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Smart Rock Technology for Real-Time Monitoring of Bridge Scour and Riprap Effectiveness – Design Guidelines and Visualization Tools

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16. Abstract This study aims to further develop and demonstrate the recently-proposed smart rock technology for scour depth and protection effectiveness monitoring. A smart rock is one or two stacked magnets encased in a concrete sphere with a specially-designed rotational mechanism. Design guidelines, rotational mechanisms, remote measurement tools and localization algorithms of smart rocks were developed and validated at three bridge sites. The effect of steel reinforcement in bridge piers/deck on the orientation of gravity-controlled magnets was negligible. The localization accuracy with a single smart rock met a general requirement of less than 0.5 m in engineering applications. The spherical smart rock placed directly on the riverbed of the Roubidoux Creek successfully demonstrated its movement to the bottom of scour hole during the December 27, 2015, flood. Those deployed in the Waddell Creek and the Gasconade River were washed away and thus replaced with smart rocks embedded in deposits such that their top is in flush with the riverbed for improved stability under water current. For rip-rap effectiveness monitoring, polyhedral smart rocks are recommended to increase their interlock with other natural rocks.			
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FINAL REPORT

OASRTRS-14-H-MST

**SMART ROCK TECHNOLOGY FOR REAL-TIME MONITORING OF
BRIDGE SCOUR AND RIPRAP EFFECTIVENESS
– DESIGN GUIDELINES AND VISUALIZATION TOOLS**

**U.S. DEPARTMENT OF TRANSPORTATION OFFICE OF THE ASSISTANT
SECRETARY FOR RESEARCH AND TECHNOLOGY**

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EXECUTIVE SUMMARY

Hydraulic effect is responsible for more than half of the bridges collapsed in the U.S. Scour monitoring with fixed and portable instrumentations has been considered as one of the most effective measures in dealing with scour effect on bridges. Fixed instrumentation with sensors installed prior to flood events is unable to detect scour other than the area instrumented and vulnerable to harsh environments during a flood event. Most of existing portable instrumentations cannot be either deployed during a severe flood event due to safety consideration or operated with confidence in a harsh river environment with debris.

The goal of this study is to develop and implement a new type of portable instrumentation with a field agent (smart rock) participated in the process of scour. A smart rock is one or more stacked magnets encased in concrete with a specially-designed rotational mechanism. When deployed around a bridge pier, the smart rock can automatically roll to the deepest point of a scour hole to be developed under water flow and thus provide the scour depth through rock positioning with remote measurement of the magnetic field intensity over time. Once integrated into a rip-rap measure, the smart rock can move together with natural rocks and is thus a potential indicator of the disassembling process of a rip-rap protection. Therefore, the smart rock technology holds great promise for both scour depth and protection effectiveness monitoring.

To achieve the above goal, this study aims to develop, validate and demonstrate the design guidelines, rotational mechanisms, remote measurement tools, localization algorithms, and three-dimensional visualization tools of smart rocks in bridge application setting. Spherical smart rocks were considered for easy rolling in field operation. Their design was based on the critical velocity of water flow as specified in Hydraulic Engineering Circular No. 18. Three rotational mechanisms of magnets were developed to create three types of smart rocks with an Arbitrarily Oriented System (AOS), an Automatically Pointing South System (APSS) and an Automatically Pointing Upward System (APUS). At the beginning of this project, a G857 magnetometer and a custom-built device were respectively used to measure the intensity and orientation of a magnetic field particularly from a river bank. Toward the second half of the project duration, a 3-axis digital flux magnetometer was acquired and used on a bridge deck. In all field tests, a lightweight test crane was designed, built, and attached to a flatbed trailer towed by a truck to lower the magnetometer sensor from the bridge deck to as close to water surface as practically can be for strong magnetic field measurement. The AOS and APSS were employed to develop and validate the localization algorithms in an open field and at a bridge site while the APUS was used in smart rock prototyping for field testing and implementation at three bridge sites: I-44W Roubidoux Creek Bridge, MO, US63 Gasconade River Bridge, MO, and State Hwy1 Waddell Creek Bridge, CA.

To ensure a minimum effect of steel reinforcement in bridge piers and decks, a gravity-controlled APUS was designed to make the South pole of magnet(s) always faced up. Smart rocks with an embedded APUS were deployed for scour depth monitoring at the three bridge sites and for rip-rap effectiveness monitoring at the Waddell Creek Bridge site. The localization accuracy with a single smart rock met a general requirement of less

than 0.5 m in engineering applications. The spherical smart rock placed directly on the riverbed of the Roubidoux Creek successfully demonstrated its movement to the bottom of scour hole during the December 27, 2015, flood. Its movement was displayed on a three-dimensional contour map created in ArcGIS based on the riverbed survey data collected with a sonar device and a total station. Those smart rocks deployed in the Waddell Creek and the Gasconade River were washed away and thus replaced with smart rocks embedded in deposits such that their top is in flush with the riverbed for improved stability under water current. For rip-rap effectiveness monitoring, polyhedral smart rocks are recommended to increase their interlock with other natural rocks. In addition, the size of smart rocks based on the critical velocity of water flow is inadequate.

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1. INTRODUCTION

Bridges connect otherwise geographically isolated communities, often become a bottleneck in a ground transportation network in terms of traffic bypass ability, and require significant capital investment. Failure of these structures can significantly impact human welfare and economic development. One failure mode of bridges is related to the removal of riverbed deposits around bridge pier and abutment foundations, a process known as scour that leads to the loss of bridge stability.

Scour and other hydraulic induced failures accounted for 58% of all bridge failures [1], resulting in direct loss of lives and hundreds of millions of dollars in damage repair. For instance, 10 people lost their lives during the collapse of the I-90 Bridge over the Schoharie Creek in New York in 1987 when a pier footing was inadequately protected from the formation of a scour hole that undermined the pier [2]. As a result of the migration of the main channel which undermined a bridge column and thus led to the collapse of the U.S. 51 Bridge over the Hatchie River in Tennessee in 1989, 8 lives were claimed [2, 3]. The collapse of I-5 Bridge over the Arroyo Pasajero River in California in 1995 costed the lives of 7 individuals after a 9.8 ft scour hole had been developed over time [3, 4]. It was reported that the repair cost of bridges with scour damage would be \$100 million per event during 1964-1972 [5]. The cost of flood repairs during the 1980s was estimated to be \$300 million [6]. Between 1993 and 1995, the costs for the Midwest floods, Georgia and Virginia were \$178 million, \$130 million, and \$40 million, respectively [7]. Additionally, bridge collapses due to scour can have a dramatic impact on local communities with financial impact estimated to be five times the actual repair cost [8]. Therefore, it is necessary to protect these critical infrastructure elements against scour-induced potential damage.

Scour induced damage can be prevented by armoring the riverbed around bridge piers to reduce the amount of scour or by modifying the river hydraulics to reduce the peak flow, both requiring a significant amount of time and financial resources for implementation. Scour monitoring, however, can be implemented quickly at a reduced cost relative to other preventive measures. For this reason, Highway Engineering Circular (HEC) No.23 considers scour monitoring as a viable countermeasure for scour critical bridges [9]. The existing monitoring methods, however, cannot be applied to assess the condition of bridge scour in real-time because the continuous change in river and flow conditions required for the prediction of the maximum scour depth [10, 11] is not made available during a flood event. Real-time monitoring and assessment of bridge scour is critical not only to maintaining ground transportation services but also ensuring the transportation safety in hours or days during flood events [2]. Therefore, real-time field scour monitoring is crucial for a more accurate prediction of scour and a further calibration of bridge design equations.

1.1. Literature Review

Over the past half a century, the United States Geological Survey (USGS) along with Federal Highway Administration (FHWA) and the state Departments of Transportation (DOTs) in the U.S. have made significant efforts into the study of scour at bridge sites. In 1987, FHWA funded the USGS to initiate the National Bridge Scour Program. After many years of studies, the USGS published a national bridge scour report

[12], which aimed to guide the practice of engineers. From the report released by the USGS, countermeasures to mitigate bridge scour usually involve physical protection, such as rip-rap, and/or monitoring. When physical countermeasures are cost prohibitive, monitoring can be used to ensure that bridge foundations are stable. Monitoring can detect the evolution of bridge scour around piers and abutments that are either always under river or flooded in heavy raining seasons, and provide warning prior to a sudden failure, thus protecting the lives of bridge users and preventing bridges from collapsing if promptly mitigated.

1.1.1. State-of-the-art development

Over the past few decades, measurement and monitoring instrumentation has been developed for bridge scour. FHWA's HEC No.18 [13] first recommended the use of fixed instrumentation and sonic fathometers (depth finders) as scour monitoring countermeasures. The NCHRP Project 21-3 [9], *Instrumentation for Measuring Scour at Bridge Piers and Abutments*, developed, tested, and evaluated fixed scour monitoring methods both in laboratory and field. The NCHRP Synthesis 396 [14], *Monitoring Scour Critical Bridges*, assessed the state of knowledge and practice for fixed scour monitoring of scour critical bridges. In addition, the technical literature documented a number of scour detection and monitoring methods that have been developed over the past two decades.

Various monitoring techniques can be classified into portable and fixed instrumentations [9]. Portable instrumentation such as diving, sounding rod, radio controlled boat, reflection seismic profile, and ground penetrating radar, involves a manual operation of measuring stream bed elevations at bridge foundations. The portable devices can be used to monitor a bridge and transported from one bridge to another so that they are cost effective tools in addressing the scour monitoring needs in a bridge network. However, the portable devices cannot offer a continuous detection on the scour condition of bridge foundations. On the other hand, fixed instrumentations involves monitoring devices that are attached to bridge structures to detect scour at a particular location when frequent measurements or real-time monitoring are desirable.

The selection of the most effective and appropriate monitoring method could be a challenge for practical engineers. Ideally, appropriate instrumentation should be selected based on site conditions, operational limitations of specific instrumentation and engineering judgment, the advantages and disadvantages of different technologies [9]. To facilitate the selection of monitoring technologies, a scour monitoring framework for instrumentation selection given site-specific bridge and stream conditions was developed on a Visual Basic for Applications (VBA) platform [15]. The framework enables an excel workbook that requires the input for site specific information of one bridge at a time, such as the details of bridge, stream, and scour; it compares the application attributes with critical characteristics of fixed scour monitoring equipment. The final output is a list of instrument ranking in the framework and an overview of how various characteristics of this application affects the ranking score for each instrument.

Although various scour monitoring techniques have been developed, by 2005 only approximately 100 out of 25,000 over-water bridges were instrumented in the U.S. due to their limitations and associated costs, among which 90% were equipped by fixed instruments. The sonar scour system was the most popular device used at 51 bridge sites, followed by magnetic sliding collar at 23 sites and float-out device at 13 sites [16]. To

date, little or no real time scour data exists from historic flood events.

1.1.2. Existing monitoring methods

Visual inspection has been applied as a primitive and rapid visual inspection technique for bridge scour, which could not only result in a poor degree of accuracy, but also pose a threat to the safety of a diver [17]. In addition, the diver must have relevant experience in scour measurement [18].

Radar. Particularly Ground Penetrating Radar (GPR) as a geophysical technique has been successfully applied to identify and determine the depth of scour [9, 18-24]. The measurement of scour depth through radar is based on the wave propagation and reflection at river bed. A diverging pulse of electromagnetic radiation from the transmitting antenna (Tx) propagates through water and experiences multiple reflections/transmissions at the bottom of the river when it encounters interfaces with different dielectric constants (e.g. sediment and river bed). The reflections propagate back to the water surface where the receiving antenna (Rx) is located. The variations recorded in the received radar signal represent the change in river bed profile.

Sonar. Following the same principle as radar, a sonar device transmits a wave toward an object to measure the time and amplitude of the reflected wave or echo. In other words, the sonar technology is based on the round trip travel time of an acoustic pulse from a sensor to the riverbed [25, 26]. Sonar instruments measure scour depth through a supersonic sensor mounted on the edge of a sounding rod extending from a bridge deck or an inspection scaffold on a bridge inspection vehicle [27]. Sonar has been developed and used to characterize the sea bed by extracting the sediment type and properties from echo signals [28]. Alternatively, sonar as a non-optical underwater imaging technology has demonstrated the most potential application in scour monitoring [29]. Underwater acoustic imaging can provide photo quality visual images of submerged elements for structural inspection documentation and channel texture information for scour monitoring during a flood event in an easy, fast and safe approach.

Although radar and sonar have been conveniently and successfully used to detect the profile of a bridge scour hole, the monitoring results are sensitive to noise and difficult to interpret especially when the water contains high concentration sediments, debris or rocks in a flooded river. Therefore, radar and sonar are usually good for applications after flooding and thus cannot detect the maximum scour depth that is achieved during a flood at a peak discharge [30].

Magnetic sliding collar (MSC). MSC is another effective device used for the detection of scour. This instrument consists of a collar wrapped around a rod with a series of magnetically activated switches at predetermined locations along the length of the rod. The rod is driven into the streambed and the collar is embedded into the streambed [1, 31]. The scour depth is determined by the movement of the collar, which slides down the magnetic rod as the deposits around the foundation is eroded away. Lu et al. [32] used an MSC and a steel rod to monitor the total bridge scour during floods. The lower tip of the steel rod was initially placed slightly below the riverbed in the main channel. When scour occurred, the steel rod would sink as the surface of the riverbed was lowered. The scour depth was determined based on the total lowering distance of the steel rod with respect to its initial position.

Tilt sensor. A tilt meter basically detects the scour-related slopes of pier or abutment foundations [33, 34]. However, it can be a challenge to differentiate the

movement by scour and other factors such as traffic, thermal, wind and ambient perturbations.

Float-out device. A float-out device has a radio transmitter buried in the riverbed at particular locations (a certain depth) near bridge piers or abutments. As scour develops and reaches that depth, the device floats up to the water surface and transmits a signal that can be detected by a receiver at a remote station such as bridge deck [9]. Float-out devices are inexpensive, but only measure the particular depth where each is buried. Furthermore, such a device requires replacement once activated and washed away in the river. Another similar technology using a high frequency band (13.56 MHz) radio frequency identification (RFID) system with advantages of simple and low cost was developed to directly monitor the scour condition around a bridge pier. A series of passive tags with a unique number code each were buried in the riverbed near a bridge foundation and interrogated by the reader antenna coil to check their existence. When a tag is washed away due to scour, its response disappears during the one-to-one interrogation from the RFID reader, indicating the position and depth of the scour by the pre-embedding information uniquely assigned to the tag identification number [35].

Sounding rods. Sounding rods are manual or mechanical (automated) gravity-based physical probes [6, 9, 14]. A gravity-based probe drops with any change to the streambed depth. As a result of self-weight, the probe may penetrate through granular soils. To prevent self-penetration and vibration of the rod from flowing water, the foot of the rod must be sufficiently large.

Radio-Controlled Boat. A Radio-Controlled Boat (RC Boat) system was developed to detect bridge scour [17]. It consists of a digital fathometer for the measurement of scour depth, a telemeter transmitter of the measured data, a telemeter receiver of the measured data, a total station installed at the river bank to locate the boat, and a personal computer. The received data from the receiver and the location data from the total station are automatically transmitted into the computer for processing and evaluation of the scour depth at the streambed. The RC Boat can provide a precise streambed condition around bridge piers, but cannot be used during a flood event when debris or ice floats on water.

TDR. In recent years, time domain reflectometry (TDR) has been developed and used for real-time monitoring of bridge scour. It operates by sending an electromagnetic pulse through a transmission line with a fixed velocity. The pulse propagates down the transmission line until the end of the line or some intermediate discontinuity (air/water interface and water/sediment interface), where part of the pulse is reflected back to the source. By measuring the returning time of the sent pulse, the physical distance between the line end or the discontinuity and the TDR source can be calculated.

In 1994, a conventional TDR sensor was vertically buried in the sediments adjacent to a structural element [36]. When scour occurred, a portion of the TDR sensor was exposed, broken off, and shortened by the stream flow, which can be detected and measured. However, the TDR sensor will be destroyed and must be replaced after each scour event. Therefore, a TDR probe made of steel pipe was proposed to be permanently installed under the river bed to identify the sediment/water interface for scour monitoring [37]. Field evaluation at several locations indicated that the probe was sufficiently rugged. Even so, the intrinsic design of the probe made it difficult to install in the field condition. The acquired signals can be difficult to interpret and the application was

limited to a relatively short sensing range. Attempts were made to develop a robust algorithm for scour measurements and systematically interpret TDR signals by understanding the electromagnetic wave phenomena and TDR system characteristics [38]. The automatic scour monitoring system was demonstrated in laboratory experiments; the robust algorithm can accurately evaluate the thickness of sedimentation. A theoretical framework of automatic scour monitoring with the TDR principle and signals was further developed to determine scour condition and sediment status [39]. TDR was demonstrated to have accurately measured the scour depth, the density of sediment materials and the electrical conductivity of river water. The robust algorithm for the analysis of TDR signals was further described, assessed and evaluated in [40-42] and compared with the ultrasonic method to illustrate the advantages of the TDR [43]. A TDR sensor with a metallic coating was designed to increase the sensing depth and the level of protection [44]. A TDR scour sensor was redesigned to make it more applicable in field conditions with a robust algorithm to retrieve scour information from the TDR signals [45]. To further improve its sensitivity, a spiral TDR sensor was proposed and validated in laboratory for scour depth detection [46]. The sensitivity of the spiral TDR is four times that of the straight TDR since the spirally wrapped copper wire around a rod increases the travel distance of electromagnetic wave per unit length in the spiral probe.

Fiber optic sensor. Fiber optic sensors have been used for scour measurement in recent years based on wavelength or intensity measurement methods. They have many advantages such as long-term stability and reliability, resistance to environmental corrosion, high resolution, serial multiplexing capability, small size, geometrical and structural compatibility, immunity to electrical and electromagnetic noise, and low cost [47]. Wavelength based sensors [48-51] consists of a number of Fiber Bragg Gratings (FBG) instrumented on a rod at predetermined locations and embedded into the sediment. The scour detection principle was based on the fact that individual sensors are subjected to increasing strains when exposed to the river flow as a result of scour [49].

Two FBG systems were designed for local scour monitoring [50]. In the first design, three FBG sensors were mounted on the surface of a cantilevered beam and arranged in series along one single fiber. In the second design, several FBG sensors were arranged along one single optical fiber, but mounted on cantilevered plates installed at different levels of a hollow steel pile attached to a pier or abutment. The beam or plates were bent in the scour process and the induced strains were measured by the FBG sensors as running water flows around the cantilevered beam or plates. The scour depth can be detected by knowing the strain information indicated from the explosion condition of the FBG sensors that were buried under the sediment or river bed [50]. This FBG-based scour sensor was subsequently installed at the Dadu Bridge site in Taiwan for scour monitoring during floods. The FBG monitoring system appeared robust and reliable for real-time scour depth measurements [51]. A new type of FBG-based scour monitoring sensors was developed to exclude the influences of soil pressure and static water pressure varying with depth [52]. In addition, FBG sensors were embedded in a fiber reinforced polymer beam to improve the accuracy and durability of measurement [53]. Three designs of a scour monitoring system using FBG sensors were compared in terms of the measurement of water level, maximum scour depth, scour process and refilling deposition height [30]. The proposed system was tested in laboratory and then implemented with two test piles at a bridge site for long-term monitoring [54]. The

intensity-based measurement of scour depth is related to the fundamental frequency of vibration of a rod embedded in the riverbed to the scour depth and a single FBG sensor was used to measure the vibration frequency to obtain the scour depth by the inverse relationship of fundamental frequency and the length of the sensor rod [34]. In addition, a scour monitoring network of polymer fiber optic sensors (PFOSs) and MicroElectroMechanical System (MEMS) such as switches, phototransistor, LED, amplifier, detector and multiplexing system [55] was designed and fabricated for monitoring and detecting scour at bridge piers and abutments; the sensor response was greatly affected by the reflection property of various mediums so that the scour was detected by the change of various mediums. However, for the use of FBG sensors, installation design and fabrication techniques remain to be improved to withstand harsh operation conditions in field application [51].

Piezoelectric film sensors. Piezoelectric films were applied to monitor the water flow condition since voltage was generated as they were deformed (bent) under the effect of water flow [56, 57]. Such a sensing device was built by attaching piezoelectric thin films to a rod at certain spacing and inserting the rod into a guide rail installed next to the bridge pier. If the embedded piezoelectric films in the riverbed were disturbed by the water current as a result of scour, the output voltage were large than that when not disturbed. Therefore, the signals from all the piezoelectric sensors can indicate the variation of soil/water interface before, during and after a flood event. This device may lead to false measurements as the result of high sensitivity [58].

Temperature sensors. Bridge scour can also be detected based on the measurement of temperature variations at the water/sediment interface. A series of thermocouples spaced 2 inches apart along a partially buried rod may determine the scour depth by measuring the temperature gradient along the length of the rod [59]. The FBG sensors were also adopted as an array of temperature sensors instrumented along the length of a rod buried in the sediment to measure in real time the scour depth around a structure under both ordinary and flood conditions [60-62]. The rate of heat loss of the heated FBG by an electrical circuit embedded in sediment is slower than that in the flow; therefore, when the temperature of sensors buried in the sediment is large than those in flowing water, the bed level can be detected. The same idea based on the theory of heat conduction was also employed to develop a new design of temperature-based sensor consisting of a stainless steel cuboid shell, a heating piece and two temperature probes for bridge scour monitoring [63]. The laboratory test, numerical analysis, and in-situ field test were conducted to study a large-diameter, hollow tube as a heat probe for scour monitoring based on the different thermal properties of two environments: water and soil [64]. These temperature-based devices are simple in concept to understand and available for scour monitoring. However, they may not be accurate enough to read a temperature change over small intervals. Their validations are mainly limited to laboratory evaluation.

Vibration based methods. Vibration-based methods have been used to relate the dynamic response of a bridge to the scour condition of bridge foundations [65]. The average spectral shape of the vibration of a bridge measured from two three-axis accelerometers deployed on the upstream and downstream side of a pier was monitored to see if the natural frequencies of the pier had been changed. A similar approach was taken to monitor both the natural frequency and the mode shape of a bridge, which were related to the sediment variation surrounding the bridge foundations [66]. A tilt sensor

was used to monitor sensitive bridge columns by relating the fundamental frequency of the bridge with the scour depth [67]. Although the vibration-based measurements are a potential indicator to the health of piers, variations in ambient temperature and traffic loading could cause more changes in the fundamental frequency of a pier than the change by the bridge scour. Vibration-based turbulent pressure sensors (VTPs) were proposed to detect scour by installing them on a partially-buried pipe [68]. The energy content of each VTP along the pipe was monitored to indicate the scour level since the energy content of the sensors exposed to water flow is one or two orders of magnitude greater than that of the sensors buried in the sediment. The VTP sensors have been shown to be reliable and robust in harsh hydraulic environments [58]. However, the VTPs are still limited to the length of a pipe and the vibration may be caused by debris or traffic loading. More recently, the natural frequency of a pile was monitored and numerically analyzed to detect the presence of scour and possibly estimate the scour depth [69]. The developed numerical model was further extended to consider the effect of a bridge superstructure and establish the relationship between the structure's natural frequency and the scour of the foundation [70]. A vehicle-bridge-soil interaction (VBSI) model was developed to possibly detect changes in frequency using the bridge dynamic response to a passing vehicle. An Extended Kalman Filter (EKF) using the time history of dynamic measurements along with a finite element model was proposed to identify the scour depth with high sensitivity and better accuracy [71].

Tracking or imaging sensors. Distributed MEMS sensors were used for pressure measurement as an indicator of the effect of scour on bridge foundations [72]. A multi-lens monitoring system was developed to track scour images and retrieve the scour information through an image recognition process [73]. Another tracking technique for sediment transport and scour around bridges was developed using radio waves, a communication between a RFID and transponders embedded in individually tracked particles that are directly involved in the process of scour [74]. A combination of multi-beam ultrasonic echo sounders and vibrating wire piezometers was used to measure and map the riverbed topography and detect local scour appeared within and around the pile group [75, 76]. A three dimensional profiling of the river bed around bridge piers has also been attempted using a rotatable sonar profiler [77, 78]. The scour monitoring around a bridge can be realized by tracking the bed-level images with a micro camera mounted on a movable holder that can be driven by the motor and moved on the rail fixed on the pier. The system can recognize in real time the bed-level position and obtain the scour-depth evolution by adopting two scour image processing methods: brightness intensity segmentation (BIS) and particle motion detection (PMD) [79].

