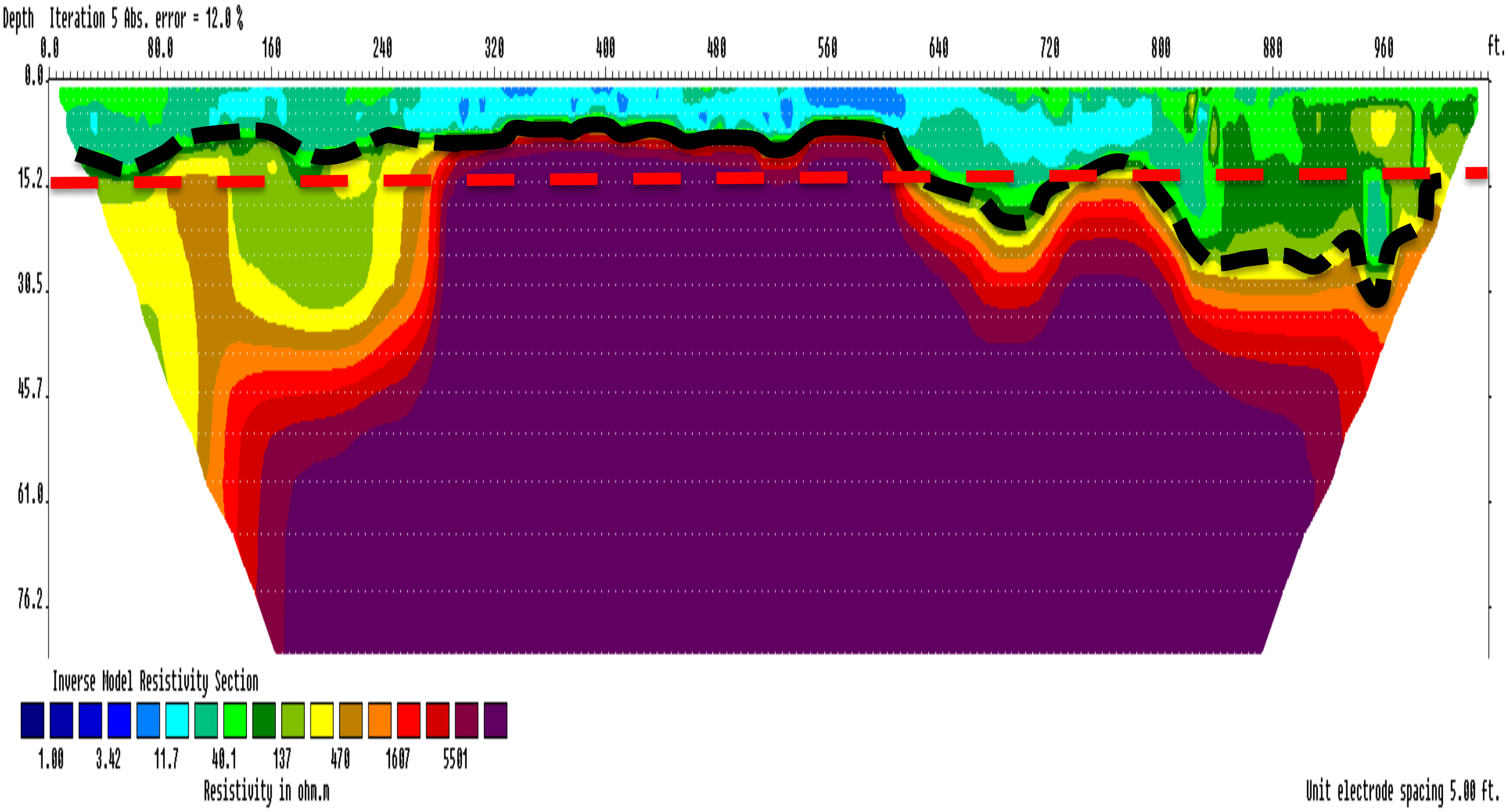

Figure 21. Three overlapping ERT profiles, acquired at the study site along a 1000-ft traverse. Solid black line represents interpreted top of bedrock, dashed black line shows estimated depth to top (dashed red line represents estimated depth to bedrock). Bedrock was characterized by a resistivity value of approximately 265 ohm-m and higher.