Smart scour sensor. A post instrumented with an array of wireless smart scour sensors at varying heights can be installed around bridge abutments or piers to monitor the sediment depth and profile around the foundation in real time [80]. The sensor array is composed of bio-inspired, whisker-shaped magnetostrictive flow sensors that are rugged, self-powered, and able to detect water flow by bending. The sensors located above the sediment level respond to the dynamic flow and the sensors located below the sediment line only return with static measurements. A real-time bridge pier scour monitoring system with low cost commercial hall-effect sensors was developed and verified in laboratory experiments [81]. The monitoring system is based on a master-slave configuration composed of a host controller (master), a gateway (slave), a Power

over Ethernet (POE) switch and a sensor node to send and receive commands and access the data collected. The sensor node is configured with a thin metal strip attached with a neodymium magnet and a hall-effect sensor. The distance between the magnet and the hall-effect sensor varies as the thin metal strip is bent due to water flow, and the variation is reflected by the output voltage of the hall-effect sensor. During experiments, it was observed that the output voltage of the hall-effect sensor dropped quickly when the sensor node buried in the sand was washed away due to the rapid scour erosion. The slow scour process and partial sand removal around the hall effect sensor module results in a slow rate of voltage change in the hall-effect sensor. Therefore, the scour condition is evaluated according to the rate of voltage change of the corresponding pre-buried hall-effect sensor node. Similarly, a rugged sensor system using an underwater sensor node buried deeply in the riverbed close to the bridge pier was developed to monitor scouring condition of the bridge pier in real time [82]. The underwater sensor node consists of two stacked octagon PCBs with a plastic enclosure that is then set up in a steel hollow ball. An accelerometer attached on the PCB is steady in normal condition when the underwater sensor is fully buried in the sand. However, it would be exposed and subjected to vibration as the sand of the riverbed is washed away due to the river water flow during a heavy rain or storm. Therefore, the vibration data of each sensor sent to the control box can be used to identify the scouring condition.

Medium property sensor. A scour probe embedded into the sediment next to a foundation to detect the underwater bed level variation based on the measurement of soil electromagnetic properties was proposed to remotely monitor in real time scour and sediment deposition processes [83]. Another similar approach for scour depth measurement was to measure the oxygen level of water to identify the water level around a pier. The optical dissolved oxygen (DO) probes [84] were installed along the buried length of a bridge pier or abutment to monitor DO levels at various depths. The scour depth is then evaluated by comparing the DO levels of sensors embedded in soil, which are negligible, to those exposed to the water flow as a result of scour, which approach the flowing water DO level.

1.2. Research Objectives and Scope of Work

The above review clearly indicated two groups of scour monitoring techniques: fixed and portable instrumentations. The fixed instrumentation is installed prior to storm events and limited to the measurement of scour condition near the fixed location around a bridge pier or abutment. Two challenges arise in applications. First, the scour information monitored may not be most critical due to fixation of the monitoring devices in horizontal plane. Second, whether the monitoring device can survive the harsh environment during a flood event is yet to be tested. Although the portable instrumentation can be applied to cover a wide area of a bridge pier or abutment, it is too risky to operate most, if not all, the portable devices during a flood event. Overall, monitoring the scour process of a pier or abutment during a flood event is an unsolved challenge in bridge engineering.

The goal of this study is to develop and implement a novel smart rock technology for the measurement of scour depths and the effectiveness detection of rip-rap mitigation measures in real time. The main objectives of this study are to: (1) develop, design, package, and prototype smart rocks; (2) develop and validate the localization algorithms of smart rocks at several test sites; and (3) implement the smart rock technology at

representative bridge sites. To achieve the main objectives, seven research tasks are planned as follows:

1. Design guidelines of smart rocks for scour monitoring and rip-rap effectiveness detection,
2. Type and prototyping of smart rocks for various characterization tests at open fields and three bridge sites,
3. Localization of a single smart rock in uniform ambient magnetic field,
4. Localization of smart rocks in non-uniform ambient magnetic field, and
5. Field validation and evolutionary mapping of smart rocks over time.

Tasks 1 and 2 address the first objective. Tasks 3 and 4 are designed to achieve the second objective. Task 5 is proposed to meet the third objective.

1.3. Organization of This Report

This report consists of six sections. Section 1 introduces the main objectives, the scope of work, literature reviews on bridge scour monitoring, and five technical tasks that will be addressed in the following sections. Section 2 introduces the development of smart rock technology, deals with the design of smart rocks for scour monitoring and rip-rap effectiveness detection, and finalizes the smart rocks for three different bridge sites. Section 3 deals with the localization of a single smart rock in uniform ambient magnetic field. Section 4 deals with the localization of one or two smart rocks in non-uniform ambient magnetic field. Section 5 presents the field implementation of smart rocks at three bridge sites and the validation of the localization algorithms developed in Section 4. Section 6 summarizes the main research outcomes, findings, and future studies.

2. SMART ROCK TECHNOLOGY FOR BRIDGE SCOUR MONITORING AND RIP-RAP EFFECTIVENESS DETECTION

Smart rocks are either natural rocks or concrete encasements with embedded permanent magnets. Properly-designed smart rocks can automatically roll to the deepest point of a scour hole when deployed in top riverbed deposits around a bridge pier. Once accurately positioned over time, they can function as field agents to collect the scour depth as scour develops. During a flood event, the scour depth data can be transmitted to the engineer-in-charge or decision makers through remote measurement of the magnetic field strength of the magnets embedded in smart rocks. In addition to the maximum scour depth that is most critical to the engineering design and maintenance of bridge foundations, smart rocks can be used to evaluate the effectiveness of a rip-rap scour countermeasure in real time since rock movement is an indication of its incipient failure.

To track the location of a smart rock, a commercial magnetometer is used to measure the intensity of a total magnetic field of the Earth, the permanent magnet inside the rock and any other ferromagnetic substances. A piece of survey equipment is employed to survey the measurement stations of the magnetometer. The position of the smart rock can be inversely obtained through a mathematical relationship between the magnetic intensity and the position of the magnet inside the smart rock. Therefore, the measured parameters for bridge scour monitoring are the intensity of magnetic field and the positions of the measurement stations.

2.1. Application Scenarios of Smart Rocks

For scour monitoring as illustrated in Figure 2.1(a), properly-designed smart rocks are near-surface deployed in riverbed deposits on the upstream of a bridge pier. When rolled to the bottom of a scour hole as it develops over time, the smart rocks can provide the maximum scour depth through their positioning by remotely measuring the magnetic field of the embedded magnet from a bridge deck. When the scour hole is refilled, the smart rocks can be buried into debris and deposits but still give the maximum scour depth to which the bridge pier is ever exposed. A smart rock can be tracked over time by measuring its disturbance to the ambient (the Earth + other ferromagnetic substances) magnetic field with a magnetometer set up at several remote stations. Since the maximum scour depth is directly associated with the position of the smart rock, localization of the smart rock is a major effort in bridge scour monitoring with the smart rock technology.

For rip-rap effectiveness detection as illustrated in Figure 2.1(b), smart rocks are mixed with natural rocks that are used to protect a bridge pier. The incipient motion of properly-deployed smart rocks is a good indication of rip-rap disassembling. Like scour hole monitoring, localization of the smart rocks is critical in this application.

2.2. Three Types of Smart Rock Systems

A smart rock can be made of a spherical concrete encasement of one or more permanent magnet(s) for easy rolling to the bottom of a scour hole. For maximum magnetic field strength, cylindrical magnets can be selected to fit into the design size of a smart rock. To date, the neodymium-iron-boron ($\text{Nd}_2\text{Fe}_{14}\text{B}$) magnet is one of the most advanced permanent magnets in the world. As such, two types of magnets, N42 (Br Max: 1.32 Tesla) with 10.2 cm (4") in diameter and 5.1 cm (2") in thickness and N45 (Br Max:

1.38 Tesla) with 15.2 cm (6") in diameter and 5.1 cm (2") in thickness are considered. The magnet(s) can be arranged differently inside a concrete encasement, resulting in different types of smart rocks. For instance, a N42 magnet can be configured to make its poles to be directed randomly, to geographical South Pole, and upward. The three configurations are referred to as Arbitrarily Oriented System (AOS), Automatically Pointing South System (APSS), and Automatically Pointing Upward System (APUS).

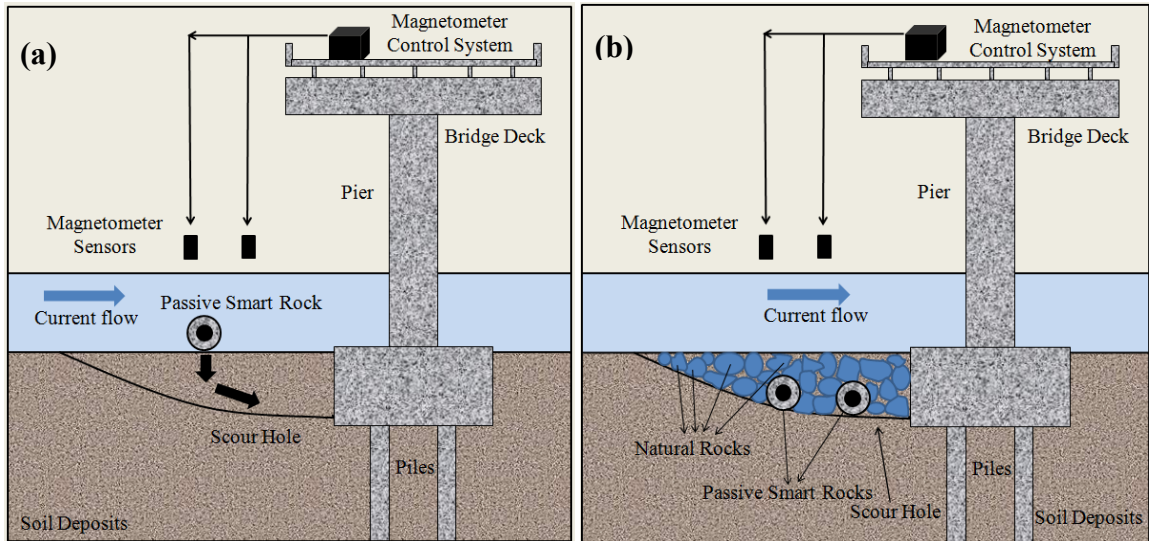


Figure 2.1. Two application scenarios of smart rocks: (a) maximum scour depth monitoring and (b) rip-rap protection effectiveness detection.

2.2.1. AOS

The simplest smart rock is a sphere concrete encasement with an embedded magnet or an AOS configuration whose pole direction rotates arbitrarily. Figure 2.2(a) and 2.2(b) show the schematic view and the primitive prototype of such a smart rock.

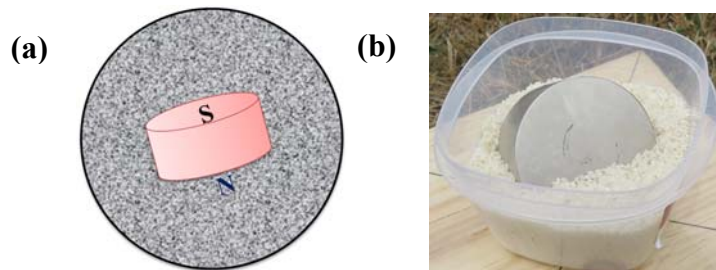


Figure 2.2. AOS design: (a) schematic view with concrete and (b) primitive view.

2.2.2. APSS

Like a compass that is widely used for direction and navigation around the world, the magnet embedded inside a smart rock can be designed such that it always points to the North Pole or near geographical south of the Earth. Such a magnet and its supporting components constitute an APSS proposed and developed in this study. The pole direction of the magnet always points to the North Pole of the Earth's magnetic field as the smart

rock moves or rotates under water flow. Since the magnetic field around a magnet is directly related to the rotation of the magnet, the fixed direction simplifies the calculation of the magnetic field and thus the optimization process to locate the smart rock.

Figure 2.3(a) shows the schematic view of an APSS design. The key to this design is to create a frictionless mechanism that makes a magnet free to rotate at all times. This design consists of an inside organic glass ball, an outside organic glass ball, low viscosity liquid filled in between the two balls, one cylindrical N42 magnet placed into the inside ball, a level indicator, and some copper beads distributed as balanced weights. As shown in Figure 2.3(b) for the final design, the magnet is 10.2 cm in diameter and 5.1 cm in height. Its side face is glued to the surface of the inside ball with a diameter of 20 cm. The outside ball has a diameter of 22 cm. The inside ball with the magnet and the level indicator is designed to remain in equilibrium or to be free to rotate once the inside ball floats within the outside ball. Therefore, the magnet in the APSS will always point to the North Pole of the Earth's magnetic field, which is near the geographical South of the Earth.

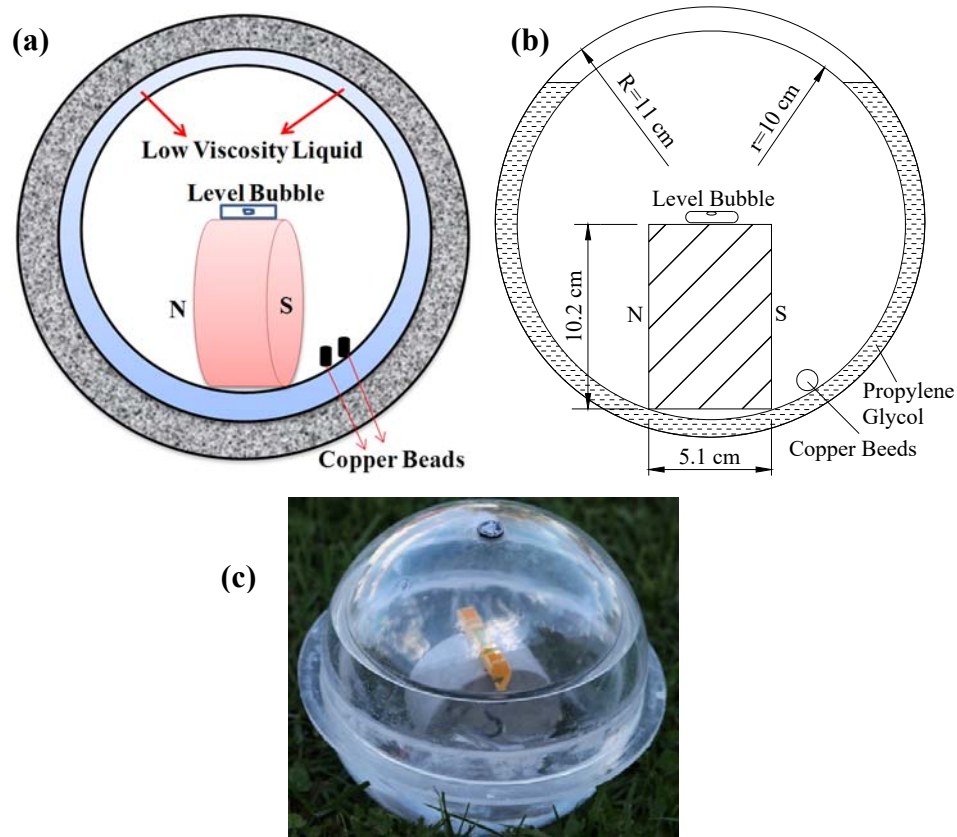


Figure 2.3. APSS Design: (a) schematic view with concrete encasement, (b) specifications, and (c) first prototype.

2.2.3. APUS

Like the APSS, an APUS is made of two concentric plastic balls. In this case, however, the center axis of the magnet fixed to the inside ball is perpendicular to the ground and the South Pole of the magnet is directed upward based on unbalanced

weights. Unlike the APSS, the gravity-based APUS is designed to be not influenced by any surrounding ferromagnetic objects in practical applications. Figure 2.4 shows the design of an APUS with the same size of two concentric balls and a N42 magnet as those of the APSS.

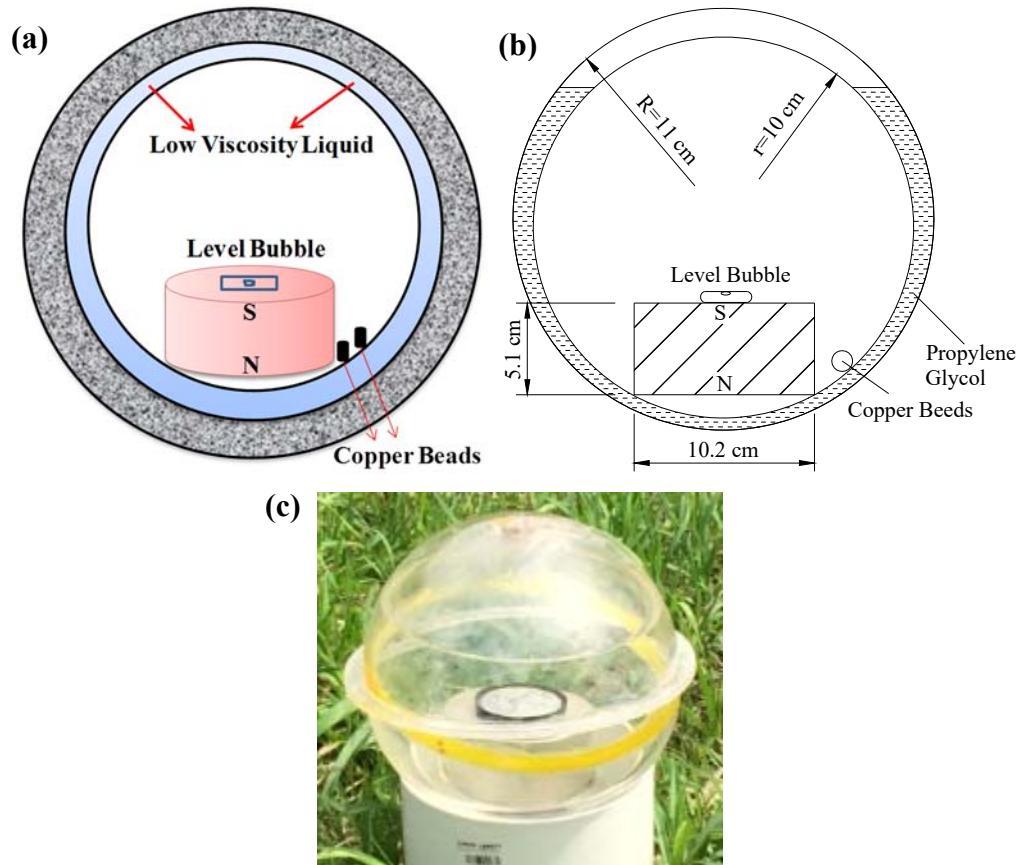


Figure 2.4. APUS design: (a) schematic view with concrete encasement, (b) specifications, and (c) first prototype.

2.3. Design Guidelines

When deployed near a scour critical bridge pier, smart rocks are displaced as their underlying deposits are eroded away. Therefore, properly-designed smart rocks can provide the critical information about the onset movement of rip-rap slope protection. If the motion of smart rocks can be controlled such that the rocks remain at the bottom of a developing scour hole near the bridge pier, the smart rocks can also provide critical information about the maximum scour depth, which is the most important parameter in bridge engineering and design for scour effect.

2.3.1. Design considerations

Smart rocks are designed to meet two requirements: 1) facilitate remote measurement for rock localization and 2) ensure automatic movement to the bottom of a scour hole to be monitored. The size of smart rocks is often constrained by the minimum size of embedded objects, such as permanent magnets, that are required for sufficient

localization accuracy and measurement distance. The size and density of smart rocks must be selected such that the rocks can always stay at the riverbed, overcome water current and roll down the slope of a scour hole, and remain at the bottom of the hole. Therefore, the density of smart rocks should range from that of water and that of rocks used in rip-rap slope protection.

To overcome water current and roll down the slope of a scour hole, the size and density of smart rocks highly depend on the critical velocity of water flow and the water depth at a bridge site. The critical velocity of water flow is defined as the velocity at which deposits at the riverbed begin to move or when the local shear stress of deposits exceeds its critical value. The water depth represents the effect of gravity on the movement of smart rocks, which affects the critical velocity of water flow.

For simplicity, the equation for the critical velocity of water flow in HEC No.18 and the equation for the rip-rap size in scour protection in HEC No.23 are referenced in the determination of the size and density of smart rocks. The two equations in SI units are rewritten as follows:

$$d = \frac{(nV_c)^2}{K_s y^{1/3} (S_s - 1)} \quad (2.1)$$

$$D_{50} = \frac{0.692(KV)^2}{2g(S_s - 1)} \quad (2.2)$$

where d represents the size of a smart rock in m ; n is the Manning's roughness coefficient; V_c is the critical velocity of flow in m/s ; K_s is a dimensionless Shields parameter related to the initiation of motion of smart rocks (0.052~0.054 for cobbles and boulders); $S_s = \rho_s/1000$ where ρ_s is the mass density of smart rocks in kg/m^3 ; y is the depth of water flow in m ; D_{50} is the median diameter of smart rocks in m ; K is the coefficient for pier shape (1.5 for round-nose piers and 1.7 for rectangle piers); V is equal to the average channel velocity, m/s , multiplied by a coefficient of 0.9 for a pier near the river bank in a straight uniform stream or 1.7 for a pier in the main current of flow around a bend; and g is the gravitational acceleration in m/s^2 .

2.3.2. Design procedure

A three-step design procedure for the selection of the size and density of smart rocks is described as follows.

Step 1: Determine hydraulics parameters near a bridge site. The flow velocity in the channel at a bridge site and the water depth directly in the upstream of scour critical piers, corresponding to a 100-year flood, are two most important parameters needed for the selection of smart rock size and density. They can often be found from hydraulic studies by the United States Geological Survey (USGS) or Federal Emergency Management Agency (FEMA).

When no hydraulic studies are available near a bridge site, the flow discharge from a recent flood event and its corresponding water depth are first estimated from the data collected at any USGS gage station deployed at the upstream or downstream of the bridge site. Considering no water loss, the flood discharge at the bridge site is assumed to be equal to that in the upstream or downstream of the bridge site. The average channel velocity can then be estimated by dividing the flood discharge by the flow cross section, which in turn depends on the water depth at the bridge site. For a given water depth, the

flow cross section can be estimated based on the as-built bridge drawings or a site visit with necessary measurements. Next, the local velocity at a scour critical bridge pier is determined by multiplying the average channel velocity by an amplification factor depending on the shape of river at the bridge site, the location of the pier (in main channel or close to the river bank), and the shape of the pier. Finally, the relationship between the local velocity and water depth can be established for sensitivity analysis.

Step 2: Constrain the size and density of a smart rock. Eq. (2.1) is applied to guide the selection of the size and density of a smart rock. With the local velocity and water depth from Step 1, the size of a smart rock can be related to the density of the rock in an inversely proportional relation. In other words, the larger a smart rock, the lighter the rock for given local velocity and water depth. In practice, either the size or density of a smart rock can be estimated from application needs. For example, the minimum dimension of a magnet to be embedded in a smart rock to meet the required localization accuracy and measurement distance can be referenced in the selection of rock size (e.g. > 20 cm). The density of the smart rock can then be determined correspondingly. Alternatively, the density of a smart rock can be considered to be the same as that of natural rocks ($2,650 \text{ kg/m}^3$), particularly when the smart rock is deployed to monitor the effectiveness of a rip-rap slope protection strategy. However, the size corresponding to the density of natural rocks is too small in general. Therefore, smart rocks should be sized first before their density is determined from the critical flow velocity and rip-rap sizing equations.

Step 3: Finalize the design of smart rocks. After the size and density of smart rocks have been estimated in accordance with the incipient motion of the rocks, the size and density must be modified by a design factor (1.2~1.3) that accounts for any uncertainties associated with the estimation of hydraulic data and the use of empirical equations. By considering the design sensitivity to the flow velocity and water depth at the bridge site and the physical constraint on the size and density of smart rocks, several choices of smart rocks are determined. The final selection of the size and density is made by rounding up their calculated numbers for easy fabrication of smart rocks, such as the use of standard mold sizes for the casting of concrete encasement.

2.4. Design of Smart Rocks

The incipient motion empirical Eq. (2.1) and Eq. (2.2) are employed to evaluate the size and density of smart rocks at different bridge sites: State Highway (Hwy) 1 over the Waddell Creek (Br. No. 36-0065), California, US63 Hwy over the Gasconade River and I-44 Hwy over the Roubidoux Creek, Missouri. To increase the effective measurement distance for magnetic fields, two stacked N42 magnets (10.2 cm or 4" in diameter and 10.2 cm or 4" in total height) or one larger N45 magnet (15.2 cm or 6" in diameter and 5.1 cm or 2" in height) were considered as the magnetic core of a smart rock for field deployment. The sizes of inside and outside balls are selected to ensure that the inside ball with the two stacked magnets can float within the outside ball. They are 25 cm and 28 cm in diameter, respectively, which are commercially available. Furthermore, to cast concrete encasement as the enclosure of a smart rock, a 36.8 cm (14.5 in)-diameter standard mold is selected. Considering $d = 36.8 \text{ cm}$ or 14.5 in. in Eq. (2.1) and Eq. (2.2), the density of smart rocks for three bridge sites are designed below.

2.4.1. Site 1: State Hwy1 Bridge over the Waddell Creek

The bridge (Br. No. 36-0065) is located approximately 28 km (17 miles) north of the City of Santa Cruz. Built in 1947, the 4-span structure as shown in Figure 2.5 is 55.1 m (180.8 ft) long and 9.7 m (31.7 ft) wide. Continuous reinforced concrete (RC) T-girders are supported on RC piers and seat-type abutments. In the upstream of the bridge, the terrain is dominated by small mountain ranges that flank both sides of the creek. In the downstream of the bridge, the channel alignment changes with flow intensity as it flows through the beach (loose, coarse sand) towards the Pacific Ocean.

In February of 2000, a storm caused severe erosion to the upstream channel banks of the south roadway approach, extending into the embankment at Abutment 1. The storm-induced high flow exposed some piles at Pier 2 up to 2.7 m (9 ft). Rock slope protection (0.7 to 1 m in diameter) was placed in March of 2000 along the eroded sections of the roadway embankments and channel banks. Since then, this bridge has been classified as scour critical. In order to estimate its scour potential, hydraulic parameters (flow skew, tidal influence, flow contraction, and pressure flow) were obtained from an advanced 2-D hydraulic model established by Caltrans.



Figure 2.5. State Hwy1 Bridge over the Waddell Creek.

The 100-year flood discharge (Q_{100}) was estimated to be $162 \text{ m}^3/\text{s}$ from the regional flood-frequency equation based on the historical gage data from USGS. The high water elevation (HWEL) reached 2.865 m, which was well below the bottom of girder elevation (El = 4.145 m). Therefore, no submersed condition existed and no pressure flow occurred. In normal conditions, the uncontrolled tide from the Pacific Ocean has no effect on the flow elevation at the bridge site. The flow depth (y) and velocity (V) in the directly upstream of various piers obtained from the 2-D analysis model are listed in Table 2.1. The materials in channel bed varied from coarse sands to large cobbles. Specifically, coarse sands were noted in the vicinity of the bridge, small pebbles were found in the upstream of the bridge, and pebbles and/or cobbles were noted in the downstream of the bridge. The Manning's roughness " n " value was 0.02 for the channel and beach areas, 0.04 for the grassy banks, 0.045 for the large rock slope protection zone, and 0.10 for the bank sections lined up with small trees.

Table 2.1. Hydraulic Parameters at Various Bents

Bent No.	2	3	4
y (m)	3.566	2.012	0.152
V (m/s)	2.286	3.048	1.585

It was concluded by Caltrans that Bent 2 would be laterally unstable during the anticipated 100-year flood event due to excessive pile exposure. Scour at Bents 3 and 4 should not have any instability issues. Therefore, the hydraulic parameters at Bent 2 were selected to estimate the size and density of smart rocks in this study. They are: $K_s = 0.052$ for fine cobbles from the USGS Scientific Investigations Report 2008-5093; $S_s = \rho_s/1000$, where ρ_s is the mass density of smart rocks in kg/m^3 ; $g = 9.81 \text{ m}/\text{s}^2$; $d = 0.368 \text{ m}$ for smart rocks based on the required space for magnet embedment; $V_c = V = 2.286 \text{ m}/\text{s}$ at Bent 2; $y = 3.566 \text{ m}$ at Bent 2; and $n = 0.041d^{1/6} = 0.0347$. That is,

$$2.286 = \frac{0.052^{1/2} \left(\frac{\rho_s}{1000} - 1 \right)^{1/2} 0.368^{1/2} 3.566^{1/6}}{0.0347}, \quad \rho_s = 1215 \text{ kg} / \text{m}^3 \quad (2.3)$$

2.4.2. Site 2: US63 Hwy Bridge over the Gasconade River

The bridge over the Gasconade River on US63 is located approximately 8.9 km (5.5 miles) southeast of Vienna in Maries County, MO. Built in 1970's, it is a 12-span concrete-girder structure as schematically shown in Figure 2.6. The main flow goes between Bents 4 and 5 during dry seasons. During a flood season, Pier 4 could be potentially subjected to severe contraction scour and local scour, threatening the safety of the bridge. The 100-year flood discharge in the channel ($Q_{100} = 4234 \text{ m}^3/\text{s}$ or $146000 \text{ ft}^3/\text{s}$) was estimated from the historical data recorded from the USGS gage station at Jerome, MO (gage No. 06933500).

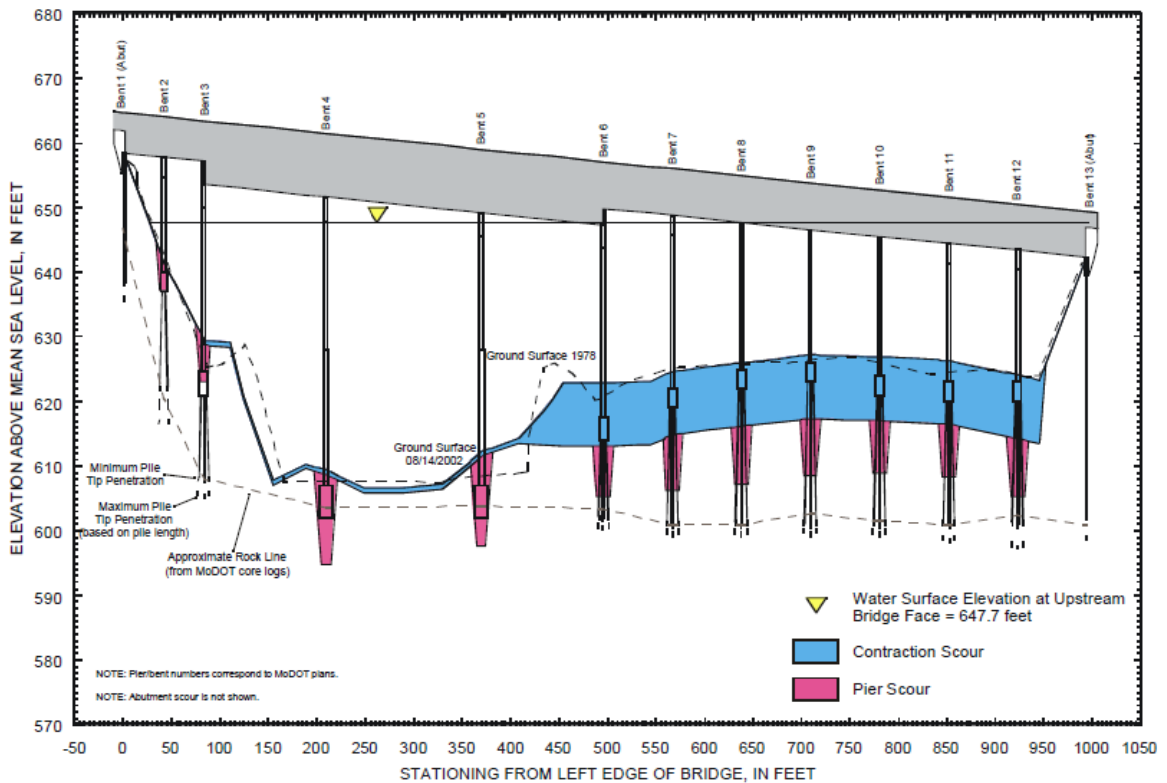


Figure 2.6. Scour condition of the Gasconade River Bridge.

The average flow velocity at the bridge site was estimated by dividing the 100-year discharge by the cross sectional area of the channel. Based on the as-built bridge drawings and flow elevations, the cross sectional area (A) was estimated to be 3395 m^2 (36544 ft^2). Thus, the average channel velocity $V_{average} = Q_{100} / A = 1.218 \text{ m/s}$. The velocity directly in the upstream of Bent 4 was then calculated by multiplying the average channel velocity by 1.7 for a pier in the main current of flow. The flow depth at Bent 4 is approximately 12.2 m (40 ft) estimated from Figure 2.6. Once again, the diameter of smart rocks was taken to be 0.368 m , and $n = 0.041d^{1/6} = 0.0347$. Therefore, the density of smart rocks can be determined from the critical velocity criterion.

$$1.218 \times 1.7 = \frac{0.052^{1/2} \left(\frac{\rho_s}{1000} - 1 \right)^{1/2} 0.368^{1/2} 12.192^{1/6}}{0.0347}, \quad \rho_s = 1117 \text{ kg} / \text{m}^3 \quad (2.4)$$

2.4.3. Site 3: I-44W Bridge over the Roubidoux Creek

The bridge (Br. No. L0039) over the Roubidoux Creek near Waynesville, MO, is located about 19 km (12 miles) South of Crocker in Pulaski County. From the bridge drawings provided by the Missouri Department of Transportation, this bridge has 10 spans with the main flow going between Bents 5 and 7 as shown in Figure 2.7. The pier at Bent 6 may be scour critical. Since there is no documented record for the 100-year flood discharge near the bridge site, the maximum discharge and flow depth ($Q_{max} = 515.4 \text{ m}^3/\text{s} = 18200 \text{ ft}^3/\text{s}$ and $y = 5.70 \text{ m} = 18.7 \text{ ft}$) recorded at the USGS gage station (USGS 0698300, Roubidoux Creek above Fort Leonard Wood, MO) during the flood event in August, 2013, were used in calculation. The cross sectional area (A) during the flood event was estimated to be 1087 m^2 (11703 ft^2) from the bridge drawings. Therefore, the average channel velocity $V_{average} = Q_{max} / A = 0.474 \text{ m/s}$, and the velocity directly in the upstream of Bent 6 was estimated by multiplying the average channel velocity by a coefficient of 1.7.

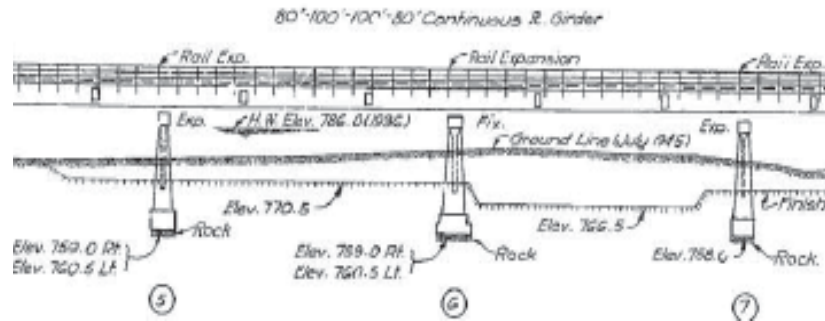


Figure 2.7. Drawing of I-44 Roubidoux Creek Bridge at Bents 5-7.

Once again, the diameter of smart rocks was kept to be 0.368 m , and $n = 0.041d^{1/6} = 0.0347$. Therefore, the mass density of smart rocks can be determined based on the critical velocity as follows.

$$0.474 \times 1.7 = \frac{0.052^{1/2} \left(\frac{\rho_s}{1000} - 1 \right)^{1/2} 0.368^{1/2} 5.70^{1/6}}{0.0347}, \quad \rho_s = 1022 \text{ kg} \quad (2.5)$$

2.4.4. Final design of smart rocks

Due to the uncertainties of estimated hydraulic parameters, the calculated mass density from the critical velocity ought to be increased by 1.2 or 1.3 times in order to prevent the deployed smart rocks from being washed away, depending on the available hydraulic data at bridge sites. For *Highway 1 Waddell Creek Bridge*, a design factor of 1.2 was considered since a detailed 2D hydraulic model was developed by Caltrans to derive the hydraulic parameters at the bridge site. Therefore, the density of smart rocks should be $1.2 \times 1215 = 1458 \text{ kg/m}^3$ based on the evaluation of critical velocity. For all other bridges, a larger design factor of 1.3 was considered due to insufficient information on the local hydraulic data at these sites. Therefore, the density of smart rocks should be $1.3 \times 1117 = 1452 \text{ kg/m}^3$ for *US63 Gasconade River Bridge*, and $1.3 \times 1022 = 1432 \text{ kg/m}^3$ for *I-44 Roubidoux Creek Bridge*. For easy fabrication, the target density of smart rocks was finally taken to be 1495 kg/m^3 for a given diameter of 0.368 m .

2.4.4.1 Internal configuration

The magnetic field of a permanent magnet changes with the orientation of the magnet. For example, the intensity at two poles of the magnet is twice as much as that at its equator. In practical applications, the magnetic field of a smart rock with an embedded magnet is measured from a magnetometer that is stationed either on the river bank or on the bridge deck.

When a magnetometer is set on the river bank, the two poles of a magnet should be aligned with the Earth's magnetic field for maximum sensitivity in an APSS as detailed in Figure 2.3. The advantage of the APSS monitored along the river bank is that the measurement station can be potentially located along the extension of South or North pole of the magnet, which accelerates the convergence of the APSS localization algorithm with high accuracy. The disadvantage of the APSS is that the direction of the magnet is easy to be affected by strong ferromagnetic substances in the river. To avoid the direction variation by surrounding ferromagnetic substances, the south or north pole of the magnet can be faced upward in an APUS as detailed in Figure 2.4. In this case, however, the measurement for maximum sensitivity is restricted to one side of the magnet, which may reduce the accuracy of rock localization. Besides, during a storm season, river banks are often submerged under water and inaccessible to field tests. Therefore, the APSS is preferable in open field tests for smart rock characterization and less desirable for deployment in the river or creek for field measurement.

When a magnetometer is set on the bridge deck, the two poles of the magnet should be aligned vertically due to several reasons. First of all, the strongest magnetic field of a magnet can be found at its two poles, which is in good alignment with the vertical sensor of the magnetometer. Secondly, the direction of the magnet is less affected by surrounding ferromagnetic substances, which ensures stable and repeatable measurements over time. Finally, the gravity-oriented direction of the magnet considerably reduces the degree of freedom in the localization algorithm. Furthermore, the south pole of the magnet should be faced up or to the bridge deck for larger intensity of the combined magnetic field of surrounding ferromagnetic substances and the magnet since the three bridges are located in northern hemisphere. In this case, the smart rocks with an APUS are a reasonable choice for field deployment.

Therefore, the final internal configuration of smart rocks for three bridge sites is

APUS. Specifically, for Highway 1 over the Waddell Creek and I-44 over the Roubidoux Creek, two stacked N42 magnets (maximum residual flux density: 1.32 Tesla) are configured for practical applications. Figure 2.8(a) shows the schematic view of an APUS with two stacked N42 magnets. The diameter of inside and outside balls are 25 cm and 28 cm, respectively, to ensure that the inside ball with two magnets placed at the bottom always remains in suspension. For the US63 highway bridge over the Gasconade River, one larger N45 magnet (maximum residual flux density: 1.38 Tesla) with 15.2 cm (6") diameter and 5.1 cm (2") height was selected to generate a stronger magnetic field for practical application. Figure 2.8(b) illustrates the schematic view of an APUS with one N45 magnet placed at the bottom of the inside ball.

2.4.4.2 Design details

A smart rock with one or two magnet(s) in an APSS or APUS configuration placed inside an organic glass ball (inside ball), an outside organic glass ball, liquid filled in between the two balls, and a concrete shell encasement. After the type and number of the magnet(s) have been determined, the diameters of two balls and the type of liquid are selected as follows.

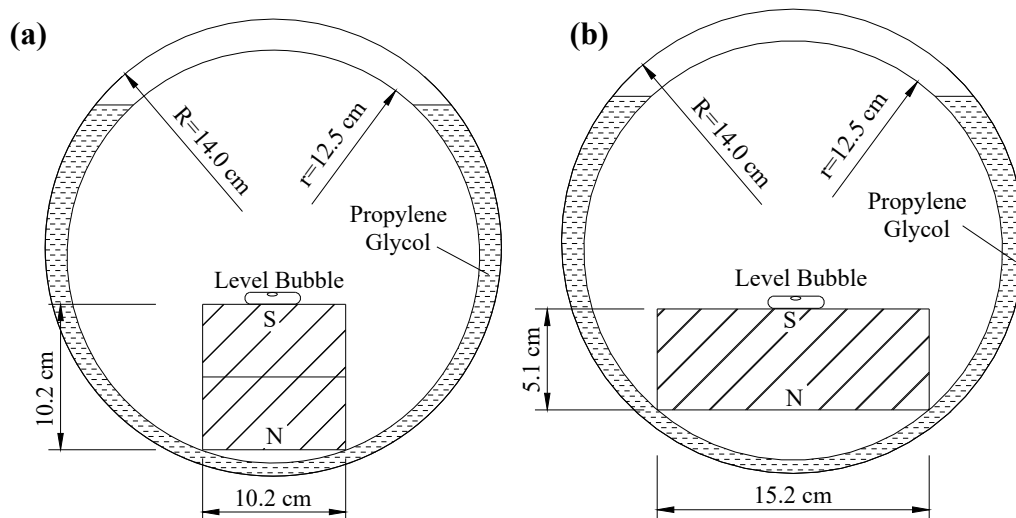


Figure 2.8. Schematic view of an APUS: (a) two stacked N42 magnets and (b) one N45 magnet.

The selection of ball diameters depends upon three factors: commercial availability of casting molds for two halves of a concrete encasement, smart rock size, and floating requirement of the inside ball with negligible friction. To ensure that the inside ball can float in the liquid, the average density of the inside ball with the embedded magnet and other components must be slightly less than that of the liquid. For an APSS or APUS with one N42 magnet, an inside ball of 20 cm in diameter was considered. In this case, the mass of the inside ball is equal to the sum of the magnet (3.06 kg), an organic glass ball and copper beads (total 0.5 kg), and glue and level indicator (negligible). That is, $\rho_0(\pi)(0.2)^3/6 = 3.06+0.5$ or $\rho_0=850 \text{ kg/m}^3$, which is less than water density (1000 kg/m^3). Therefore, an inner diameter of 20 cm is a viable choice for the inside ball. The inner diameter of the outside ball can be approximately selected to be 21

cm, which will leave a sufficient space for lubrication liquid between the inside and outside balls. For an APUS with two N42 magnets or one N45 magnet, the inside ball of 25 cm is considered as the total mass of the inside ball is 6.82 kg (6.12 kg of two N42 magnets and 0.7 kg of the total weight of glass ball, glue and level indicator) and the density of inside ball is 834 kg/m^3 . The outside ball is selected as 28 cm for commercial available.

The liquid between the inside and outside balls must be selected such that the inside ball with the magnet can always float without inducing any notable friction force on the inside ball as it rotates inside the outside ball. For a 20 cm or 25 cm-diameter inside ball, the liquid density must exceed 850 kg/m^3 and 834 kg/m^3 . Although water is a viable candidate in terms of density and nontoxicity requirements, water does not provide sufficient lubrication between the two balls. Lubrication oil is good for minimum friction but insufficient in mass density of the inside ball floating requirement. Consequently, propylene glycol with a mass density of 1040 kg/m^3 is chosen for satisfactory lubrication and nontoxicity requirements.

2.4.5. Fabrication of smart rocks

Two steps are taken to fabricate smart rocks. The first step is to prepare a prototype of APSS and APUS. The second step is to cast a concrete encasement of either APSS or APUS.

2.4.5.1 APSS and APUS prototyping

To fabricate an APSS as shown in Figure 2.9(a), a level indicator with bubble was first attached and glued on one side of a magnet. The opposite side of the magnet was glued to the bottom of half an inside ball with attached copper beads for weight balance. The other half of the inside ball was attached and sealed to complete the inside ball. The complete inside ball was then placed in half of a larger ball, and covered and sealed by the other half to complete the outside ball. Next, a 1-cm-diameter hole was drilled on the outside ball and propylene glycol liquid was injected into the outside ball until the inside ball completely floated and the top of the inside ball was in contact with the outside ball to avoid a large drift of the inside ball. Finally, the injection hole was sealed with a small piece of plastic with adhesives.



Figure 2.9. Prototype: (a) APSS with one N42 magnet, (b) APUS with two stacked N42 magnets, and (c) APUS with one N45 magnet.

For the fabrication of an APUS prototype as shown in Figures 2.9(b) and 2.9(c) with two stacked N42 magnets and one N45 magnet, respectively, a high-precision level indicator was glued to the top face (South pole) of a magnet. The bottom face (North Pole) of the magnet was glued to the bottom of half an inside ball. Adhesives were used as needed to provide unbalanced weights. The remaining fabrication steps for the APUS are the same as those for an APSS.

2.4.5.2 Concrete encasement

For field deployment at bridge sites, each APUS smart rock was cast in a spherical concrete encasement. The smart rock with concrete encasement as schematically shown in Figure 2.10 was cast in a 36.8 cm-diameter mold. The total density of the smart rock is $\rho_s = [(0.28^3 \text{ m}^3) (850 \text{ kg/m}^3) + (0.368^3 \text{ m}^3 - 0.28^3 \text{ m}^3) \times (2000 \text{ kg/m}^3)] / 0.368^3$ or $\rho_s = 1495 \text{ kg/m}^3$, which is appropriate for all three bridge sites.

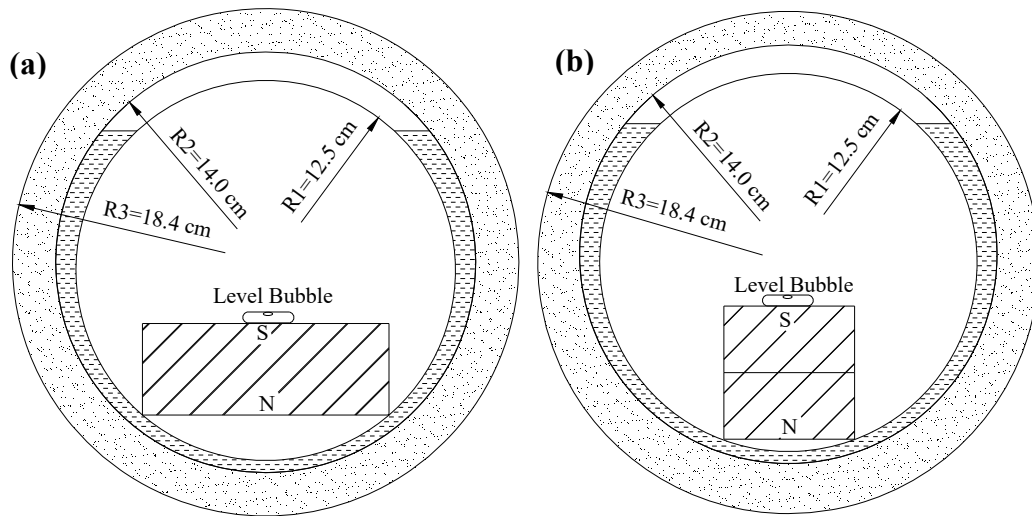


Figure 2.10. Schematic view of concrete encasement: (a) APUS with one N45 magnet, and (b) APUS with two stacked N42 magnets.