Multichannel Analysis of Surface Wave (MASW)

A total forty one MASW data sets were acquired along forty one traverses 1000 ft. long at the study site, at stations spaced at 25 foot along the center of the northbound lane. In this site a seismic array of 24 geophones spaced at 1.5ft and 10 ft. offset. The expected achievable depth of investigation was approximately 60 ft. One-dimensional shear-wave velocity profiles were generated for each of the forty one data sets. One of these profiles is shown in (Figure 22) the top of rock in central Missouri is typically characterized by shear-wave velocities in excess of 1,000 ft/s.

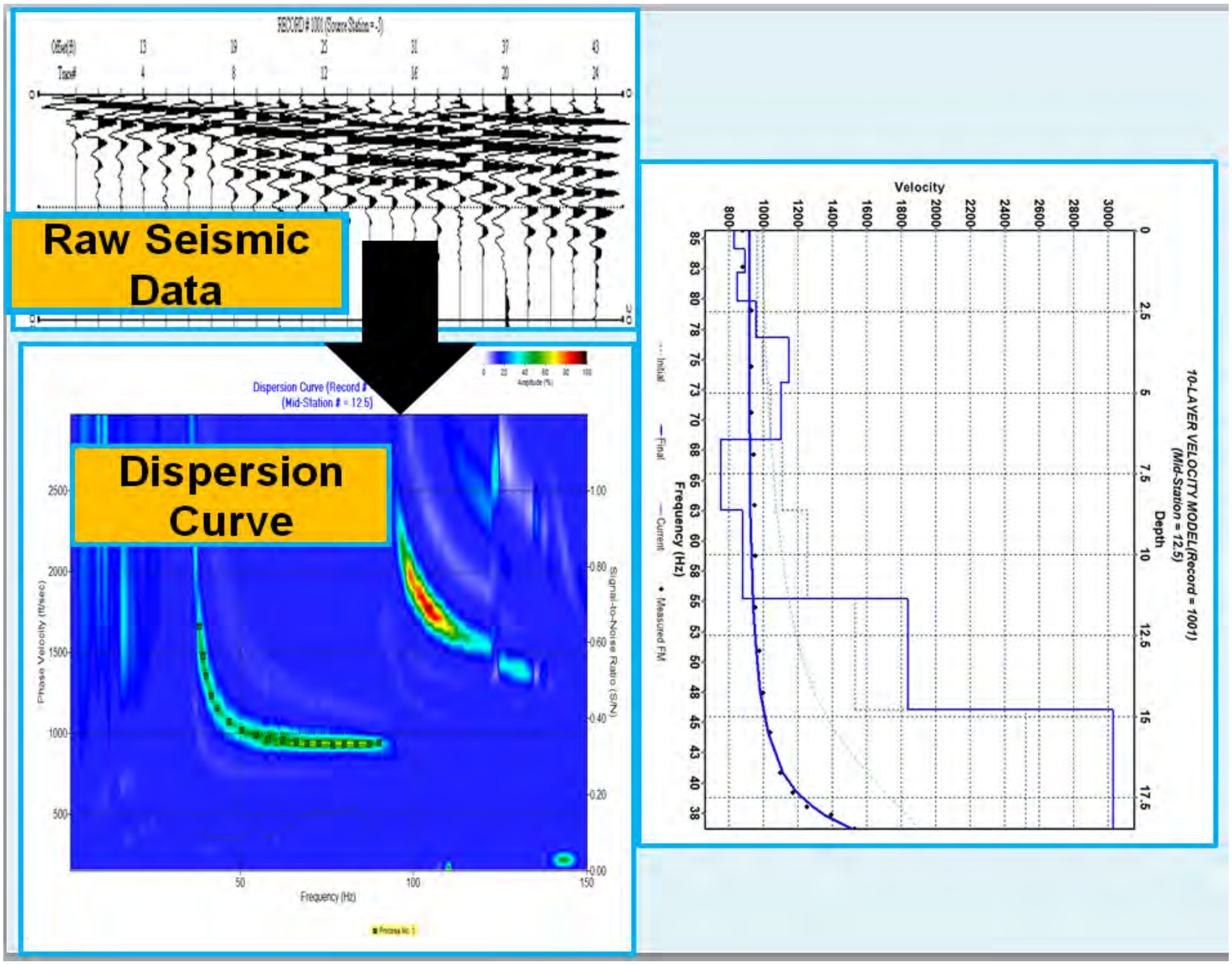

Figure 22. Raw seismic data, Dispersion curve and 1-D shear-wave velocity profile #13 centered at 300-ft mark. Interpreted top of rock (1,000 ft/s) is at a depth of 11.5 ft.

Comparison of ERT and MASW Data

All the one-dimensional shear-wave velocity profiles were combined by MATLAB software into a two-dimensional shear-wave velocity profile (Figure 23 B) due to the long 1000-ft distance of the MASW arrays and the variation in shear-wave velocities with depth. The 2 D shear-wave velocity profiles that combined were compared to the three overlapping ERT profiles that acquired at the same site along a 1000-ft traverse. Top of rock on ERT and MASW profiles correlated well in the areas with competent rock.