The mix proportion of concrete was selected to be: water = 288 kg/m³, cement = 640 kg/m³, sand (diameter = 4.75 mm) = 1023 kg/m³, fiber = 2 kg/m³ and water reducer admixture = 8 kg/m³. The concrete fiber (FORTA ULTRA-NET) was made of virgin homopolymer polypropylene and came in a collated fibrillated twisted bundle, which is often used to reduce plastic and hardened concrete shrinkage, improve impact strength, and increase fatigue resistance and concrete toughness. A rope across the outside ball and concrete encasement was tied around the stiffener of two halves of the outside ball and used to pull the smart rock into its final position during field deployment and mark the rock location after the deployment. The four-step fabrication process of concrete encasement is shown in Figure 2.11: 1) preparing fiber reinforced concrete; 2) pouring a small amount of concrete into the bottom half of a plastic mold, placing and pushing an APUS into the concrete, and covering the APUS with the top half of the mold; 3) filling the mold with concrete while tapping the mold with a hammer to remove potential air bubbles; and 4) removing the mold once concrete is set in one day and putting the smart rock under water to cure for 14 days.



Figure 2.11. Four-step fabrication of concrete encasement: (1) preparing fiber reinforced concrete, (b) placing an APUS into concrete and mold, (c) filling the mold with concrete, and (d) curing the concrete encasement in water for 14 Days.

2.4.6. Two implementation issues

Whether the APUS is indeed insensitive to its surrounding ferromagnetic substances must be verified in field condition. In addition, the effect of deposit resetting on the magnetic field measurement with smart rocks needs to be investigated.

2.4.6.1 *Effect of deposit resetting on magnetic field*

In practice, a scour hole is created due to deposit erosion but may be refilled over time. The smart rocks rolling down to the bottom of the scour hole may be covered by the refilling deposits. Whether deposit resetting affects the measurement of magnetic fields was investigated at the Gasconade River Bridge site.

As shown in Figure 2.12, a 1-m deep hole was excavated approximately 10 m away from a bridge pier. A magnet was first wrapped with a plastic bag that was tied with a rope, and then placed into the bottom of the hole. The rope was used to pull the magnet out of the refilled hole after the test was over. The two sensors (S_1 and S_2) of a magnetometer were fixed on the top of two wood poles that were inserted into the ground on two sides of the hole. The magnetometer was set in between the two sensors. Another wood pole was placed next to the magnet with marks in 0.5 m interval up to 1.5 m to measure the height of the refilling deposits. As indicated in Figure 2.13, the measurements were first taken with no deposits, then with the excavated soils refilled to the 0.5 m and 1.0 m marks, and finally with additional deposits piled up to 1.5 m .

Table 2.2 lists the measured intensity of magnet's and ambient magnetic fields. It can be seen from Table 2.2 that the maximum variation of the intensities measured for deposits refilled to various heights is 0 nT and 10 nT at S_1 and S_2 , respectively. These

variations are significantly less than 100 nT , the level of intensity change that begins to notably influence the localization accuracy of the magnet. These variations may be caused by the change in Earth's magnetic field at different times of measurement or by other disturbances on the sensor head in the process of deposits refilling.

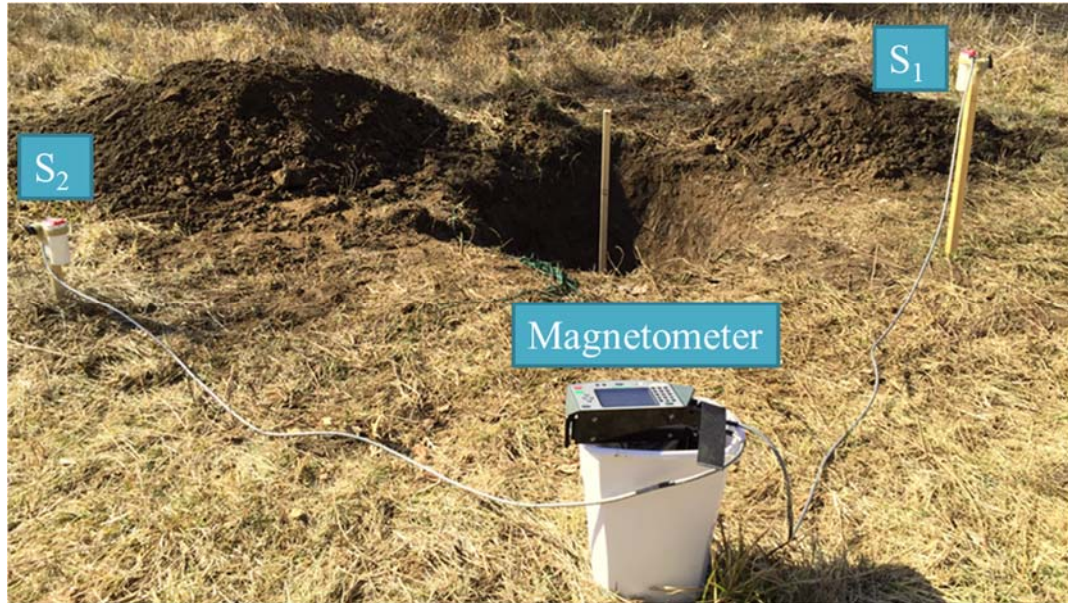


Figure 2.12. Overall arrangement of resetting tests.

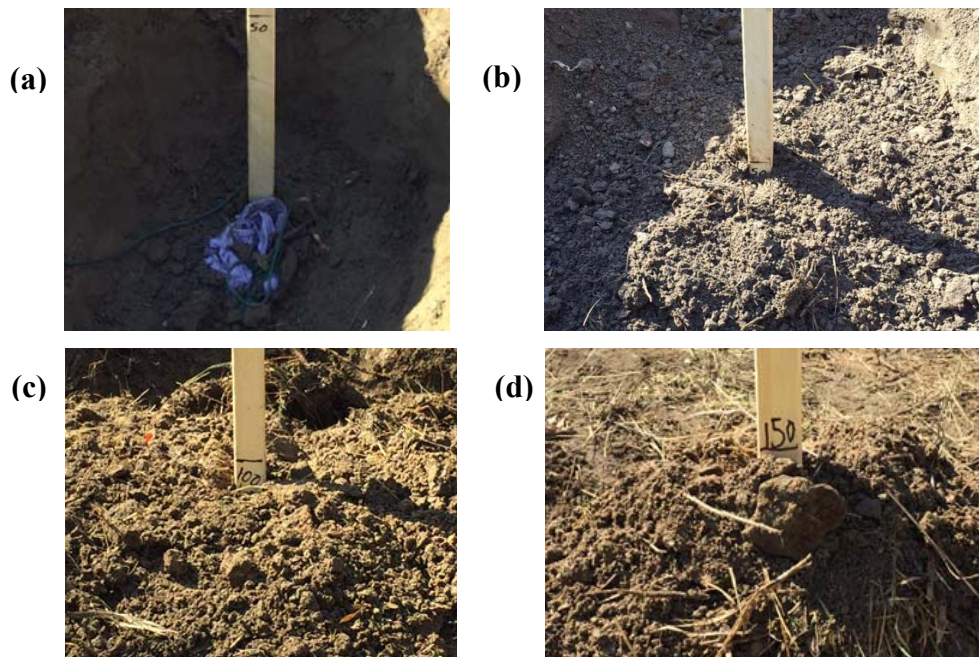


Figure 2.13. Deposits refilled to various heights: (a) 0.0 m, (b) 0.5 m, (c) 1.0 m, and (d) 1.5 m.

Table 2.2. Intensity at various deposit heights

Deposit Height (m)	Intensity (10^4 nT)	
	F1	F2
0.0	5.087	5.073
0.5	5.087	5.073
1.0	5.087	5.072
1.5	5.087	5.072

2.4.6.2 Effect of steel reinforcement on smart rock operation

An attempt was made to keep the two poles of a magnet aligned vertically during measurements so that the magnet orientation is known *a priori* and the localization of the magnet becomes simplified. One concern to this effort in practical applications is the potential influence of the ferromagnetic substances in bridge piers or abutments. Therefore, a simple field test was carried out to rule out this possibility.

Figures 2.14 and 2.15 show the APUS prototype placed next to a bridge pier and on the bridge footing, respectively. It can be seen from Figures 2.14 and 2.15 that the bubble slightly deviated from the center of a high-precision level, indicating an inclination angle of less than 0.5° and thus little effect on the localization of the APUS. It was verified during the field tests that the bubble remained in the center of a high-precision level attached on the APUS when placed at least 10 m away from the bridge pier and footing.



Figure 2.14. The APUS prototype placed next to a bridge pier.



Figure 2.15. The APUS prototype placed on a bridge footing.

2.5. Summary

In this section, the working principle of the smart rock technology was introduced for the monitoring of maximum scour depth and for the detection of rip-rap effectiveness. Three types of smart rocks (AOS, APSS, and APUS) were proposed, designed, and prototyped. The design guidelines of smart rocks were developed. The equation for critical flow velocity in HEC No.18 was mainly used to establish the relationship between the size and density of smart rocks based on their incipient motion. The equation was applied into three bridge sites in the states of California and Missouri. The size of smart rocks was first determined to meet the requirements for fabrication and measurement. The density of smart rocks was calculated from their incipient motion.

The effect of resetting deposits on the magnetic field near the Gasconade River Bridge site was tested. To this end, a hole was excavated near a bridge pier, a magnet was placed at the bottom of the hole and covered by deposits to various heights, and the intensity of the magnetic field of the magnet and other ferromagnetic substances were measured at two fixed locations. As expected, the resetting deposits had little effect on the magnetic field measurement. In addition, whether steel reinforcement in a bridge pier would affect the magnetic measurement was investigated. Based on the field tests, no obvious change was observed in the orientation of a magnet when placed near a bridge pier with steel reinforcement.

The final design of smart rocks was a sphere of 0.368 m in diameter and 1495 kg/m³ in density, which was determined by multiplying a design factor by the density calculated from the analysis of incipient motion. The design factor was introduced to take into account the uncertainties about the hydraulic parameters and the empirical equation for critical velocity. A factor of 1.2 was considered for bridge sites with detailed hydraulic analysis and 1.3 for bridge sites with no hydraulic analysis. A gravity-oriented magnet was embedded inside each smart rock so that the pole direction of the magnet would be known *a priori* and remained vertical during measurements. When the sensors of a magnetometer are placed vertically, the gravity-oriented magnet also results in the most sensitive range of measurement. The designed smart rocks were then prototyped as a concrete encasement in applications.

3. LOCALIZATION OF A SINGLE SMART ROCK IN UNIFORM AMBIENT MAGNETIC FIELD

Tracing a magnet from its magnetic field has been widely used in medical science to detect any change of human bodies [85]. A tiny magnet simplified as a dipole with non-invasive and non-wire power is employed to generate the magnetic strength around a human body. The dipole can be positioned by an inverse calculation of a mathematic function, thus leading to the change of the human body through continuous monitoring. Similarly, a permanent magnet as the core of a smart rock would be simplified as a dipole to establish a mathematical relationship between the magnetic field and the position of the magnet. A single smart rock placed in a uniform ambient magnetic field (due to the Earth only) is localized in order to determine the movement of the rock in scour monitoring application. Two types of smart rock prototypes, AOS and APSS developed in Section 2, are considered as models of the smart rocks. The localization mechanism for AOS and APSS is introduced and analyzed by measuring the ambient magnetic field of the Earth and a combined magnetic field of the Earth and the smart rock. The magnetic field parameters of the magnet and the Earth are first evaluated by an approach proposed in this section. The proposed approach and the localization algorithm are then validated at an open site for two types of smart rocks with AOS and APSS, respectively. Finally, an application example is conducted using an APSS to simulate the movement of the smart rock in practical application setting.

3.1. The Magnetic Field of a Permanent Magnet

The magnetic field of a permanent magnet can be numerically solved using an equivalent magnetic charge method [86], an Amperian current method [87], and a finite element method. The equivalent charge and current methods are used to derive the analytical solution of permanent magnets in simple shape while the finite element method is used to address the integral or differential equation expressed for permanent magnets with intricate shapes. Also known as the scalar magnetic potential method in engineering applications, the equivalent charge method employs the key concept of an imaginary magnetic charger and its surface density. The magnetic field of a permanent magnet is then calculated by superimposing the magnetic fields generated by all magnetic chargers. The Amperian current method, also referred to as the magnetic vector potential method, deals with the circular electric current with a certain density that exists in a permanent magnet. Specifically, the inner circular electric current is canceled out for a uniform magnetization of the magnet. However, a certain surface current density still exists in the boundary of the magnet. For example, the uniformly magnetized cylinder magnet has the cylindrical surface current that is equal to the circular current loops uniformly distributed along the cylinder length. Thus, the magnetic field generated in space from a magnet can be computed by integrating the magnetic field produced from each circular electric current. These two equivalent models involve differential equations derived from the Maxwell's equations with scalar magnetic potential and magnetic vector potential, respectively. Numerical approaches are then adopted to solve the differential equations for the magnetic field in space.

In this section, a cylindrical or disc permanent magnet is considered. The Amperian current model is employed to represent and calculate the magnetic field of the

cylindrical magnet since it is easier than the magnetic charge model in terms of numerical calculation. An idealized solenoid with strictly azimuthal current in a thin sheet wrapped around a right circular cylinder [88] can serve as a better model of a permanent cylindrical magnet, provided that its magnetization is sufficiently uniform and homogeneous. The ideal solenoid was treated as a stack of loops to calculate its magnetic field by a straightforward integration of circular current loop that is analytically expressed in elliptic integrals [88]. The exact solution of the solenoid was developed in a simple and efficient way with a single function and a generalized complete elliptic integral. In terms of computation, the simplified point dipole model of an ideal solenoid with finite length is quite simple and fast [88]. The simplified model is valid when the distance between a point of interest and the solenoid significantly exceeds the size of the solenoid or the permanent magnet.

The localization of a permanent magnet is an inverse problem from the measured magnetic field to the source magnet [89]. The magnetic field signals generated by the magnetic dipole can be measured by magnetometers at various spatial points around the dipole. The positions of these spatial points can also be surveyed. The localization parameters such as positions and orientation of the dipole can be computed by solving a high-order nonlinear function with an appropriate optimization algorithm [90-92]. The non-linear optimization algorithms, such as Powell's [93], Newton's method [91], Levenberg-Marquardt (LM) [89, 92-96], genetic algorithm [97], and particle swarm optimizer [97, 98], the linear optimization algorithm [99], the combined nonlinear (LM) and linear algorithm [100], and the Random Complex Algorithm (RCA) [101] were investigated. In this study, a magnetic dipole is used as the simplification of a cylindrical magnet since the measurement points are considered far away from the magnet.

3.1.1. Mathematic expression for a cylindrical magnet

Consider a cylindrical magnet of $2a$ in diameter and $2b$ in length in a cylindrical coordinate system as shown in Figure 3.1. Here, the origin of the coordinate system is located at the centroid of the magnet, y axis represents the magnetized direction from South Pole to North Pole inside the magnet, and ρ axis represents the radial direction perpendicular to the y axis.

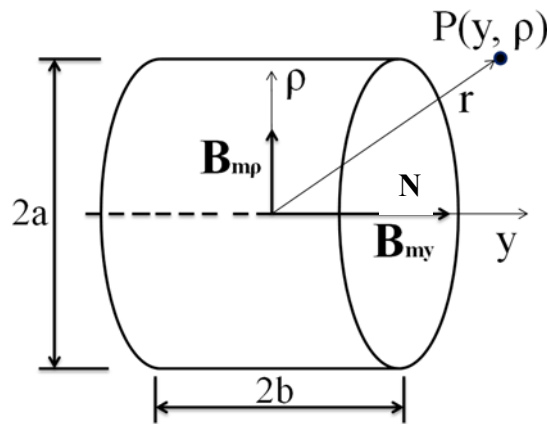


Figure 3.1. A cylinder magnet in a cylindrical coordinate system.

The magnetic field induced by the magnet is axis-symmetric about the centerline of the magnet. It can be represented by a vector $\mathbf{B}_m(y, \rho)$ at any point P. The magnetic field vector can be decomposed into a longitudinal component \mathbf{B}_{my} and a radial component $\mathbf{B}_{m\rho}$. When the radial coordinate ρ (absolute value) at Point P is significantly larger than the radius a of the magnet or the longitudinal coordinate y (absolute value) is significantly larger than half of the magnet length b , the magnitudes B_{my} and $B_{m\rho}$ of two components of the magnetic field vector can be approximated by [88]:

$$\begin{cases} B_{my}(y, \rho) = k \frac{(2y^2 - \rho^2)}{r^5} \\ B_{m\rho}(y, \rho) = k \frac{3\rho y}{r^5} \end{cases} \quad (3.1a)$$

$$B_m(y, \rho) = \sqrt{B_{my}^2(y, \rho) + B_{m\rho}^2(y, \rho)} \quad (3.1b)$$

where $k = \mu_0 \mu / 4\pi$ is a coefficient related to the strength of the magnet, μ_0 is the permeability of vacuum in $T \cdot m/A$, and μ is the magnetic moment of the dipole produced by the magnet in T. These parameters are either obtained from the manufacturers (e.g. technical specification of permanent magnets) or evaluated by the calibration test developed in this study.

3.1.2. Magnetic field in Cartesian coordinate systems

As shown in Figure. 3.2, the local Cartesian coordinate system (p -xyz) is originated and fixed at the center of a cylindrical magnet. The y axis is from South to North Pole of the magnet. Since it moves together with the magnet, the local coordinate system cannot be used to define the position of the magnet. Therefore, a global Cartesian coordinate system O-XYZ is introduced and fixed in space. The Y -axis points to the North Pole of the Earth's magnetic field that has a declination angle with the geographical South Pole. Perpendicular to the Y -axis, X -axis has a declination angle with the geographic west and Z -axis is vertically upward. For convenience, the Y -axis is simply referred to the geographical south, and the X -axis to the geographical west. The center of the magnet is designated as Point P at global coordinates (X_M, Y_M, Z_M) and as Point p at local coordinates $(0, 0, 0)$. An arbitrary point in space is designated as Point Q_i (X_i, Y_i, Z_i) and Point q (x_i, y_i, z_i) in the global and local coordinate systems, respectively.

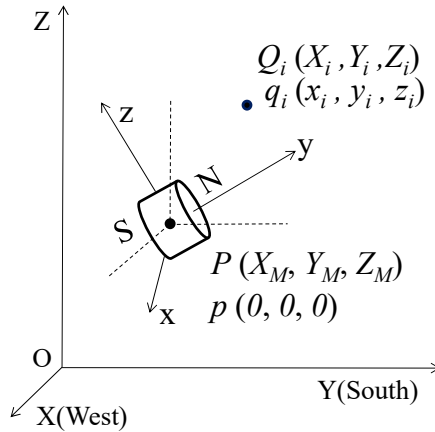


Figure 3.2. Global versus local Cartesian coordinate systems.

The magnetic field expressed in Eq. (3.1) in the cylindrical coordinate system must be translated to the global Cartesian coordinate system in order to be combined with the magnetic fields generated by other sources. In the local coordinate system (p -xyz) as shown in Figure 3.2, the magnetic field vector of a magnet at an arbitrary point $q(x_i, y_i, z_i)$ can be written as $\mathbf{B}_{mi}=(B_{mxi}, B_{myi}, B_{mzi})$. The two components of the magnetic field generated by the magnet are given in Eq. (3.1). The radial component can be further decomposed into x- and z-components. The x-, y- and z-components of the magnetic flux at point q in the p-xyz coordinate system can then be expressed into:

$$\begin{cases} B_{mxi} = k \frac{3x_i y_i}{r_i^5} \\ B_{myi} = k \frac{2y_i^2 - x_i^2 - z_i^2}{r_i^5} \\ B_{mzi} = k \frac{3z_i y_i}{r_i^5} \end{cases} \quad (3.2a)$$

$$r_i = \sqrt{x_i^2 + y_i^2 + z_i^2} \quad (3.2b)$$

$$B_{mi} = \sqrt{B_{mxi}^2 + B_{myi}^2 + B_{mzi}^2} \quad (3.2c)$$

In order to transfer the magnetic field components from the local coordinate to the global coordinate, the global coordinate system must be first rotated at its origin to become parallel to the local coordinate system and then moved translationally to the local coordinate system. Consider three Euler angles, $\alpha \in [0, 2\pi]$, $\beta \in [0, 2\pi]$, and $\gamma \in [0, 2\pi]$ about X-, Y-, and Z-axis following the right-hand rule. A rotation matrix from the XYZ coordinate system to the xyz coordinate system can be expressed into:

$$\mathbf{R} = \begin{bmatrix} \cos \beta \cos \gamma & \cos \beta \sin \gamma & -\sin \beta \\ \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma & \sin \alpha \sin \beta \sin \gamma + \cos \alpha \cos \gamma & \sin \alpha \cos \beta \\ \cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma & \cos \alpha \sin \beta \sin \gamma - \sin \alpha \cos \gamma & \cos \alpha \cos \beta \end{bmatrix} \quad (3.3)$$

After translational movement from the global to local coordinate system, the local coordinate at Point Q_i can be derived as:

$$\begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} = \mathbf{R} \cdot \begin{pmatrix} X_i - X_M \\ Y_i - Y_M \\ Z_i - Z_M \end{pmatrix} \quad (3.4)$$

According to the vector rotation transformation \mathbf{R} in Eq. (3.3), the magnetic field at any point $Q_i (X_i, Y_i, Z_i)$ around the magnetic dipole can be written as $\mathbf{B}_{Mi} = (B_{MXi}, B_{MYi}, B_{MZi})$ in the global coordinate system and can be related to that in the local coordinate system by:

$$\begin{pmatrix} B_{MXi} \\ B_{MYi} \\ B_{MZi} \end{pmatrix} = \mathbf{R}^{-1} \begin{pmatrix} B_{mxi} \\ B_{myi} \\ B_{mzi} \end{pmatrix} = \mathbf{R}^{-1} \begin{pmatrix} k \frac{3x_i y_i}{r_i^5} \\ k \frac{2y_i^2 - x_i^2 - z_i^2}{r_i^5} \\ k \frac{3z_i y_i}{r_i^5} \end{pmatrix} \quad (3.5a)$$

$$B_{Mi} = \sqrt{B_{MXi}^2 + B_{MYi}^2 + B_{MZi}^2} \quad (3.5b)$$

By substituting Eqs. (3.3) and (3.4) into Eq. 3.5, the three components (B_{MXi} , B_{MYi} , B_{MZi}) of the magnetic field at an arbitrary point can be completely represented by its relative position to the magnet in the global coordinate system. In general, six parameters are required to define the location of a magnet: position (X_M , Y_M , Z_M) and orientation that is represented by a unit vector of y-axis in the global coordinate system, $\mathbf{n}_y = (l, m, n)^T$. Since the flux intensity is invariant to a rotation of the magnet about y-axis, the orientation of the magnet can be uniquely determined by the unit vector of y-axis. Considering the constraint on the directional cosines of any unit vector, $l^2 + m^2 + n^2 = 1$, only five unknowns must be determined to define the location of the magnet in theory. In practice, however, the magnetic field generated from the magnet is to be combined with those from other sources that are not axis-symmetric, the axis-symmetric property of the magnet is not explicitly considered in the following derivation.

As indicated in Eq. (3.5a), when left multiplied by \mathbf{R}^{-1} , a unit vector of y-axis in the local coordinate system, $(0, 1, 0)^T$, becomes the y-axis in the global coordinate system, represented by $(l, m, n)^T$. Therefore, the second column of \mathbf{R}^{-1} (corresponding to the second row of the rotation matrix \mathbf{R} since $\mathbf{R}^{-1} = \mathbf{R}^T$) is equal to the orientation vector $(l, m, n)^T$. That is, $l = \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma$, $m = \sin \alpha \sin \beta \sin \gamma + \cos \alpha \cos \gamma$, and $n = \sin \alpha \cos \beta$. Therefore, solving for the directional cosines l , m , and n is equivalent to solving for the Euler angles α , β , and γ .

3.2. Localization Algorithms

The scalar magnetometer G858 used in the early part of this study measures a total intensity of the magnetic fields of the Earth, the magnet, and nearby ferromagnetic substances. At any point, the magnitude and direction of a geomagnetic vector can be determined according to its longitude and latitude. The magnitude B_E can be measured from the magnetometer G858. The direction is described by a dip angle θ of the Earth's magnetic field lines with a horizontal plane and the hemisphere in which the investigated site is located. The dip angle can be either evaluated by inputting the longitude and latitude of a certain point to the software provided together with the magnetometer, or computed using the approach developed in this study. When the nearby substances are neglected at an open site and the Earth's magnetic field is assumed to be unchanged over time and in a small space of interest, the total magnetic field intensity B_{Ti} depends upon the Earth's magnetic field intensity B_E , the dip angle θ , and the coefficient k of the magnet in addition to the coordinates (X_M , Y_M , Z_M , α , β , γ). That is, $B_{Ti} = B_{Ti}(B_E, \theta, k, X_M, Y_M, Z_M, \alpha, \beta, \gamma)$.

3.2.1. Localization of AOS

As shown in Figure 3.3, the geomagnetic field vector, \mathbf{B}_E , is parallel to the YOZ plane in the XYZ Cartesian coordinate system. Its direction depends on whether the investigated site is located in north or south hemisphere of the Earth. Since the project (bridge) sites in this study are located in North America, the geomagnetic field vector slightly points to the geographical North and faces to the ground with a corresponding dip angle of the field site. Therefore, the Earth's magnetic field vector is $\mathbf{B}_E = (0, -B_E \cos \theta, -B_E \sin \theta)^T$ in the global coordinate system. The total magnetic field vector, B_{Ti} , at an arbitrary point Q_i can then be expressed into:

$$B_{Ti} = \sqrt{(B_{MXi})^2 + [B_{MYi} + (-B_E \cos \theta)]^2 + [B_{MZi} + (-B_E \sin \theta)]^2} \quad (3.6)$$

Note that, the magnitude of \mathbf{B}_E is measured by means of the magnetometer prior to the deployment of the magnet at a project site. Given the coefficients k and θ and the Earth's magnetic intensity B_E for the project site, the total magnetic intensity of the Earth and a magnet, B_{Ti} , at any point $Q_i (X_i, Y_i, Z_i)$ is a function of (X_M, Y_M, Z_M) and (α, β, γ) only. To determine the location and orientation (6 parameters) of a magnet, measurements must be taken at a minimum of six stations in practical applications.

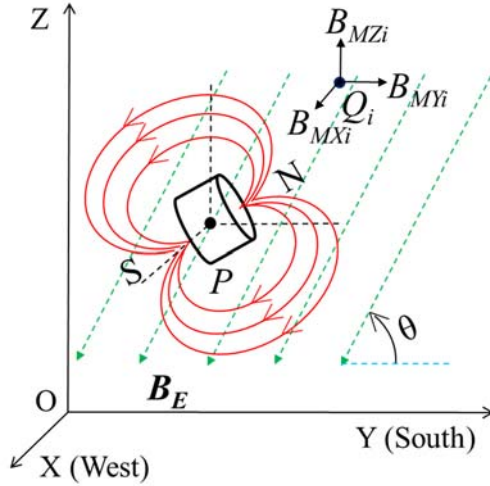


Figure 3.3. The magnetic field of an AOS.

Eq. (3.6) is a high-order nonlinear function of the 6 location and orientation parameters of a magnet. To solve for the parameters $(X_M, Y_M, Z_M, \alpha, \beta, \gamma)$, a nonlinear optimization algorithm is developed based on an objective error function that represents the difference between the predicted and measured magnetic field intensities. Let a N number of measurements, $B_{Ti}^{(M)}$ ($i=1, 2, \dots, n$), be taken at n stations $Q_i (X_i, Y_i, Z_i)$ ($i=1, 2, \dots, n$). At each station, the theoretically predicted intensity $B_{Ti}^{(P)} = B_{Ti}$ can be calculated from Eqs. (3.4) - (3.6). Therefore, the square-root-of-the-sum-of-the-squared (SRSS) error between the calculated intensity $B_{Ti}^{(P)}$ and the measured intensity $B_{Ti}^{(M)}$, $J(X_M, Y_M, Z_M, \alpha, \beta, \gamma)$, can be evaluated by:

$$J(X_M, Y_M, Z_M, \alpha, \beta, \gamma) = \sqrt{\sum_{i=1}^n [B_i^{(P)} - B_i^{(M)}]^2} \quad (3.7)$$

The objective error function J is minimized to solve for the unknown location and orientation of the magnet embedded in a smart rock. Specifically, six equations will be formulated by taking the derivative of J with respect to any one of the six unknown parameters. Multiple solutions may be obtained from the high-order nonlinear equations due to unknown orientations. Engineering judgment must be exercised to select an appropriate solution in practical application based on the previous location and orientation of the magnet. Therefore, AOS is not an ideal candidate for the development of smart rocks in practical applications.

3.2.2. Localization of APSS

In an APSS, the y-axis from South to North pole points to the opposite direction of the South. Therefore, $\alpha = \pi$, $\beta = 0$, and $\gamma = 0$. Figure 3.4 shows an APSS located at Point P in the global coordinate system XYZ . The total magnetic field intensity B_{Ti} as shown in Eq. (3.6) at an arbitrary point Q_i is significantly simplified into a function of X_M , Y_M , and Z_M given the Earth's magnetic field intensity B_E , the dip angle θ , and the coefficient k of the magnet. By substituting the rotation matrix in Eq. (3.3) and the relation in Eq. (3.4) into Eq. (3.5), the three components (B_{MXi} , B_{MYi} , B_{MZi}) in Eq. (3.6) can be expressed into:

$$\begin{pmatrix} B_{MXi} \\ B_{MYi} \\ B_{MZi} \end{pmatrix} = \begin{pmatrix} -k \frac{3(X_i - X_M)(Y_i - Y_M)}{\left(\sqrt{(X_i - X_M)^2 + (Y_i - Y_M)^2 + (Z_i - Z_M)^2}\right)^5} \\ -k \frac{2(Y_i - Y_M)^2 - (X_i - X_M)^2 - (Z_i - Z_M)^2}{\left(\sqrt{(X_i - X_M)^2 + (Y_i - Y_M)^2 + (Z_i - Z_M)^2}\right)^5} \\ -k \frac{3(Z_i - Z_M)(Y_i - Y_M)}{\left(\sqrt{(X_i - X_M)^2 + (Y_i - Y_M)^2 + (Z_i - Z_M)^2}\right)^5} \end{pmatrix} \quad (3.8)$$

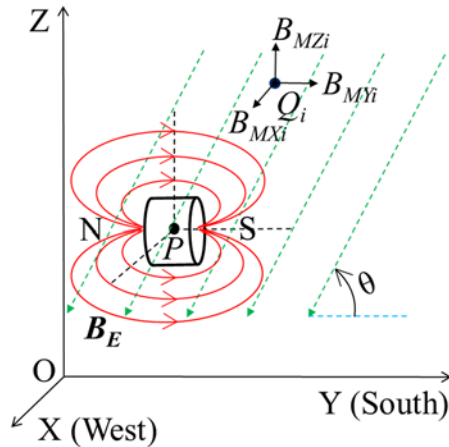


Figure 3.4. The magnetic field of an APSS.

The total magnetic field intensity B_{Ti} for an APSS is then obtained by substituting Eq. (3.8) into Eq. (3.6). The SRSS error in Eq. (3.7) is also reduced into $J(X_M, Y_M, Z_M)$ in which $B_{Ti}^{(P)} = B_{Ti}$ can be evaluated by Eq. (3.6). As such, only three unknown parameters must be solved to define the location of the magnet.

For both AOS and APSS, the sequential quadratic programming (SQP) algorithm [102] was used to iteratively find the optimization solution for the position of the magnet from the high-order nonlinear equation sets. The algorithm was implemented in MATLAB through the use of Fmincon code for non-linearly constrained optimization problems. It has been proven to be among the most effective general algorithm currently available.

3.3. Determination of the Magnet Location in Open Field

A field test was carried out at an open site located in Ber Juan Park, Rolla, MO to validate the feasibility of the magnet localization algorithm. At the test site, the Earth magnetic field lines are parallel to each other, which is considered as a uniform magnetic field in this study.

3.3.1. Experimental layout

The test layout is shown in Figure 3.5(a). The APSS or AOS was located at the origin of the Cartesian Coordinate O-XYZ as shown in Figure 3.5(b). To locate the APSS or AOS, a sensor head of G858 Magnetometer [103] was separately stationed at $Q_1, Q_2, Q_3 \dots, Q_{25}, Q_{26}$ and Q_{27} as shown schematically in Figure 3.5(c). The selection of the 27 measurement points for the total magnetic intensity and X-, Y-, Z- coordinates took into account the influence of the inclination angle and distance on the intensity. Specifically, the measurement points were selected with a radial distance of 1.5 m and 5 m from the magnet. In addition, the wooden poles with various heights from 0.2 m to 1.0 m with an increment of 0.1 m were used to taking into account the impact of the inclination angle. A total station was set up at a far distance to survey the coordinates of APSS, AOS and 27 sensor positions with a prism placed on top of each wooden pole. The coordinates surveyed from the total station were then transferred to the coordinate system O-XYZ as shown in Figure. 3.5(c).



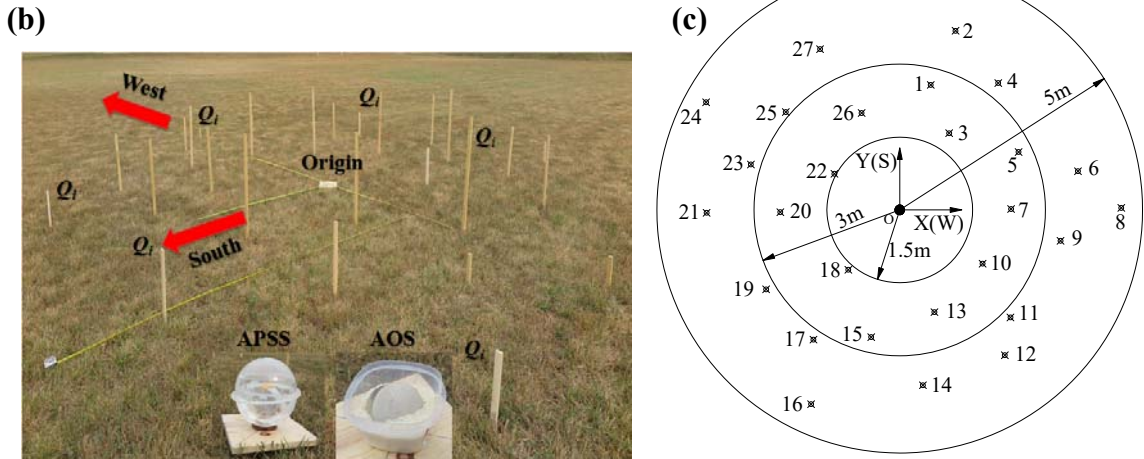


Figure 3.5. Field tests in Ber Juan Park, Rolla, MO: (a) test setup and layout, (b) layout of sensor and magnet, and (c) schematic view of measurement points.

3.3.2. The Earth magnetic field intensity

The Earth's magnetic field intensity, B_E , generally changes from one place to another. At the open site, however, the Earth's magnetic field lines are considered to be parallel to each other since there are no electric lines, train tracks, and other ferromagnetic substances. During the tests, mobile phones and magnets were taken far away from the magnetometer sensor heads. Based on 15 measurements, the average Earth's field intensity at the field test site was found to be 52342 nT with a standard deviation of 0.23 nT . The latitude and longitude coordinates of the test site at Rolla, MO, are $37^\circ 57' 12'' \text{N}$ and $91^\circ 45' 27'' \text{W}$, respectively.

3.3.3. Coefficient k and θ

Both the coefficient k and the inclination angle θ are involved in the calculation of the total magnetic field intensity B_{Ti} in Eq. (3.6) at each measurement point. The coefficient of the magnet may change slowly over time potentially due to demagnetization. The inclination angle may change from one place to another. Both parameters need to be evaluated at a particular study site.

A trial-and-error method was used to determine the k and θ in three steps from n sets of calibration test data collected at the test site, each including the total magnetic field intensity as a function of the XYZ coordinates. In Step 1, k is assumed to vary from 36000 to 48000 with a step size of 50 based on manufacturers' data for various magnets. For each k value, θ_i ($i=1, 2, \dots, n$) was calculated with a set of the test data (intensity and coordinate) from the equality of the calculated and the measured intensities. In Step 2, the n numbers of θ_i were used to determine the unbiased mean and standard deviation:

$$\bar{\theta} = \frac{1}{n} \sum_{i=1}^n \theta_i \quad \sigma = \sqrt{\frac{\sum_{i=1}^n (\theta_i - \bar{\theta})^2}{n-1}} \quad (3.9)$$

In Step 3, the k value corresponding to the minimum standard deviation and its

corresponding average $\bar{\theta}$ value is determined. They contributed to the least-square error in comparison with the measured data as specified in Eq. (3.7).

A calibration test was conducted to determine the k and θ at the same test site as for the B_E evaluation as shown in Figure 3.6(a, b). The APSS and AOS were adopted to calibrate the magnet coefficient and the dip angle of the Earth. They were placed separately at the origin to generate the magnetic field around them. A total of 21 points, labeled as N1, N2, ..., and N21 on the top of wood poles of various heights, were selected in a distance range of 1.3 m to 3.0 m along the Y-axis. The total station as shown in Figure 3.5(a) was employed to survey the 21 calibration points. The AOS was achieved by placing a magnet in half a plastic ball that floated on water in a bucket as shown in Figure 3.6(a). A high-precision level with an accuracy of 0.025° was placed on top of the AOS to keep the axis of the magnet in horizontal plane by weight balance.

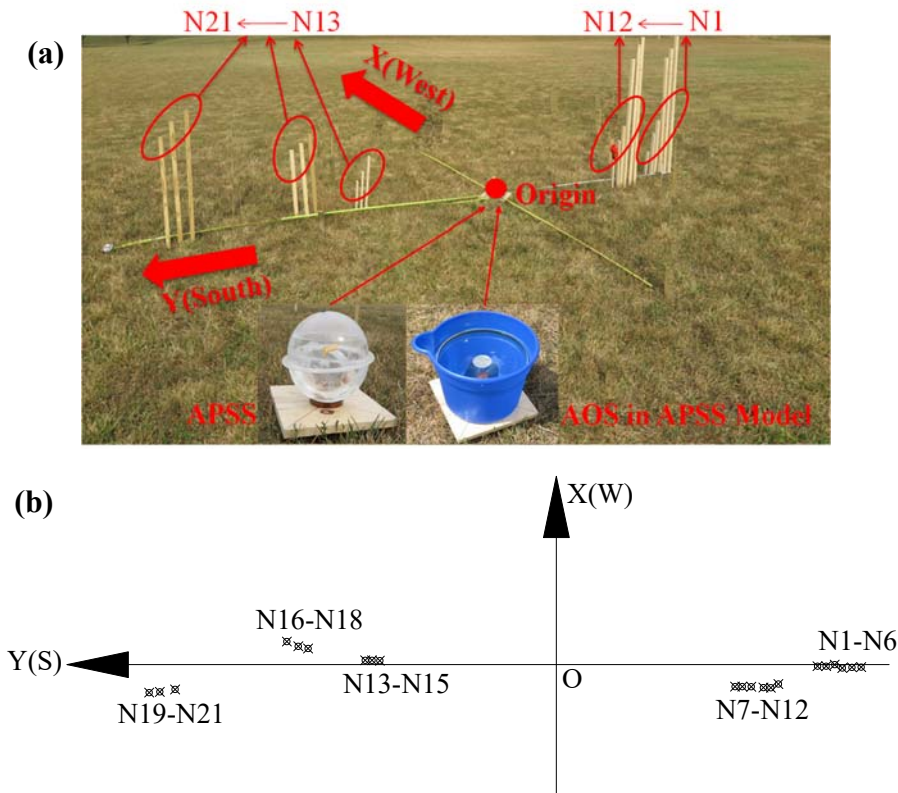


Figure 3.6. Calibration test: (a) experimental setup and (b) relative locations of the magnet and measurement points in horizontal plane.

Based on a preliminary sensitivity analysis in MATLAB, 8 out of the 21 data sets from the APSS and AOS, as listed in Table 3.1, were chosen to evaluate the k and θ . Note that M_{APSS} and M_{AOS} in Table 3.1 represent the magnets in the APSS and AOS. The first four points were located on the plus Y-axis side and the remaining four on the minus Y-axis side. In the case of the APSS, eight inclination angles were related to each coefficient k as shown in Figure 3.7(a) using the trial-and-error method. Their corresponding unbiased standard deviation σ is presented in Figure 3.7(b). It can be seen from Figure 3.7 that the standard deviation is a minimum when the eight θ values are

67.3°, 67.9°, 67.8°, 68.0°, 67.5°, 67.3°, 68.1°, and 67.6° with $k = 42542 \text{ nT}\cdot\text{m}^3$. The mean and standard deviation of θ values are 67.7° and 0.34°, respectively. The coefficient of variation of θ is $0.340^\circ/67.7^\circ = 0.42\%$.

Table 3.1. Coordinates and total magnetic field intensities at selected points

	APSS				AOS				
	X_i (m)	Y_i (m)	Z_i (m)	B_{APSS} (10^4 nT)	X_i (m)	Y_i (m)	Z_i (m)	B_{AOS} (10^4 nT)	
M_{APSS}	0.00	0.00	0.00	NA	M_{AOS}	0.00	0.00	0.00	N/A
N2	-0.03	-2.30	1.32	5.086	N1	-0.03	-2.38	1.42	5.102
N3	-0.04	-2.23	1.23	5.081	N3	-0.04	-2.23	1.19	5.098
N7	-0.16	-1.73	1.43	4.858	N7	-0.16	-1.73	1.39	4.873
N9	-0.19	-1.61	1.22	4.787	N9	-0.19	-1.61	1.19	4.815
N16	0.12	1.94	0.61	6.006	N16	0.12	1.94	0.58	6.006
N18	0.17	2.10	0.49	5.818	N18	0.17	2.10	0.45	5.807
N20	-0.22	3.09	0.81	5.413	N19	-0.20	2.97	0.84	5.439
N21	-0.23	3.17	0.70	5.394	N21	-0.23	3.17	0.67	5.394

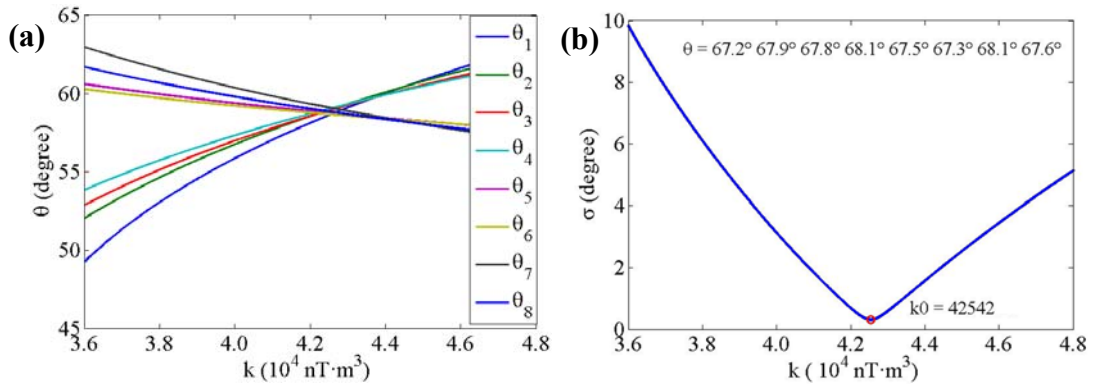


Figure 3.7. Evaluation of θ and k values from the APSS: (a) eight θ samples for each k , and (b) standard deviation of eight θ samples as a function of k value.

Similarly, in the case of the AOS, the eight curves shown in Figure 3.8(a) provide a k value of $41890 \text{ nT}\cdot\text{m}^3$ corresponding to the minimum standard deviation as presented in Figure 3.8(b). In this case, the eight θ values are 66.9° , 66.4° , 66.2° , 66.0° , 66.7° , 66.8° , 66.3° , and 66.1° with their mean and standard deviation of 66.4° and 0.32° , respectively. The coefficient of variation of θ is $0.322^\circ/66.4^\circ = 0.48\%$. The differences in the evaluation of k and θ were likely caused by the approximate trial-and-error method, the imperfect alignment between the Y-axis and y-axis, the small angle deviation from due south of the APSS, and the misalignment of the prism and the magnetometer sensor for coordinate measurements.

To sum up, the k values for the APSS and AOS obtained from the calibration test are $42542 \text{ nT}\cdot\text{m}^3$ and $41890 \text{ nT}\cdot\text{m}^3$, respectively. The θ values for the APSS and AOS are 67.7° and 66.4° , respectively. Due to low accuracy with the level bubble used on top of the APSS, an initial angle exists between the axis of the magnet and the horizontal plane. As a result, the 67.7° is the angle between the dip angle of the Earth's magnetic field and the axis of the magnet instead of the horizontal plane. On the other hand, a high-precision

level bubble was installed on top of the AOS to ensure that the axis of the magnet aligns with the horizontal plane. Therefore, $\theta = 66.4^\circ$ is considered as the final inclination angle of the uniform Earth's magnetic field in the open field.

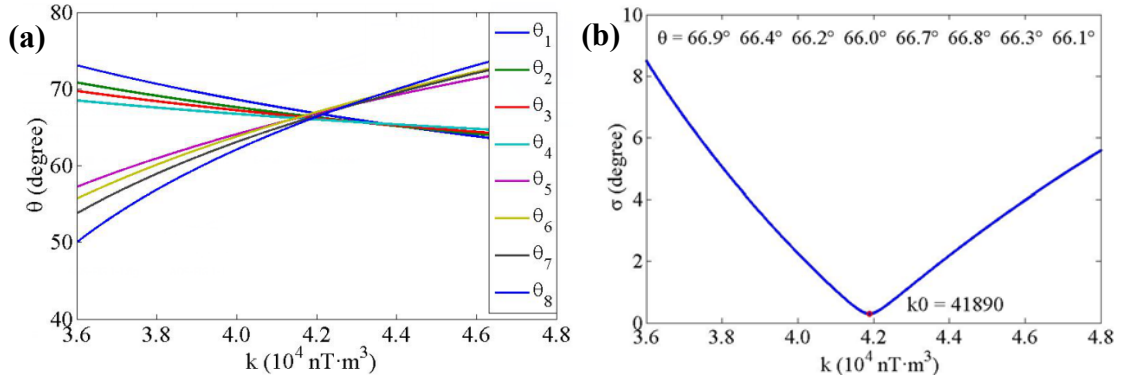


Figure 3.8. Evaluation of θ and k values from the AOS: (a) eight θ samples for each k and (b) standard deviation of eight θ samples as a function of k value.

3.4. Results and Discussion of Magnetic Localization

The measured data collected from the test were used to determine the location of AOS in terms of three orientations and the location of APSS placed at the origin of the global coordinate system to validate the localization algorithms. Also, the selection of measurement points was analyzed to determine the effective measurement points during the test.

3.4.1. Location of AOS

Three orientations OR1, OR2, and OR3 of an AOS configuration as shown in Figure 3.9 are considered. They were selected arbitrarily to represent the random rotation of a smart rock. In the global coordinate system O-XYZ as shown in Figure 3.9, the south-to-north pole directions of the magnet in OR1, OR2, and OR3 point to the northwest & down, southeast & up, and southwest & up octants, respectively.

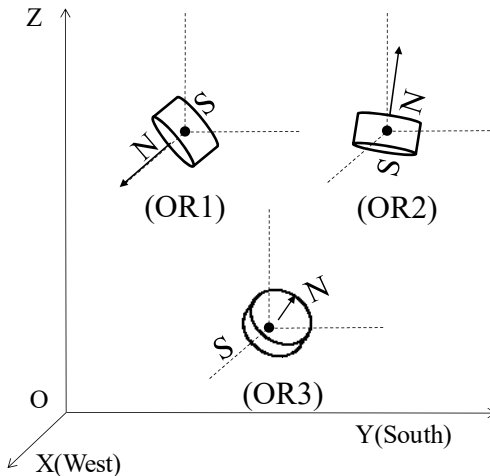


Figure 3.9. Three orientations of the AOS.

Table 3.2 shows the coordinates (X_i, Y_i, Z_i) and total magnetic field intensity $B_{Ti}^{(M)}$ of the AOS measured at locations Q_1 to Q_{27} , respectively. The coordinate and orientation of the magnet in each of the three cases (OR1, OR2, OR3) were determined by first substituting the coordinates of 27 points into Eq. (3.4-3.6) to obtain the relationship between the predicted total intensity $B_{Ti}^{(P)}$ and the six unknowns, and then minimizing the objective error function in Eq. (3.7) after substituting the corresponding the total intensity $B_{Ti}^{(M)}$ measured to evaluate the six unknowns.