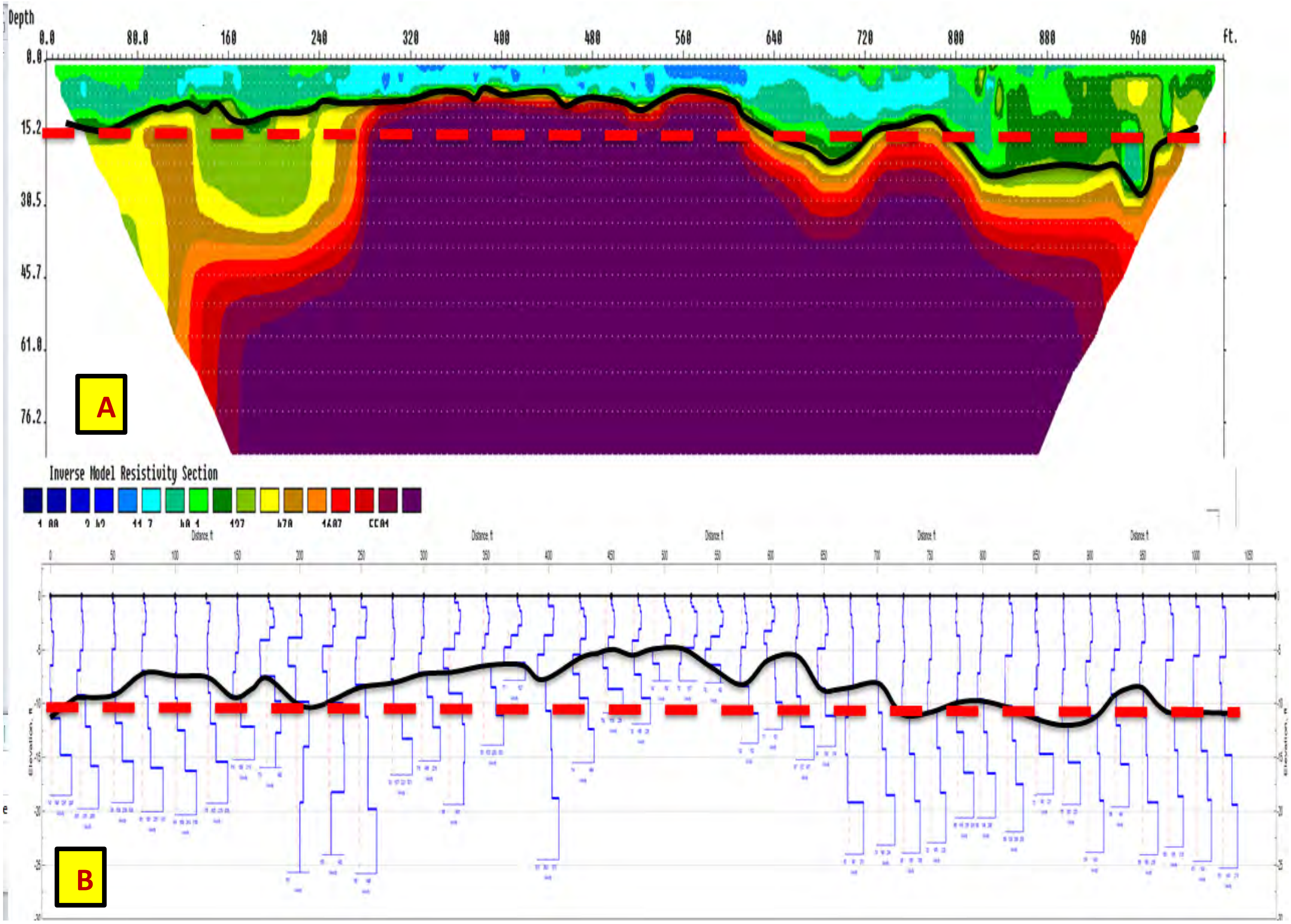

Figure 23. ERT profile with superposed interpreted top of rock (red line) based on MASW shear-wave velocity profiles. Red line represents interpreted top of rock based on MASW shear-wave velocity of 1,000 ft/s. ERT imaged the subsurface to an average depth of 80 ft; MASW imaged to a depth of approximately 60 ft. Top of rock on ERT and MASW profiles correlated well in the areas with competent rock: top of rock at a depth of 8 - 15 ft (MASW) and 10 - 17 ft (ERT). From 0 -ft mark to 280-ft mark top of rock at a depth of 8 to 12ft (MASW), and 10 to 15ft (ERT); from 280-ft mark to 600-ft mark top of rock at a depth of 8 - 10ft (MASW), and 10 - 12ft (ERT); from 600-ft to 1000-ft mark a depth of approximately 15ft (MASW), and 17ft (ERT).

Ground Penetrating Radar (GPR)