Table 3.2. Measured data for the AOS in three orientations

Sensor Head	X_i (m)	Y_i (m)	Z_i (m)	$B_{Ti}^{(M)}$ (10^4 nT)		
				OR1	OR2	OR3
Q_1	0.64	2.57	0.65	5.265	5.305	5.001
Q_2	1.15	3.69	0.25	5.182	5.284	5.180
Q_3	1.02	1.58	0.68	5.189	5.486	4.593
Q_4	2.03	2.61	0.57	5.170	5.325	5.142
Q_5	2.45	1.19	0.74	5.058	5.416	5.153
Q_6	3.67	0.80	0.50	5.152	5.314	5.244
Q_7	2.29	0.02	0.88	4.918	5.517	5.253
Q_8	4.56	0.04	0.22	5.193	5.274	5.254
Q_9	3.31	-0.64	0.49	5.138	5.333	5.285
Q_{10}	1.71	-1.11	0.95	4.852	5.581	5.437
Q_{11}	2.28	-2.21	0.65	5.159	5.331	5.293
Q_{12}	2.16	-2.99	0.47	5.203	5.287	5.257
Q_{13}	0.71	-2.10	0.88	5.002	5.504	5.401
Q_{14}	0.48	-3.61	0.81	5.189	5.299	5.244
Q_{15}	-0.59	-2.62	0.95	5.093	5.398	5.312
Q_{16}	-1.83	-4.00	0.32	5.201	5.278	5.218
Q_{17}	-1.78	-2.67	0.59	5.135	5.352	5.249
Q_{18}	-1.06	-1.23	0.40	4.517	6.106	5.766
Q_{19}	-2.75	-1.63	0.66	5.134	5.341	5.297
Q_{20}	-2.46	-0.05	0.91	5.223	5.289	5.447
Q_{21}	-3.98	-0.06	0.14	5.180	5.286	5.269
Q_{22}	-1.34	0.74	0.74	6.129	4.959	5.619
Q_{23}	-3.07	0.94	0.13	5.181	5.317	5.319
Q_{24}	-3.99	2.22	0.22	5.223	5.254	5.257
Q_{25}	-2.35	2.01	0.39	5.264	5.265	5.277
Q_{26}	-0.79	1.99	0.77	5.597	5.111	4.979
Q_{27}	-1.64	3.31	0.32	5.254	5.255	5.217

Table 3.3 summarizes the predicted and measured coordinates of the magnet in the AOS configuration, named M_{AOS} , in three orientations (OR1, OR2, and OR3) as well as the SRSS prediction errors in M_{AOS} location estimation. Since the AOS in each of the three orientations (OR1, OR2 and OR3) was placed at the origin of the O-XYZ coordinate system, the ground truth coordinates of the AOS were zero. It can be observed from Table 3.3 that the SRSS prediction errors for the location of three orientations are

0.01 m, 0.01 m and 0.01 m, respectively. They are small compared to the size of the magnet, which is about 0.1 m in diameter.

Table 3.3. Predicted and measured coordinates of the magnet M_{AOS} in three orientations

	OR1			OR2			OR3		
	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)
Predicted Location	-0.01	0.00	0.01	0.00	0.00	-0.01	0.00	0.01	-0.01
Measured Location	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Component Error	-0.01	0.00	0.01	0.00	0.00	-0.01	0.00	0.01	-0.01
Total SRSS Error	0.01			0.01			0.01		

Table 3.4 lists the predicted rotation angles α , β and γ and the directional cosines l , m , and n of the magnet in the AOS in the global coordinate system. The rotation angles (α , β , γ) adopted for the coordinate transformation are difficult to visualize in space while the directional cosines (l , m , n) of the magnet represent the angles between the local y-axis (south-to-north pole direction) and the global axis X (west), Y (south) and Z (up), respectively.

Table 3.4. Predicted orientations of the AOS in three cases

Orientation	OR1			OR2			OR3		
Rotation (rad)	α	β	γ	α	β	γ	α	β	γ
	1.04	3.88	3.12	4.67	3.69	2.77	3.36	3.33	2.59
Directional cosine	l	m	n	l	m	n	l	m	n
	0.56	-0.52	-0.64	-0.47	0.23	0.85	0.47	0.86	0.21

3.4.2. Location of APSS

Similarly, Table 3.5 shows the measured coordinates (X, Y, Z) of 27 points and their corresponding total magnetic field intensities of the APSS as well as the SRSS error in location prediction. It can be observed from Table 3.5 that the SRSS prediction error in location is 0.07 m, which is quite small compared to the size of the APSS with 0.2 m in diameter of the outside plastic ball. It is noted that the orientation of magnet in the APSS is known *a priori* so that the process of locating the APSS is significantly simpler than that of the AOS. Therefore, the APSS is a preferable configuration of smart rocks in practical applications with measurements taken on a river bank.

3.4.3. Effect of measurement point selection

As shown in Figure 3.5(c), the measurement points were selected between 1.5 m and 5 m distances from the APSS or AOS placed at the origin of the coordinate system. They were well distributed around the APSS or AOS in near and far radial distances. Although a minimum of three measurement points are required for three unknown location parameters of the APSS and six measurement points for six unknown location parameters of the AOS, more measurement points lead to a more robust and accurate estimation of the APSS or AOS location. Herein, 27 points were initially selected to

ensure the convergence and high accuracy in the estimation of the unknown parameters.

Table 3.5. Predicted and measured data for the APSS location M_{APSS}

Sensor Head	X_i (m)	Y_i (m)	Z_i (m)	$B_{Ti}^{(M)}$ (10^4 nT)
Q_1	0.64	2.57	0.63	5.450
Q_2	1.15	3.69	0.24	5.294
Q_3	1.02	1.58	0.67	5.861
Q_4	2.03	2.61	0.56	5.309
Q_5	2.45	1.19	0.73	5.254
Q_6	3.67	0.80	0.49	5.208
Q_7	2.29	0.02	0.87	5.116
Q_8	4.56	0.04	0.21	5.212
Q_9	3.31	-0.64	0.48	5.183
Q_{10}	1.71	-1.11	0.94	4.985
Q_{11}	2.28	-2.21	0.64	5.209
Q_{12}	2.16	-2.99	0.45	5.243
Q_{13}	0.71	-2.10	0.86	5.155
Q_{14}	0.48	-3.61	0.80	5.245
Q_{15}	-0.59	-2.62	0.94	5.199
Q_{16}	-1.83	-4.00	0.31	5.252
Q_{17}	-1.78	-2.67	0.58	5.234
Q_{18}	-1.06	-1.23	0.39	5.239
Q_{19}	-2.75	-1.63	0.65	5.185
Q_{20}	-2.46	-0.05	0.90	5.137
Q_{21}	-3.98	-0.06	0.12	5.200
Q_{22}	-1.34	0.74	0.72	5.629
Q_{23}	-3.07	0.94	0.12	5.200
Q_{24}	-3.99	2.22	0.21	5.229
Q_{25}	-2.35	2.01	0.38	5.281
Q_{26}	-0.79	1.99	0.76	5.730
Q_{27}	-1.64	3.31	0.31	5.297
Predicted Location $M^{(P)}_{APSS}$	0.02	0.01	0.07	
Measured Location $M^{(M)}_{APSS}$	0.00	0.00	0.00	N/A
Component Location Error	0.02	0.01	0.07	
Total SRSS Error				0.07 m

Since the magnetic flux intensity of a permanent magnet decreases with a cubic function of the measurement distance, effective measurements that allow a reverse estimation of the magnet location must be taken in a certain range of distance. On one hand, to simplify the permanent magnet as a dipole in Eq. (3.2), the distance from a field point to the magnet is at least ten times the size of the magnet or 0.1 m. Considering the presence of dead zones with the magnetometer used in this study, where the magnetometer cannot provide the correct magnetic field intensity, the lower limit of measurement distance is determined to be 1.5 m.

On the other hand, the upper limit of measurement distance depends on the coefficient k , which represents the magnetic strength of the dipole. The larger the

coefficient k , the stronger the magnetic flux intensity of the permanent magnet at a certain distance. Therefore, the larger the coefficient k , the further distance the magnetic flux intensity can be detected with confidence. For the magnets used in the open field tests, $k = 42542 \text{ nT}\cdot\text{m}^3$ or $41890 \text{ nT}\cdot\text{m}^3$ determines the upper limit of measurement distance for effective localization of the magnets. Figure 3.10(a) presents the total magnetic field intensity as a function of distance along the symmetry axis (Y direction) of the dipole at five elevations in Z direction. That is, $x = 0, 1.5 \text{ m} \leq y \leq 7.0 \text{ m}, z = 0.3 \text{ m}, 0.5 \text{ m}, 0.7 \text{ m}, 0.9 \text{ m}$ and 1.0 m in Eq. (3.6). Obviously, the total intensity decreases rapidly from 1.5 m to 4.0 m and then slowly afterward. As shown in Figure 3.10(b) for the zoom-in view, at a low level of 0.3 m in Z direction, the attenuations of the magnetic intensity from 4.0 m to 5.0 m and from 5.0 m to 6.0 m are 330 nT and 123 nT , respectively. The decreases in magnetic intensity from 4.0 m to 5.0 m distance are $368 \text{ nT}, 397 \text{ nT}, 415 \text{ nT}$ and 420 nT for $Z = 0.5 \text{ m}, 0.7 \text{ m}, 0.9 \text{ m}$ and 1.0 m , respectively; the decreases from 5.0 m to 6.0 m are $154 \text{ nT}, 166 \text{ nT}, 176 \text{ nT}$ and 180 nT , respectively. In practical applications, the measured magnetic intensity can deviate from the calculated intensity by $\pm 200 \text{ nT}$ as a result of such combined experimental errors as the deviation of the sensor position for magnetic intensity measurement, the coordinate deviation of the measurement points, and the change of the Earth magnetic field because of the solar storm. Therefore, those attenuations from 5.0 m to 6.0 m at various Z levels, less than 200 nT , are not a sensitive and effective distance range for measurement points' selection compared to those attenuations from 4.0 m to 5.0 m larger than 300 nT .

Figure 3.11(a) displays the magnetic field changes along Z direction at three Y positions ($4.0 \text{ m}, 5.0 \text{ m}, 6.0 \text{ m}$) in YOZ plane. The magnetic field intensity first increases from $Z = 0 \text{ m}$ to $Z = 2.0 \text{ m}$ and then decreases monotonically with the distance in Z direction. Figure 3.11(b) shows an amplified observation on the magnetic intensity over the distance in Z direction. It is also seen from Figure 3.11 (b) that the desirable distance in Z direction for the collection of sensitive magnetic intensities is less than 5.0 m as would be between 5 m and 6 m in Y direction for a magnetic field difference of less than 200 nT . The same idea is applicable to the magnetic intensity variation in X direction. Therefore, the upper limit of 5.0 m for the selection of measurement points was determined in XOY plane as shown in Figure 3.5(c).

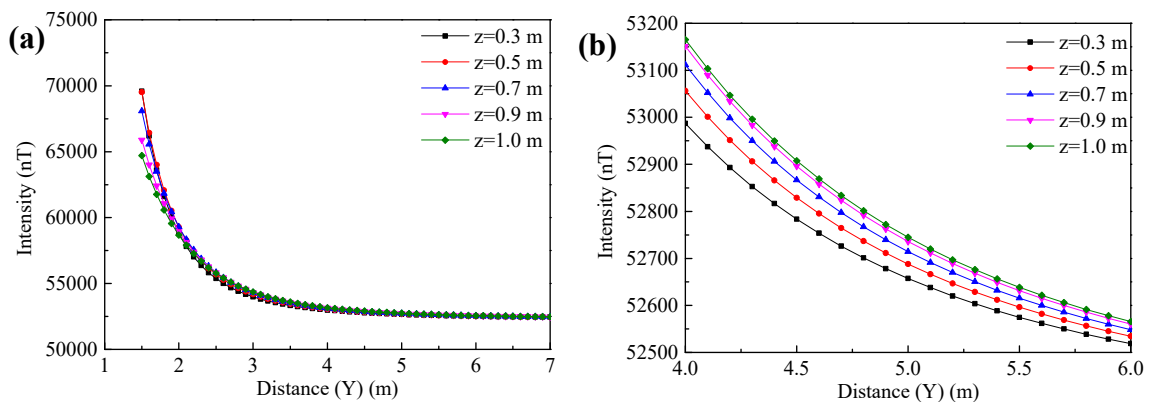


Figure 3.10. Magnetic field intensity vs. measurement distance in Y direction: (a) overall view and (b) zoom-in view.

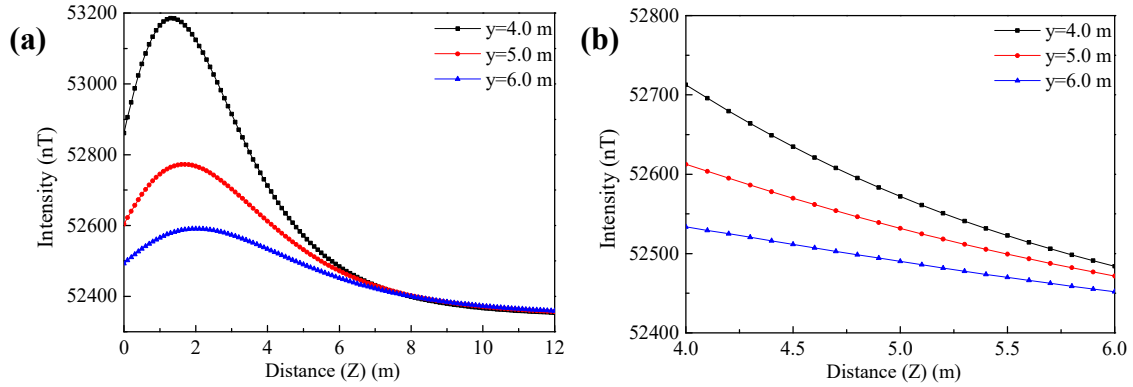


Figure 3.11. Magnetic field intensity vs. measurement distance in Z direction: (a) overall and (b) zoom-in view.

3.5. Application of the APSS

As stated previously, the smart rock technology is developed to mainly monitor the maximum depth of a scour hole developed around bridge piers or abutments in real time. Thus, tracking the movement of a smart rock over time is highly desirable during a flood event. Another field test was conducted to demonstrate the movement characteristic of a smart rock with the APSS on a slope and validate the localization method developed in this study.

3.5.1. Simulation of APSS movement

A natural slope located in the same open field at Ber Juan Park, Rolla, MO, was chosen as the test site as shown in Figure 3.12(a). The natural slope from the top to bottom was used to simulate the movement of the smart rock in a scour hole. Along the slope, eight stops of the APSS were marked as M1 to M8 in Figure 3.12(a). The eight APSS stops were surrounded by a total of 44 measurement points designated as S_1, S_2, \dots, S_{44} , as marked in Figure 3.12(b). A total station was set up at the origin of the O-XYZ coordinate system with the Y-axis approximately pointed to the geographic South, the X-axis perpendicular to Y-axis pointed to West, and the Z-axis pointed up according to the right-hand rule. The total station was used to survey the coordinate of each measurement point and the ground truth coordinate of the APSS. Prior to the APSS deployment, the magnetometer G858 was employed to measure the uniform ambient magnetic field intensity. After the APSS had been deployed at each of the eight positions, the total magnetic field intensity was measured again. For each APSS deployment, 18 measurement points were selected out of 44 points within a radial distance between 1.5 m and 5.0 m.

When the APSS was placed at M1, each measurement includes the total magnetic field intensity and its corresponding coordinate in the O-XYZ Cartesian coordinate system. By minimizing the objective error function in Eq. (3.7), the coordinate of M1 was predicted as designated as M1' in Table 3.6. Similarly, the predicted locations of the APSS at M2 to M8 can be determined and represented by M2' to M8' in Table 3.6.

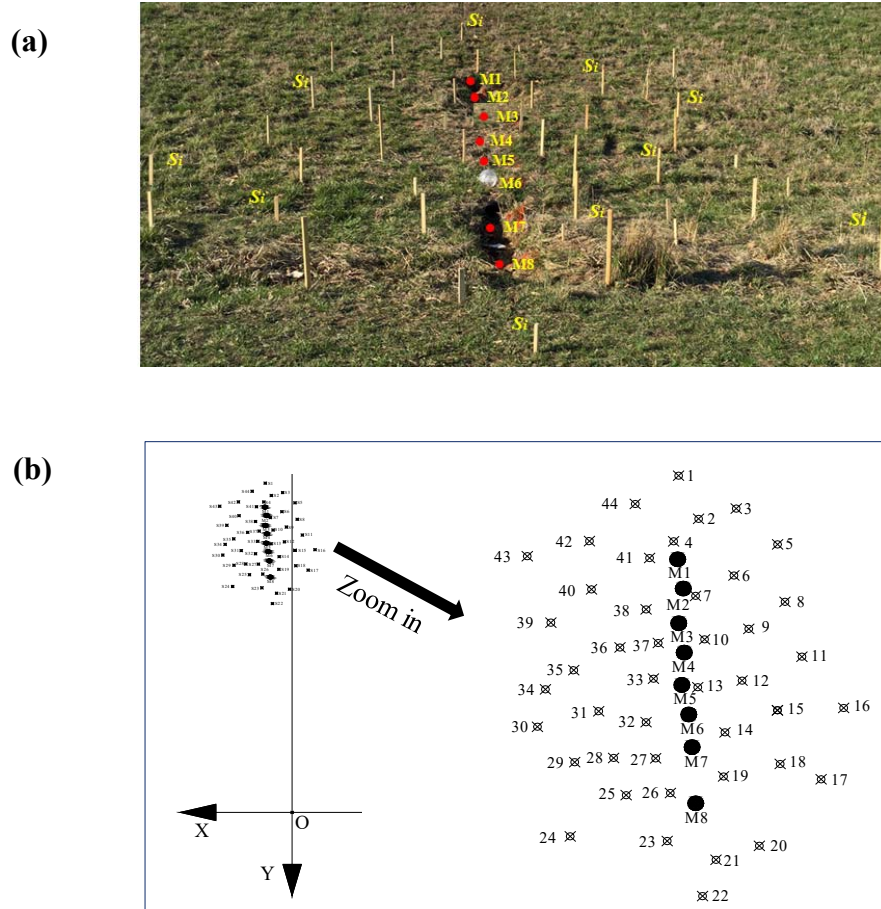


Figure 3.12. The APSS and measurement points: (a) test site and (b) schematic view.

3.5.2. Test results

Table 3.6 shows the measured and predicted locations of the APSS in the O-XYZ system and the prediction error. It can be seen from Table 3.6 that the component and SRSS errors for eight locations of the APSS are all less than 13.6 mm. Therefore, the accuracy of the localization algorithm in Eq. (3.7) is sufficient in the uniform ambient magnetic field. Figure 3.13 shows a graphical presentation of the eight measured and predicted locations of the APSS on a three-dimensional slope surface. Each pair of the measured and predicted locations are nearly overlapped. In practical applications, such as the monitoring of a bridge scour process, the APSS is initially deployed at the M1 location and the other locations from M2 to M8 represent the water flow induced movement of the APSS at various steps over time.

3.6. Summary

The smart rock technology offers an alternative to investigate the behavior of scour development around a bridge pier or abutment and the effectiveness of a rip-rap counter measurement. Properly-designed smart rocks should roll and fall into the scour hole around a pier or abutment. Their position is thus related to the depth of the scour hole.

Table 3.6. Predicted and measured data for the APSS location

Stop	Measured Coordinate			Stop	Predicted Coordinate			Total Error SRSS (m)
	X (m)	Y (m)	Z (m)		X' (m)	Y' (m)	Z' (m)	
M1	-2.31	-29.44	-0.17	M1'	-2.31	-29.44	-0.15	0.01
M2	-2.16	-28.63	-0.39	M2'	-2.16	-28.64	-0.39	0.00
M3	-2.28	-27.67	-0.63	M3'	-2.28	-27.68	-0.64	0.01
M4	-2.14	-26.86	-0.84	M4'	-2.14	-26.86	-0.83	0.01
M5	-2.20	-25.97	-1.09	M5'	-2.20	-25.97	-1.09	0.00
M6	-2.02	-25.15	-1.24	M6'	-2.02	-25.16	-1.24	0.00
M7	-1.94	-24.25	-1.62	M7'	-1.93	-24.25	-1.63	0.01
M8	-1.84	-22.70	-1.62	M8'	-1.85	-22.70	-1.62	0.01

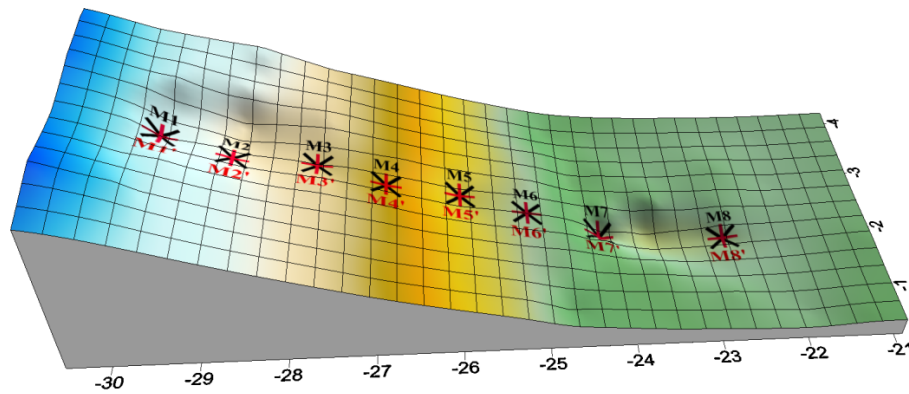


Figure 3.13. Comparison between the measured and predicted APSS locations.

The permanent magnet embedded in a smart rock generates the magnetic field that can be detected by magnetic sensors or a magnetometer. The detected magnetic field intensities and the given magnetometer's positions can be utilized to locate the smart rock. In this section, smart rocks with the AOS and APSS have been demonstrated for the field evaluation of their localization. The AOS is simple in fabrication and high in localization accuracy. However, the localization algorithm is complex with six unknowns: three location coordinates and three orientations of the magnet. The APSS with fixed orientation reduces unknowns to three location coordinate only, which greatly simplifies the localization algorithm and improves the computational efficiency without sacrificing the localization accuracy. Therefore, the APSS is a preferred configuration in practical applications.

The localization tests in the open field have demonstrated that the magnetic dipole simplification of a permanent magnet is sufficiently accurate for the localization of smart rocks with the AOS and APSS. The Earth's magnetic field in the form of parallel vectors at an open site cannot be separated from the magnetic field generated from a magnet in field measurements.

The movement of a smart rock in a scour hole created under water flow in application was simulated with an APSS when placed at eight stops on a natural slope. This test further demonstrated the high accuracy and repeatability of the localization of the APSS at various locations in the same uniform ambient field.

4. LOCALIZATION OF SMART ROCKS IN NON-UNIFORM AMBIENT MAGNETIC FIELD

The total magnetic field around a bridge site is affected by a permanent magnet, the Earth, and any other ferromagnetic substances such as the reinforcement in bridge piers and deck. Since the magnetic field distribution of other substances is unknown, the combined effect of the Earth and other substances or the ambient magnetic field at the bridge site is non-uniform. To enable the localization of smart rocks, the non-uniform ambient magnetic field intensity must be evaluated accurately.

In this section, the localization algorithms of the AOS and APSS in non-uniform magnetic field at the bridge site are developed by modifying the algorithms presented in Section 3. Unlike the Earth's magnetic field with parallel magnetic lines, the non-uniform ambient magnetic field makes the direction and intensity of the magnetic field vary at each measurement point. Therefore, a custom-built device is designed and built to detect the ambient magnetic field direction. It can determine inclination and declination angles of the ambient magnetic field at various measurement points. The experimental field tests were carried out at the bridge site of Highway 63 over the Gasconade River to demonstrate the localization procedure and validate the localization algorithm using the AOS and APSS. The magnetometer G858 was used to collect the ambient and total magnetic field intensities. The custom-built device was used to detect the direction of the ambient magnetic field at each measurement point.