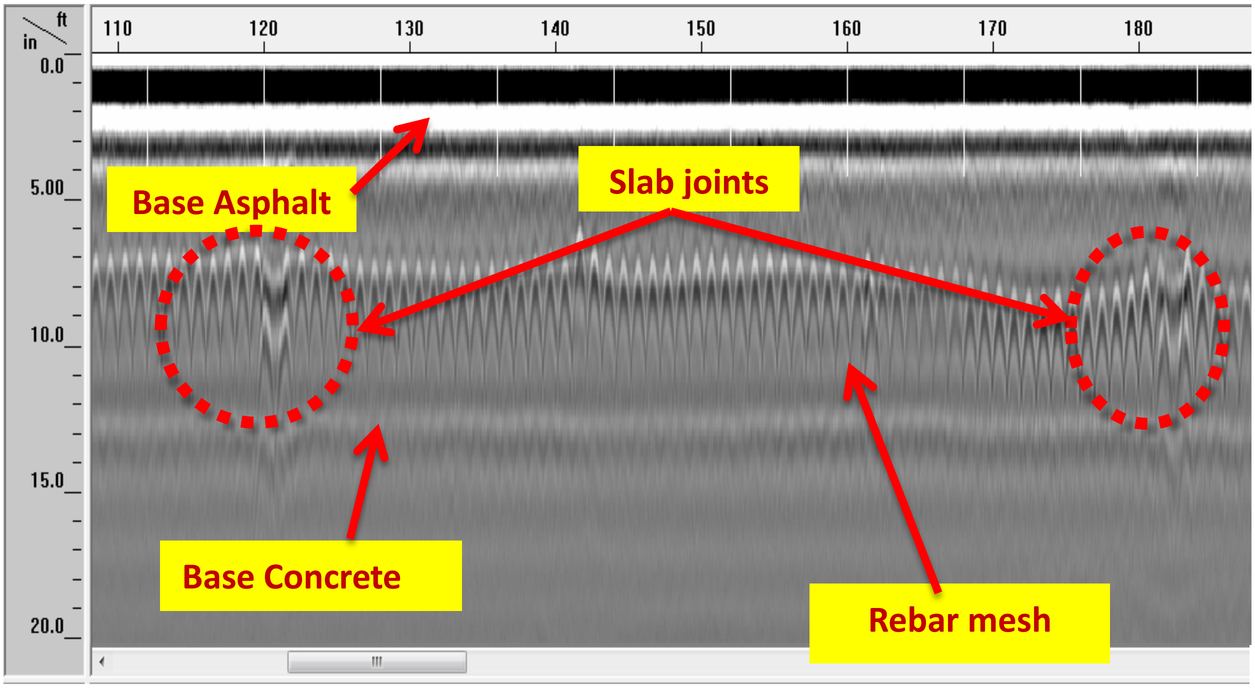

Figure 24. Visual examination of a GPR (profile #3 section 110- 180ft).