4.1. The Magnetic Field at a Bridge Site

The magnetic field at a bridge site is a combined effect of the Earth and the magnetized steel rebar embedded in bridge piers and deck or the magnetized steel girders. This combination at a local area such as bridge site is designated as the ambient magnetic field (AMF), which is a vector superposition of the Earth's magnetic field and the field from ferromagnetic substances such as steel objects. Although the AMF cannot be simply expressed in a mathematical model, its magnitude and direction at any point can be measured by a 3-axis magnetometer or the custom-built device, respectively.

The local magnetic field generated by a magnet is referred to as the magnet's magnetic field (MMF), which can be represented by a mathematic equation. A vector summation of the AMF and MMF forms the total magnetic field measured at a bridge site after smart rocks have been deployed.

As illustrated in Figure 4.1 in the global O-XYZ Cartesian coordinate system, an arbitrary measurement station is located at Point $Q_i(X_i, Y_i, Z_i)$ ($i=1$ to n). The AMF at Point $Q_i(X_i, Y_i, Z_i)$, is represented by a vector \mathbf{B}_{Ai} , which is determined by a magnetic flux density B_{Ai} and two angles, θ and φ . The parameter φ in $[0, 2\pi]$ is the angle spanned from the X axis to the projected vector of the AMF vector \mathbf{B}_{Ai} in XOY plane. The parameter θ in $[0, \pi]$ represents the angle spanned from the projected vector to \mathbf{B}_{Ai} . Therefore, the three components (B_{AXi} , B_{AYi} , B_{AZi}) of the ambient magnetic field along X-, Y-, and Z-directions are:

$$B_{AXi} = B_{Ai} \cos \theta_i \cos \varphi_i \quad (4.1a)$$

$$B_{AYi} = B_{Ai} \cos \theta_i \sin \varphi_i \quad (4.1b)$$

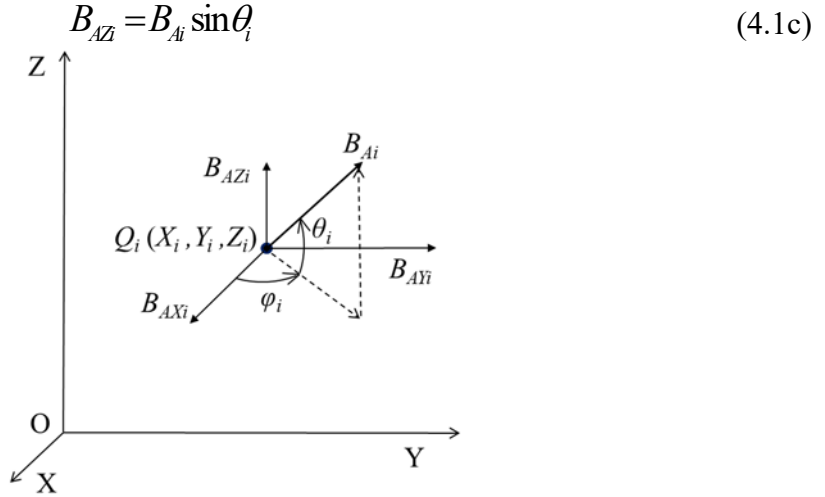


Figure 4.1. A measurement point Q_i in the global Cartesian coordinate system O-XYZ.

A permanent magnet with uniform magnetization can be modeled as a magnetic dipole when measurements are taken at a distance from the magnet, which is significantly greater than the largest dimension of the magnet. The magnetic flux density of a magnetic dipole source is a high-order nonlinear function of the coordinates at a measurement point. As illustrated in Figure 4.2, the center of the magnet is located at Point $P(X_M, Y_M, Z_M)$ in the global Cartesian coordinate system O-XYZ and $p(0, 0, 0)$ in the local Cartesian coordinate system p -xyz. Point $q(x_i, y_i, z_i)$ in the local coordinate system and point $Q_i(X_i, Y_i, Z_i)$ in the global coordinate system represent an arbitrary measurement point. The magnetic field vector of the magnet at Point $Q_i(X_i, Y_i, Z_i)$ ($i=1$ to n) is represented by \mathbf{B}_{Mi} and its three components ($B_{MXi}, B_{MYi}, B_{MZi}$) are given in Eqs. (3.3 – 3.5).

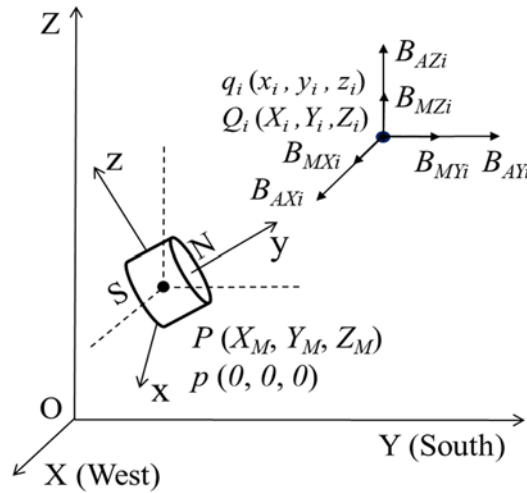


Figure 4.2 AOS in local and global coordinate systems and the AMF.

The total magnetic field intensity B_{Ti} at Point Q_i from the magnet and the non-uniform AMF (the Earth and other ferromagnetic substances such as magnetized steel reinforcement) can be expressed into:

$$B_{Ti} = \sqrt{(B_{MXi} + B_{AXi})^2 + (B_{MYi} + B_{AYi})^2 + (B_{MZi} + B_{AZi})^2} \quad (4.2)$$

It changes with B_{Ai} , θ_i , φ_i , k , X_M , Y_M , Z_M , α , β , and γ . That is, $B_{Ti} = B_{Ti}(B_{Ai}, \theta_i, \varphi_i, k, X_i, Y_i, Z_i, X_M, Y_M, Z_M, \alpha, \beta, \gamma)$. The intensity B_{Ai} , the θ_i and φ_i angles of the AMF are measured using the 3-axis magnetometer or the custom-built device prior to AOS deployment at a predetermined site. The coefficient k related to the magnetic moment of the magnet is obtained from the calibration test or from the technical specifications of the magnet provided by the manufacturer. Given k , θ_i , φ_i and B_{Ai} at each measurement point (X_i, Y_i, Z_i) of a project site, the total magnetic field intensity of the ambient and magnet B_{Ti} is a function of (X_M, Y_M, Z_M) and (α, β, γ) .

4.2. Localization Algorithm for a Single Smart Rock

In this section, localization of a single smart rock in the non-uniform AMF is developed with the minimization of an objective error function. Three types of smart rocks (AOS, APSS, and APUS) are considered.

4.2.1. AOS

To solve the six parameters $(X_M, Y_M, Z_M, \alpha, \beta, \gamma)$ in the highly-nonlinear equations, an objective error function is formulated in the optimization algorithm. Assume that n number of measurements, $B_{Ti}^{(M)}$ ($i=1, 2, \dots, n$), are taken with the G857 magnetometer at n stations around the AOS, (X_i, Y_i, Z_i) ($i=1, 2, \dots, n$). At each station, the predicted intensity $B_{Ti}^{(P)} = B_{Ti}$ can be calculated from Eq. (4.2), which is a summation of the effect of the magnet and the measured AMF. That is, $B_{TXi}^{(P)} = B_{MXi} + B_{AXi}^{(M)}$, $B_{TYi}^{(P)} = B_{MYi} + B_{AYi}^{(M)}$, $B_{TZi}^{(P)} = B_{MZi} + B_{AZi}^{(M)}$, and $B_{Ti}^{(P)} = \sqrt{(B_{TXi}^{(P)})^2 + (B_{TYi}^{(P)})^2 + (B_{TZi}^{(P)})^2}$ in which the magnetic field of the magnet, B_{Mi} ($B_{MXi}, B_{MYi}, B_{MZi}$), at any point Q_i (X_i, Y_i, Z_i) can be evaluated from Eq. (3.3-3.5). The SRSS error between the predicated intensity $B_{Ti}^{(P)}$ and the measured intensity $B_{Ti}^{(M)}$, $J(X_M, Y_M, Z_M, \alpha, \beta, \gamma)$, can then be expressed into:

$$J(X_M, Y_M, Z_M, \alpha, \beta, \gamma) = \sqrt{\sum_{i=1}^n [B_i^{(P)} - B_i^{(M)}]^2} \quad (4.3)$$

By minimizing the SRSS error in Eq. (4.3) through a numerical algorithm, the location and orientation parameters of the magnet can be determined. Specifically, the sequential quadratic programming (SQP) algorithm implemented in the Fmincon code in MATLAB was used to find the solution for the minimization of the SRSS error in Eq. (4.3).

4.2.2. APSS

As discussed in Section 3, the APSS can be represented by $\alpha = \pi$, $\beta = 0$, and $\gamma = 0$ in the global coordinate system as shown in Figure 4.3(a). The local xyz coordinate system with y-axis from the South to North pole of the magnet is identical to the XYZ coordinate system when rotated counter-clockwise by 180° . In this case, the three components ($B_{MXi}, B_{MYi}, B_{MZi}$) of the magnetic field generated from the magnet at an arbitrary point Q_i can be evaluated from Eq. (3.8). With the known Euler angles ($\alpha = \pi$, $\beta = 0$, and $\gamma = 0$), Eq. (4.2) and Eq. (4.3) are simplified into a function of three unknown position coordinates (X_M, Y_M, Z_M) . In this case, the SRSS error can be written as:

$$J(X_M, Y_M, Z_M) = \sqrt{\sum_{i=1}^n [B_i^{(P)} - B_i^{(M)}]^2} \quad (4.4)$$

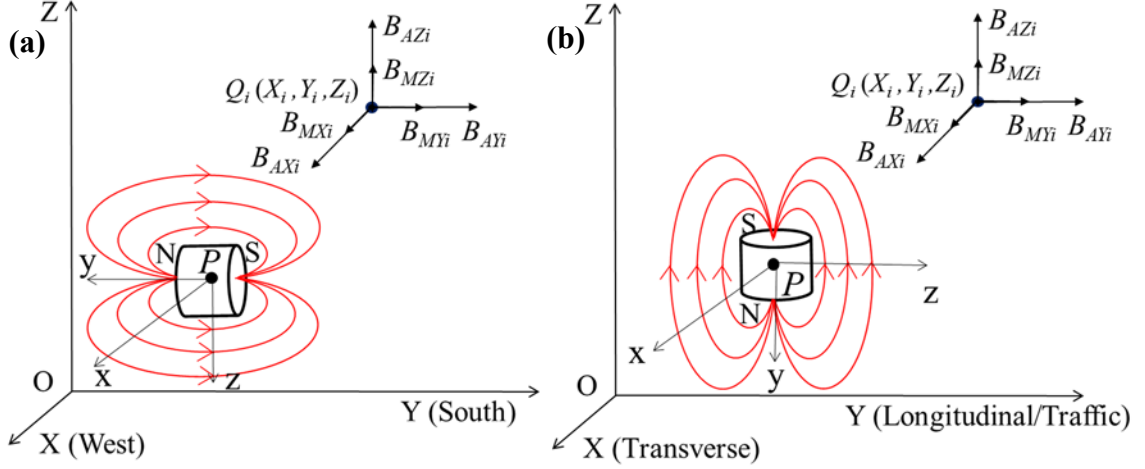


Figure 4.3 The magnetic fields of the AMF and: (a) an APSS and (b) an APUS.

4.2.3. APUS

As discussed in Section 2, the South pole of one or two magnets in an APUS smart rock is faced upward for the magnetic field measurement on a bridge deck. The downward y-axis from South to North pole of the magnet(s) is controlled by the gravity effect and has nothing to do with the geographical south of the Earth. Therefore, Figure 4.3(b) refers to the longitudinal/traffic direction and transverse direction of the bridge as will be discussed further in Section 5. Since the cylinder magnet(s) are axis-symmetric about the y-axis, the local x-axis and z-axis perpendicular to the y-axis can be selected for convenience so long as they follow the right-hand rule. In this study, the local x-axis is selected to be in parallel with the global X-axis. The orientation of the magnet(s) thus corresponds to Euler angles $\alpha = 3\pi/2$, $\beta = 0$, and $\gamma = 0$ in the global coordinate system. That is, the local xyz coordinate system with y-axis of the magnet is identical to the XYZ coordinate system when rotated counter-clockwise by 270° . By substituting the Euler angles into Eqs. (3.3) to (3.5), the magnetic field of the magnet(s) can be expressed into:

$$\begin{pmatrix} B_{MXi} \\ B_{MYi} \\ B_{MZi} \end{pmatrix} = \begin{pmatrix} -k \frac{3(Z_i - Z_M)(X_i - X_M)}{\left(\sqrt{(X_i - X_M)^2 + (Y_i - Y_M)^2 + (Z_i - Z_M)^2}\right)^5} \\ -k \frac{3(Z_i - Z_M)(Y_i - Y_M)}{\left(\sqrt{(X_i - X_M)^2 + (Y_i - Y_M)^2 + (Z_i - Z_M)^2}\right)^5} \\ -k \frac{2(Z_i - Z_M)^2 - (X_i - X_M)^2 - (Y_i - Y_M)^2}{\left(\sqrt{(X_i - X_M)^2 + (Y_i - Y_M)^2 + (Z_i - Z_M)^2}\right)^5} \end{pmatrix} \quad (4.5)$$

4.3. Localization Algorithm for Two Smart Rocks

Let two magnets in the APUS configuration be centered at Point $P_1 (X_{M1}, Y_{M1}, Z_{M1})$ and $P_2 (X_{M2}, Y_{M2}, Z_{M2})$, respectively, in a Cartesian coordinate system O-XYZ. As shown in Figure 4.4, the Y-axis is set in longitudinal/traffic direction of a bridge, the X-axis is in transverse direction, and the Z-axis points upward. The AMF of the Earth and other ferromagnetic substances (e.g., steel reinforcement), $\mathbf{B}_{Ai}^{(M)} (B_{AXi}^{(M)}, B_{AYi}^{(M)}, B_{AZi}^{(M)})$, and the total magnetic field of the Earth, the smart rocks, and the other ferromagnetic substances, $\mathbf{B}_{Ti}^{(M)} (B_{TXi}^{(M)}, B_{TYi}^{(M)}, B_{TZi}^{(M)})$, are measured at any Point $Q_i (X_i, Y_i, Z_i)$ ($i=1, 2, \dots, n$) near the two smart rocks.

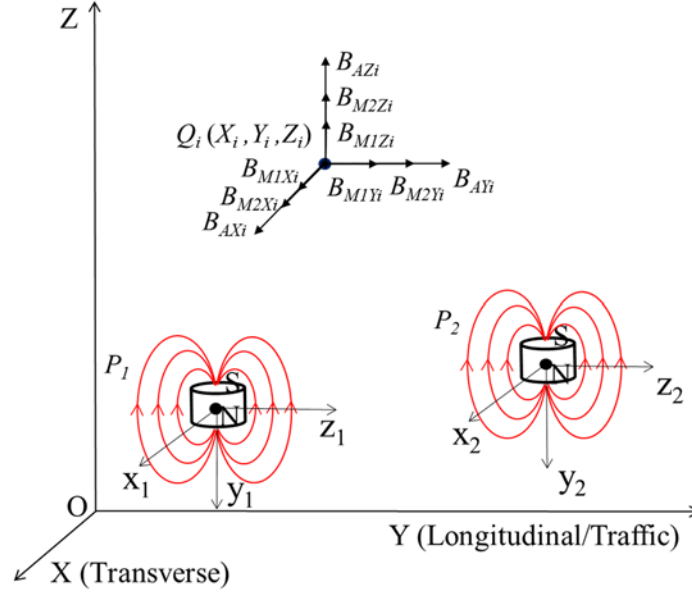


Figure 4.4. Two magnets and various magnetic field measurements.

The total magnetic field can also be expressed into a summation of the effect of the two magnets and the measured AMF. That is,

$$B_{TXi}^{(P)} = B_{M1Xi} + B_{M2Xi} + B_{AXi}^{(M)} \quad (4.6a)$$

$$B_{TYi}^{(P)} = B_{M1Yi} + B_{M2Yi} + B_{AYi}^{(M)} \quad (4.6b)$$

$$B_{TZi}^{(P)} = B_{M1Zi} + B_{M2Zi} + B_{AZi}^{(M)} \quad (4.6c)$$

$$B_{Ti}^{(P)} = \sqrt{(B_{TXi}^{(P)})^2 + (B_{TYi}^{(P)})^2 + (B_{TZi}^{(P)})^2} \quad (4.6d)$$

in which the magnetic field of the magnets, $\mathbf{B}_{M1i} (B_{M1Xi}, B_{M1Yi}, B_{M1Zi})$ and $\mathbf{B}_{M2i} (B_{M2Xi}, B_{M2Yi}, B_{M2Zi})$, at any point (X_i, Y_i, Z_i) can be derived in the same way as for Eq. (4.5) and evaluated by:

$$\begin{pmatrix} B_{M1Xi} \\ B_{M1Yi} \\ B_{M1Zi} \end{pmatrix} = \begin{pmatrix} -k_1 \frac{3(Z_i - Z_{M1})(X_i - X_{M1})}{\left(\sqrt{(X_i - X_{M1})^2 + (Y_i - Y_{M1})^2 + (Z_i - Z_{M1})^2}\right)^5} \\ -k_1 \frac{3(Z_i - Z_{M1})(Y_i - Y_{M1})}{\left(\sqrt{(X_i - X_{M1})^2 + (Y_i - Y_{M1})^2 + (Z_i - Z_{M1})^2}\right)^5} \\ -k_1 \frac{2(Z_i - Z_{M1})^2 - (X_i - X_{M1})^2 - (Y_i - Y_{M1})^2}{\left(\sqrt{(X_i - X_{M1})^2 + (Y_i - Y_{M1})^2 + (Z_i - Z_{M1})^2}\right)^5} \end{pmatrix} \quad (4.7a)$$

$$\begin{pmatrix} B_{M2Xi} \\ B_{M2Yi} \\ B_{M2Zi} \end{pmatrix} = \begin{pmatrix} -k_2 \frac{3(Z_i - Z_{M2})(X_i - X_{M2})}{\left(\sqrt{(X_i - X_{M2})^2 + (Y_i - Y_{M2})^2 + (Z_i - Z_{M2})^2}\right)^5} \\ -k_2 \frac{3(Z_i - Z_{M2})(Y_i - Y_{M2})}{\left(\sqrt{(X_i - X_{M2})^2 + (Y_i - Y_{M2})^2 + (Z_i - Z_{M2})^2}\right)^5} \\ -k_2 \frac{2(Z_i - Z_{M2})^2 - (X_i - X_{M2})^2 - (Y_i - Y_{M2})^2}{\left(\sqrt{(X_i - X_{M2})^2 + (Y_i - Y_{M2})^2 + (Z_i - Z_{M2})^2}\right)^5} \end{pmatrix} \quad (4.7b)$$

Here, k_1 and k_2 represent the strength factors of the two magnets in $nT \cdot m^3$. They can be calculated from the maximum residual flux density (or Br) of the magnets.

To locate the two smart rocks, an objective error function is defined as a SRSS difference between the predicted and the measured magnetic field intensities at all measurement points $Q_i(X_i, Y_i, Z_i)$ ($i=1, 2, \dots, n$). That is,

$$J(X_{M1}, Y_{M1}, Z_{M1}; X_{M2}, Y_{M2}, Z_{M2}) = \sqrt{\sum_{i=1}^n [B_{Ti}^{(P)} - B_{Ti}^{(M)}]^2} \quad (4.8)$$

The objective error function in Eq. (4.8) is minimized to determine the coordinates of the two smart rocks, $P_1(X_{M1}, Y_{M1}, Z_{M1})$ and $P_2(X_{M2}, Y_{M2}, Z_{M2})$.

4.4. Detection of AMF Orientation

An Ambient Magnetic Field Orientation Detection (AMFOD) device was developed to determine the direction of the AMF at a bridge site. The AMFOD device is composed of an orientation detector (OD), an OD support, a data reading system, two laser pointers, a high-precision bubble level and a tripod to support the measurement setup. Figures 4.5(a) and 4.5(b) show a schematic view and a prototype of the AMFOD device.

The OD was created based on the APSS model. It was utilized to capture the direction of the AMF at each measurement point in a quite accurate way. The OD consists of an inside ball and an outside ball, two identical cylindrical hollow magnets,

and liquid filled in between the two balls. The key to the design of the two balls is to keep the geometrical center of the inside ball aligned with that of the outside ball. The inside ball and the outside ball were produced by a 3D printer using the Polymeric Methyl Methacrylate due to their high precision requirement. The two cylindrical hollow magnets are 19 mm in diameter and 25.4 mm in height with a 2 mm diameter hole through its center line. The reserved space through the center line of the inside ball was designed to place the two cylindrical magnets. The liquid used to make the inside ball rotate freely is the propylene glycol with a mass density of 1040 kg/m^3 to satisfy both lubrication and nontoxicity requirements.

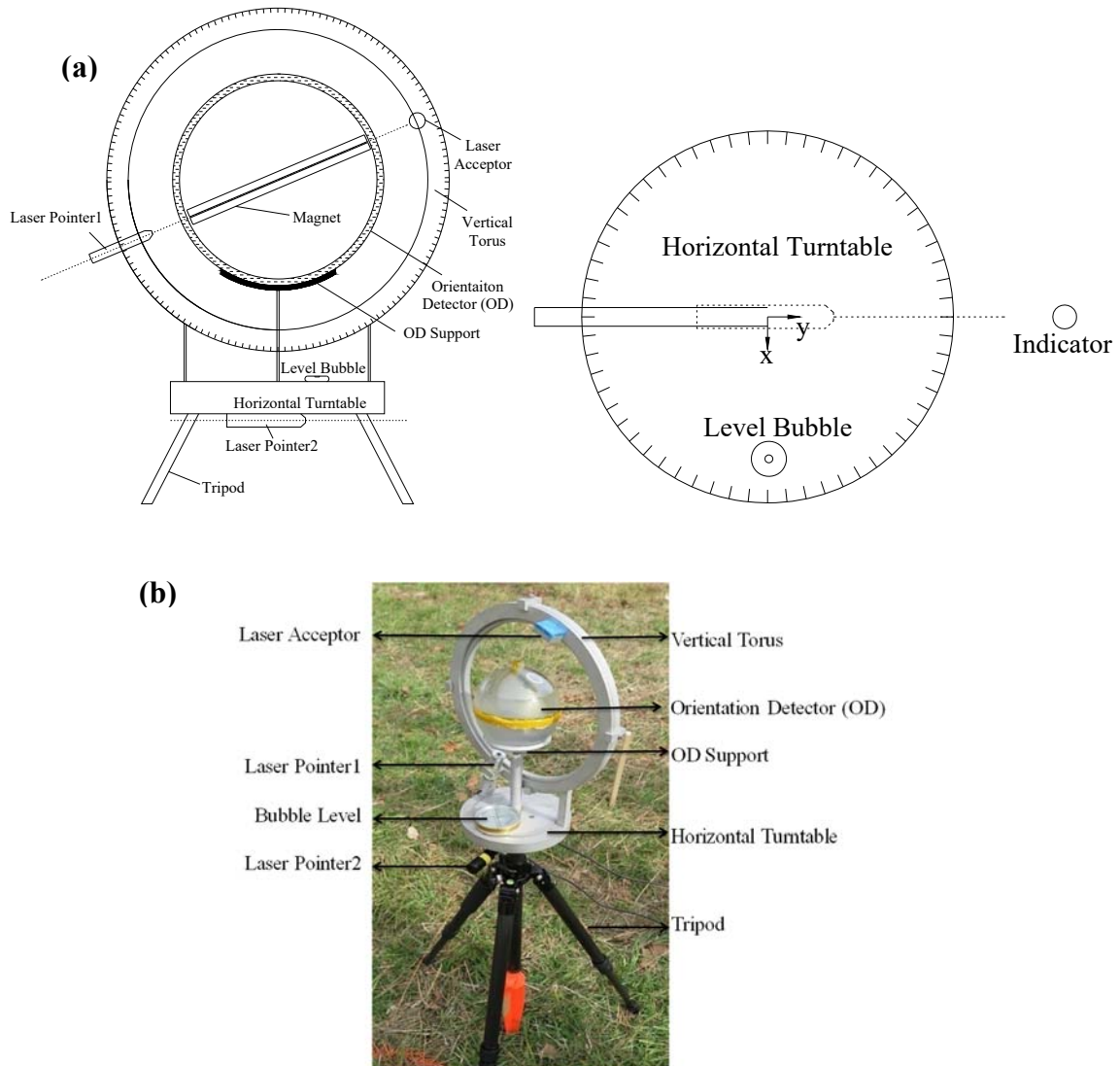


Figure 4.5 Overall design of AMFOD: (a) schematic view and (b) prototype.