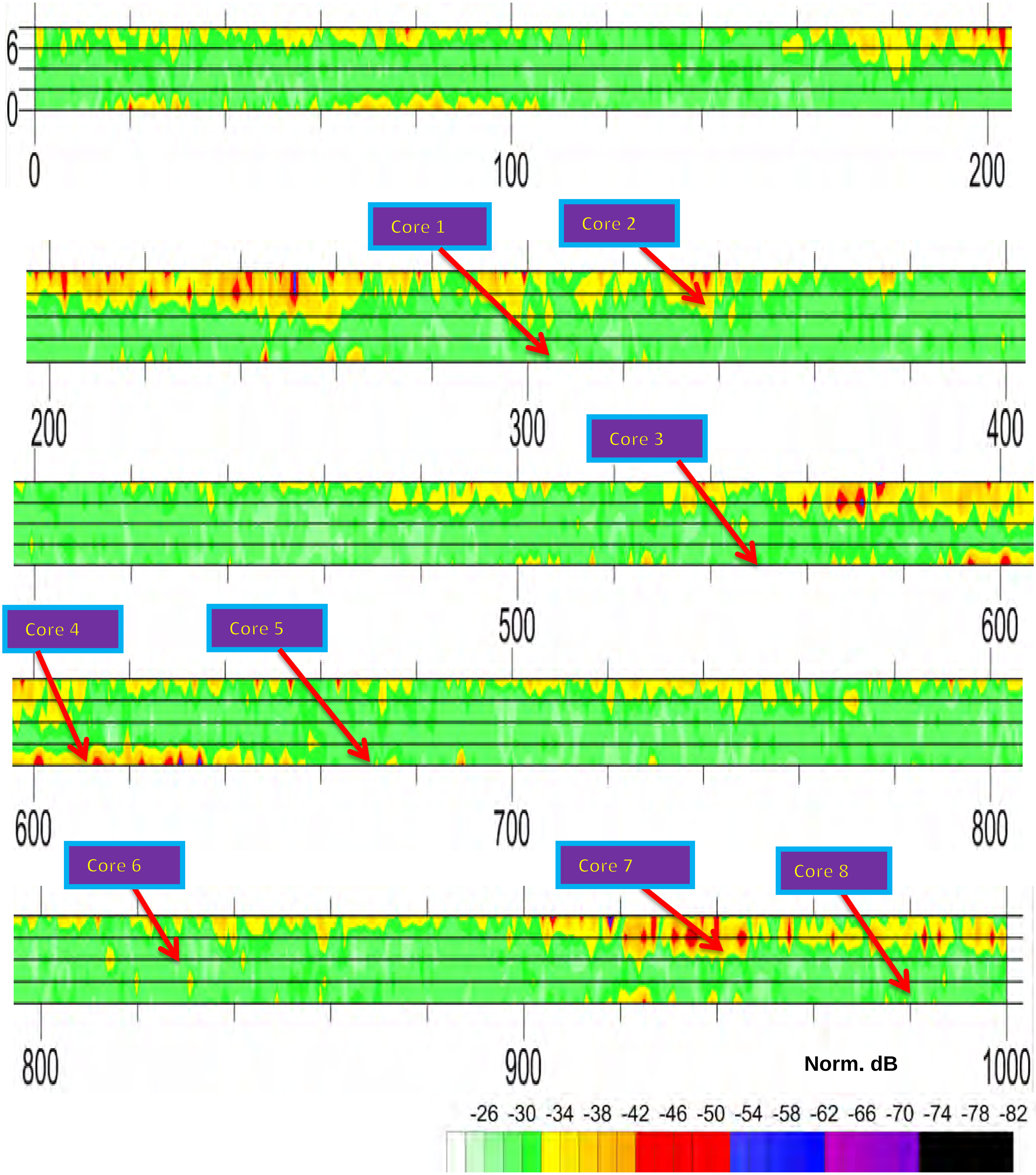

Figure 26. GPR amplitude map of asphalt layer base.

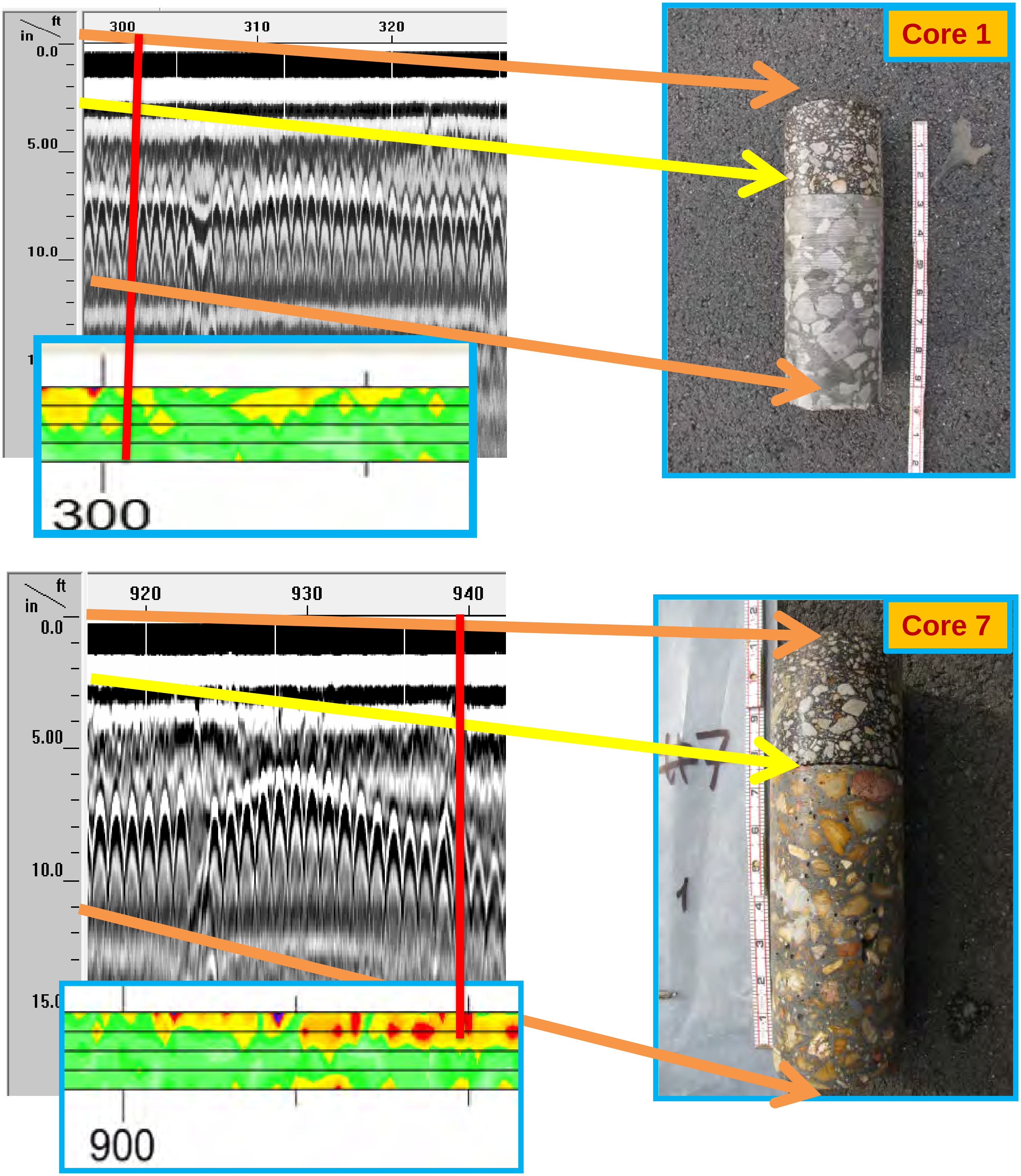

Figure 26. Shows correlation of two core samples on GPR profile and on amplitude map. The thickness of pavement section on GPR profile was matched with core control. The results correlated well in the study site.

7. Budget

This work is funded by Missouri Department of Transportation (MoDOT). The budget for this project has been summarized in (Table 3) and divided into parts: part 1 will be estimated cost to acquire field data at one test site. This part includes; crew size and time to acquire data, equipment rental and/or depreciation and vehicle rental and/or depreciation plus fuel. Part 2 will be estimated cost to process field data. This part includes; processing costs include processor's time and hardware/software rental and/or depreciation.

Tool	**GPR (1.5 GHZ)** **GPR (400 MHz)**	**PSPA**	**ERT**	**MASW**	**Cost**
Estimated cost to acquire field data at one test site	Basic field costs include: a). Crew time depending on the size of the site plus mobilization/demobilization time; B) equipment rental and/or depreciation; C) vehicle rental				
Crew size	1	2	4 - 5	3 -4	
Time to acquire data	0.5 day	0.5 day	2 days	1 day	
Estimated cost to process field data	Basic processing costs include: a) processor's time; b) hardware/software rental and/or depreciation.				
Usefulness					

Table 3. Budget summary for the project.

8. Significance of Proposed Research

The significance of proposed research is to identify and evaluate geophysical methods to rapidly obtain network-level and project-level information relevant to in situ pavement condition to enable pavement maintenance decisions. The focus of these efforts will be to explore existing and new technologies that can be used to collect data and develop the knowledge, procedures, and techniques that will allow MoDOT to perform pavement evaluation that will ultimately enable pavement maintenance decisions that minimize cost and maintain/improve pavement quality. In other word, is to thoroughly assess the cost-effectiveness and utility of the non-invasive technologies as applicable to MoDOT roadways.

9. Broad Impact of Proposed Research

The broad impact of proposed research includes; **(**1) Development of a comprehensive information about the combination of geophysical technologies used in this project, including a matrix on what cost-effective site assessment technologies are applicable, how to employ them, and what site condition data can be obtained in both network level or project level sites (2) Compare and quantify pavement data collection methods using geophysical technologies in terms of applicability, relative ease, and relative cost and identify potential improvements to current MoDOT data collection practices. (3) The optimal utilization of appropriate non-invasive imaging technologies will result in more accurate pavement assessments at significantly reduced costs. (4) This project will provide the basis and data to establish the value of different non-invasive imaging technologies in various conditions so that MoDOT can use the most effective means available to characterize future sites.

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