The data reading system is composed of the OD support, the vertical torus for angle θ reading, and the horizontal turntable for angle φ reading. The accuracy of the data reading system is 0.1° . The data reading system was made of aluminum alloy without any ferromagnetic substances.

Two laser pointers were used in the design of the AMFOD device. Laser Pointer 1 was installed on vertical torus to shoot light on a laser acceptor through the hole along the centerline of the OD. The laser acceptor was fixed on the vertical torus. The light will go through the magnet, the geometric center of the OD, the center of the vertical torus and the center of the laser acceptor. Thus, the angle of θ is highlighted by the shooting light and read by the operator of the equipment. Laser Pointer 2 is fixed at the bottom of the horizontal turntable and aligned with the diameter line of the turntable. The angle φ is obtained through this horizontal light shooting on a predefined point during a test. The two laser pointers are made of aluminum alloy and are charged by an external battery. Hence, the influence from the laser pointers on the magnetic field to be detected is negligible.

The bubble level made of plastic is placed on top of the horizontal turntable to ensure that it is indeed horizontal. The accuracy of the level bubble is 0.025° . The specially-designed tripod is made of carbon fiber that has no effect on the magnetic field to be measured. The connector between the tripod and the horizontal turntable is made for easy use during a large number of measurements in field conditions.

4.5. Experimental Validation

In this section, one smart rock with an APSS and another smart rock with an AOS were tested at the Gasconade River Bridge site to validate their localization algorithms. Specifically, all tests were conducted near a bridge pier on the river bank for easy operation. The application and validation of one or two smart rocks with an APUS will be discussed in Section 5.

4.5.1. Evaluation of k , B_A , θ and φ

The coefficient k of a magnet was first evaluated in an open field (Ber Juan Park, Rolla, MO) before the smart rocks were tested at the bridge site. For the APSS and AOS, $k = 42542 \text{ nT}\cdot\text{m}^3$ and $41890 \text{ nT}\cdot\text{m}^3$, respectively, as discussed in Section 3.3.3.

At the bridge site, the AMF lines are no longer in parallel due to the combined effect of the Earth and other ferromagnetic substances, such as reinforcement in bridge piers and deck. The AMF varies in space and can be uniquely defined by three parameters (B_A , θ and φ) at each measurement point. To evaluate these parameters, the AMFOD device was used to measure the angles θ and φ at each measurement point in addition to a magnetometer for field intensity measurement.

4.5.2. Test setup and procedure

All tests were conducted near the bridge pier as shown in Figure 4.6. The bridge foundation was surrounded by a small scour hole created during previous flood events. As shown in Figure 4.7, three locations of the APSS or AOS, designated by M1, M2 and M3 in Figure 4.7(a), were selected to take into account a combination of horizontal positions and depths in bridge scour monitoring. M1, M2, and M3 were well spaced in horizontal plane. M3 was placed in the scour hole. To locate the APSS or AOS, a total of 34 measurement points (Q_1 to Q_{34} , marked by 34 wooden and plastic poles during actual tests), were selected around M1, M2, and M3. The sensor head of a G858 Magnetometer was placed on top of each wooden or plastic pole to measure the ambient and total magnetic intensities for each magnet location. A total station was used to survey the

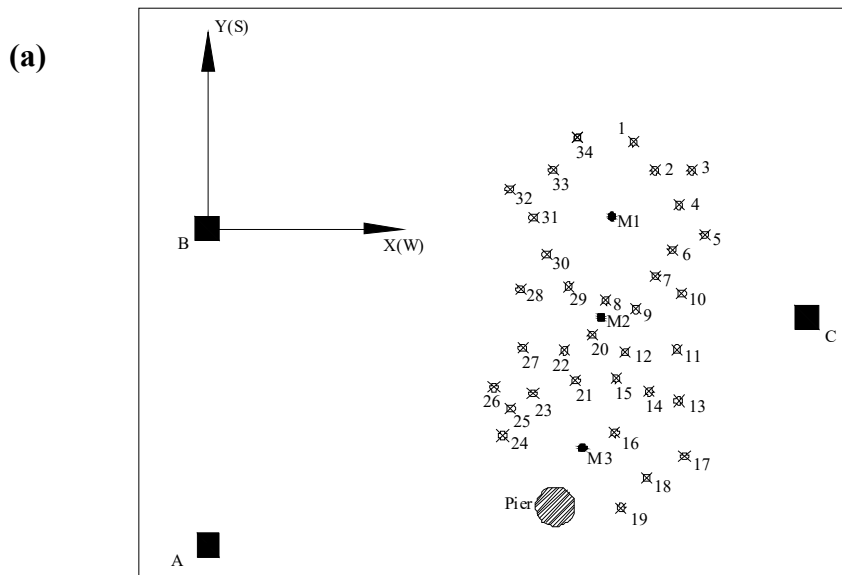
coordinates of three magnet's locations and 34 sensor positions as ground true data. A prism was placed at the same location of the sensor head on top of the wooden poles to ensure that the magnetic field intensity and the coordinates were collocated. In addition, the AMFOD device was set at the 34 points to measure the angles of θ and φ before the smart rocks were deployed at any location.



Figure 4.6. The bridge pier with a scour hole as a field test site.

A step-by-step test procedure was developed and implemented systematically at the bridge site. The seven steps involved in locating the APSS or AOS are detailed below:

(1) *Set the XYZ Coordinate System.* As shown in Figure 4.7(a), Point A marked by a wooden pole was first selected far away from the bridge pier to avoid potential measurement interference by ferromagnetic substances of the bridge pier. A high-precision military compass was then placed on the wooden pole to survey the geographical South direction. Next, Point B was selected on the extension line of the south direction to ensure that all of the measurement points were in the line of sight from Point B. Finally, Point B was selected as the origin of the XYZ Cartesian coordinate system with the Y-axis pointing South from Point A to B, the X-axis pointing West and the Z-axis perpendicular to the XOY plane as shown in Figure 4.7(a).



(b)

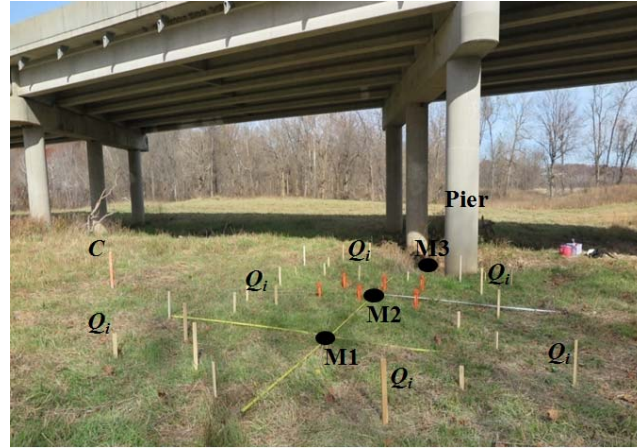


Figure 4.7. Test setup at the bridge site: (a) schematic view of smart rock and sensor locations in plane and (b) layout of smart rocks and sensor head.

(2) *Select the Locations of Smart Rocks and Sensor Head.* As shown in Figure 4.7(a, b), the smart rocks were located from far away to close to the bridge pier in order to understand the variation of the AMF, the angles, and the total magnetic field. Magnet locations, M1, M2 and M3, were marked on the ground for easy placement of smart rocks and convenient collection of their coordinates. The 34 wooden poles, Q_1 to Q_{34} , were distributed around M1, M2 and M3 and bounded between the circles with a diameter of 1.5 m and 5 m in order to avoid the dead zone of the magnetometer at each location of smart rocks. Three measurement tapes crossed at M1 and M2 were displayed to assist in the estimation of distance between a magnet and the sensor head.

(3) *Select a Calibration Point C for AMFOD Device.* A fixed object was needed to assist in the final determination of angle φ . As such, Point C marked by a tall wooden pole as indicated in Figure 4.7(a, b) was selected in addition to the 34 measurement points. The selection of Point C was to ensure that the light from the horizontal laser pointer 2 can reach the wooden pole at Point C when the AMFOD device was stationed at each sensor point.

(4) *Determine the Coordinates of Smart Rocks, Sensor Head and Calibration Point.* A total station was used to survey the coordinates of various points at the test site. Throughout the tests, one person operated the total station and another person held one prism as seen in Figure 4.8 to ensure that the coordinates were measured consistently. For each survey, the bottom center of the prism was aligned with the center of the top of the wooden pole and bottle caps since the magnetic field intensity is very sensitive to Z-coordinate.

(5) *Measure θ and φ .* As shown in Figure 4.9, the AMFOD device was placed at one measurement point by aligning the center of its tripod to the top center of the plastic pole, in which the center of the high-precision APSS should be kept along the extension line of the plastic pole by adjusting the tripod with the high precision bubble level attached on the horizontal disk of the AMFOD device. At each measurement point, the tripod was first adjusted horizontally without presence of the high-precision APSS. That is, after the horizontal Laser 2 was switched on, the tripod was rotated until the shooting light hit on the wooden pole at Point C and immediately locked at that position. The high-precision APSS was then put back to the tapered support. After the inside ball with a

magnet was automatically aligned to the AMF in several seconds, Laser 1 was switched on and its supporting ring was manually turned vertically, in combination with horizontal adjustment by the tunable disk, to make sure the light going through the hole at the center line of the high-precision APSS and hit on the center of the laser acceptor. Finally, the two lasers were switched off and the two angles θ and φ can be read from the digital marks on the vertical ring and horizontal disk, respectively. The above process was repeated for all 34 points.



Figure 4.8. Total station and prism for positioning.

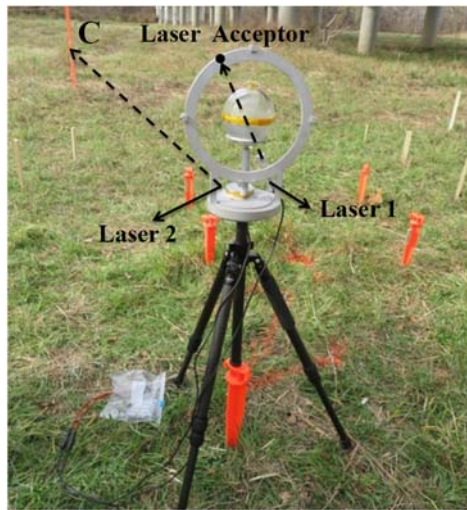


Figure 4.9. AMFOD setup and operational mechanism.

(6) *Measure the AMF Intensity.* One sensor head of the magnetometer was faced on the ground and ensured to be perpendicular to the ground by a bubble level attached onto the sensor head as shown in Figure 4.10. It was noted that a 57.7 cm wooden stick fastened onto the sensor head was to keep the center of the sensor head the same location at the center of the high-precision APSS in the AMFOD device so that the magnetometer and the AMFOD provided the corresponding magnitude and direction of an AMF vector.

In addition, measurements should be taken when there are no vehicles on the bridge deck to avoid any potential interference. At each point, at least three measurements were taken to ensure accuracy and repeatability.



Figure 4.10. Magnetometer setup and operation.

(7) *Measure the Total Magnetic Field Intensity of APSS at M1, M2 and M3.* The APSS smart rock was placed at each point M1, M2 or M3 as seen in the Figure 4.11. The center of the magnet was aligned with the center of the bottle cap at each point. The total magnetic field was generated by the magnet and the ambient magnetic field. The same setup of the magnetometer stated in Step (6) was applied and repeated to measure the total magnetic field intensity when the APSS was deployed at M1, M2 and M3, respectively.

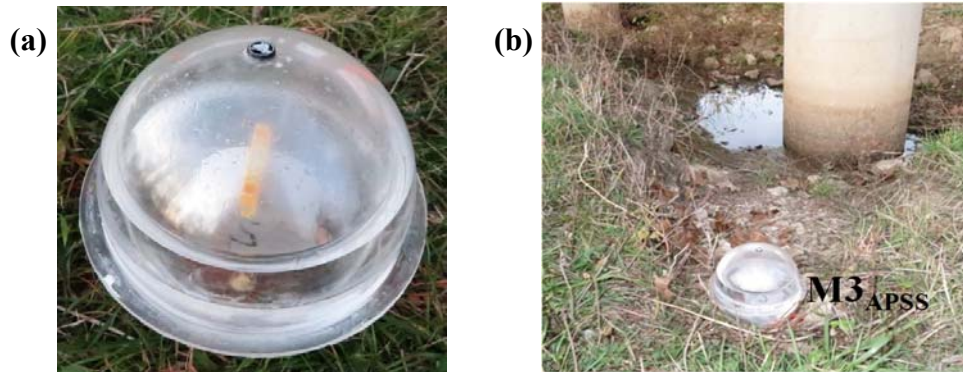


Figure 4.11. APSS deployment: (a) M1_{APSS} or M2_{APSS} and (b) M3_{APSS}.

(8) *Measure the Total Magnetic Field Intensity of AOS at M1, M2 and M3.* In this final step, the AOS was placed at point M1, M2 and M3 as shown in Figure 4.12. The center of the plastic box with the centered magnet was kept in alignment with the center of the bottle cap at each point. The same setup of the magnetometer stated in Step (6) was applied and repeated to measure the total magnetic field intensity for all the AOS at M1, M2 and M3.

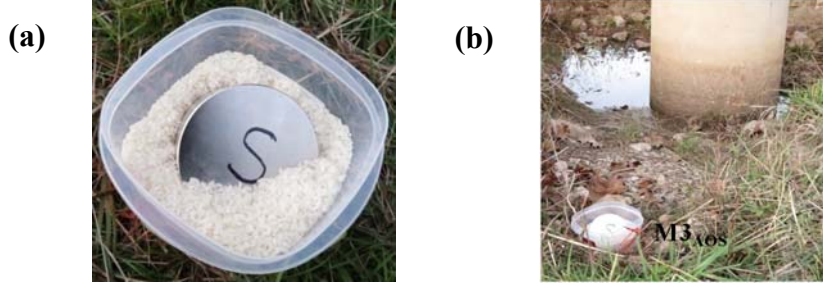


Figure 4.12. AOS deployment: (a) M1_{AOS} or M2_{AOS} and (b) M3_{AOS}.

4.6. Test Results and Discussion

In this section, the AMF intensity at each measurement point was calculated through geometrical calculations based on the collected data. The localization results of the AOS and APSS at three positions were evaluated and summarized.

4.6.1. AMF intensity in the XYZ coordinate system

The θ angle can be directly read from the digital marks on the vertical torus of the AMFOD device. However, the φ angle must be transformed from the directly measured angle φ' read from the digital marks on the horizontal turntable of the AMFOD device and the φ_0 angle from the test setup in the XYZ coordinate system. As shown in Figure 4.13, $\mathbf{B}_{Ai}^{Q_i}$ denotes the AMF vector at measurement point Q_i in XOY plane, Q_iC represents the light of Laser 2 shooting to the wooden pole at Point C, the local coordinate system xQ_iy is parallel to the global coordinate system of XOY, and φ' in $[0, \pi]$ is the angle spanned from the extension of vector $-\mathbf{B}_{Ai}^{Q_i}$ to the line Q_iC in counterclockwise direction. Therefore, the direction of the AMF φ in $[0, 2\pi]$ in XOY plane is equal to $\pi - \varphi' + \varphi_0$, where φ_0 in $[0, 2\pi]$ is equal to $\arctan[(Y_C - Y_{Q_i}) / (X_C - X_{Q_i})]$, representing the counterclockwise angle between line Q_iC and the X-axis.

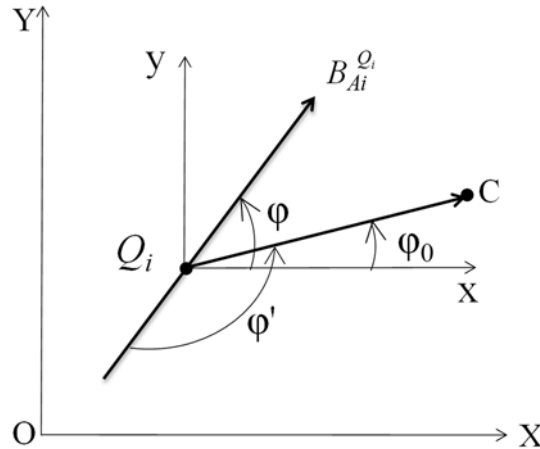


Figure 4.13. Angle adjustment.

Table 4.1 summarizes the coordinates of 34 sensor locations in the O-XYZ coordinate system, and the direction and intensity of the AMF vector at each measurement point. They will be used in the localization of smart rocks as follows.

Table 4.1. Sensor coordinates and ambient magnetic field intensities

Measurement Point	Sensor Coordinates (m)			AMF Direction (rad)		AMF Intensity (10^4 nT)			
	X_i	Y_i	Z_i	θ_i	φ_i	B_{Ai}	B_{AXi}	B_{AYi}	B_{AZi}
C	15.28	-2.26	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Q_1	10.88	2.20	-0.55	1.21	1.50	5.080	0.121	1.775	5.080
Q_2	11.43	1.48	-0.45	1.22	1.53	5.142	0.081	1.757	5.142
Q_3	12.37	1.48	-0.58	1.22	1.48	5.136	0.164	1.749	5.136
Q_4	12.04	0.59	-0.48	1.20	1.49	5.137	0.160	1.867	5.137
Q_5	12.70	-0.16	-0.51	1.20	1.51	5.130	0.110	1.877	5.130
Q_6	11.87	-0.54	-0.59	1.19	1.45	5.136	0.230	1.893	5.136
Q_7	11.45	-1.21	-0.61	1.18	1.29	5.147	0.539	1.895	5.147
Q_8	10.17	-1.84	-0.71	1.15	1.28	5.195	0.616	2.021	5.195
Q_9	10.94	-2.07	-0.72	1.14	1.37	5.179	0.425	2.105	5.179
Q_{10}	12.12	-1.66	-0.70	1.15	1.34	5.135	0.486	2.048	5.135
Q_{11}	11.99	-3.08	-0.62	1.13	1.42	5.169	0.324	2.177	5.169
Q_{12}	10.67	-3.16	-0.73	1.13	1.50	5.256	0.169	2.248	5.256
Q_{13}	12.03	-4.40	-0.80	1.13	1.36	5.205	0.478	2.189	5.205
Q_{14}	11.28	-4.17	-0.70	1.12	1.29	5.274	0.643	2.195	5.274
Q_{15}	10.44	-3.83	-0.70	1.11	1.38	5.337	0.455	2.321	5.337
Q_{16}	11.40	-5.22	-0.72	1.16	1.34	5.332	0.487	2.070	5.332
Q_{17}	12.19	-5.82	-0.54	1.14	1.31	5.240	0.571	2.114	5.240
Q_{18}	11.22	-6.36	-0.56	1.15	1.14	5.414	0.937	2.012	5.414
Q_{19}	10.57	-7.12	-0.60	1.16	1.13	5.592	0.959	2.043	5.592
Q_{20}	9.82	-2.72	-0.70	1.14	1.28	5.273	0.637	2.101	5.273
Q_{21}	9.41	-3.88	-0.81	1.13	1.29	5.462	0.662	2.256	5.462
Q_{22}	9.12	-3.12	-0.75	1.12	0.94	5.357	1.375	1.883	5.357
Q_{23}	8.31	-4.22	-0.56	1.11	1.33	5.565	0.585	2.387	5.565
Q_{24}	7.54	-5.29	-0.70	1.10	1.60	5.903	-0.075	2.661	5.903
Q_{25}	7.75	-4.59	-0.92	1.10	1.53	5.732	0.107	2.618	5.732
Q_{26}	7.32	-4.06	-0.79	1.13	1.41	5.530	0.381	2.341	5.530
Q_{27}	8.04	-3.05	-0.61	1.13	1.24	5.357	0.749	2.172	5.357
Q_{28}	7.99	-1.55	-0.69	1.14	1.33	5.205	0.521	2.095	5.205
Q_{29}	9.22	-1.48	-0.69	1.19	1.27	5.194	0.577	1.841	5.194
Q_{30}	8.65	-0.66	-0.79	1.19	1.30	5.160	0.516	1.854	5.160
Q_{31}	8.32	0.28	-0.76	1.16	1.43	5.136	0.296	2.035	5.136
Q_{32}	7.71	1.01	-0.63	1.14	1.46	5.133	0.237	2.123	5.133
Q_{33}	8.81	1.49	-0.72	1.14	1.51	5.133	0.126	2.125	5.133
Q_{34}	9.46	2.32	-0.44	1.16	1.41	5.142	0.326	2.016	5.142

4.6.2. AOS localization

Table 4.2 gives the measured coordinates (X, Y, Z) and the measured total magnetic field intensities ($B_{Ti}^{(M)}$) at 18 sensor points when the AOS is located at M1. The measured data were used to determine the predicted location of M1, which was compared with the ground truth data. Table 4.3 and Table 4.4 provide similar results when the AOS is located at M2 and M3, respectively. Overall, it can be observed from the test results at

M1, M2, and M3 that the SRSS prediction error ranges from 9.3 cm to 15.4 cm, which is quite small in comparison with the diameter of smart rocks (approximately 30 cm).

Table 4.2. Predicted and measured location of the AOS: M1_{AOS}

Location of Sensor Head	X_i (m)	Y_i (m)	Z_i (m)	$B_{Ti}^{(M)}$ (10^4 nT)
Q_1	10.88	2.20	-0.52	5.356
Q_2	11.43	1.48	-0.42	5.277
Q_3	12.37	1.48	-0.55	4.975
Q_4	12.04	0.59	-0.45	4.790
Q_5	12.70	-0.16	-0.48	4.890
Q_6	11.87	-0.54	-0.56	4.590
Q_7	11.45	-1.21	-0.58	4.686
Q_8	10.17	-1.84	-0.68	4.863
Q_9	10.94	-2.07	-0.69	4.967
Q_{10}	12.12	-1.66	-0.67	4.957
Q_{20}	9.82	-2.72	-0.67	5.154
Q_{28}	7.99	-1.55	-0.66	5.061
Q_{29}	9.22	-1.48	-0.66	4.815
Q_{30}	8.65	-0.66	-0.76	4.770
Q_{31}	8.32	0.28	-0.73	5.050
Q_{32}	7.71	1.01	-0.60	5.134
Q_{33}	8.81	1.49	-0.69	5.491
Q_{34}	9.46	2.32	-0.41	5.454
Predicted AOS Location	10.26	0.24	-1.46	
Measured AOS Location	10.33	0.30	-1.42	N/A
Component Location Error	-0.06	-0.07	-0.03	
Total SRSS Error				0.10 m

Table 4.3. Predicted and measured location of the AOS: M2_{AOS}

Location of Sensor Head	X_i (m)	Y_i (m)	Z_i (m)	$B_{Ti}^{(M)}$ (10^4 nT)
Q_4	12.04	0.59	-0.45	5.158
Q_5	12.70	-0.16	-0.48	5.104
Q_6	11.87	-0.54	-0.56	5.135
Q_7	11.45	-1.21	-0.58	5.129
Q_{10}	12.12	-1.66	-0.67	4.882
Q_{11}	11.99	-3.08	-0.59	4.817
Q_{13}	12.03	-4.40	-0.77	5.137
Q_{14}	11.28	-4.17	-0.67	5.116

Table 4.3. Predicted and measured location of the AOS: M2_{AOS} (Cont'd)

Location of Sensor Head	X_i (m)	Y_i (m)	Z_i (m)	$B_{Ti}^{(M)}$ (10^4 nT)
Q_{15}	10.44	-3.83	-0.67	4.926
Q_{16}	11.40	-5.22	-0.69	5.306
Q_{21}	9.41	-3.88	-0.78	5.112
Q_{23}	8.31	-4.22	-0.53	5.425
Q_{25}	7.75	-4.59	-0.89	5.654
Q_{26}	7.32	-4.06	-0.76	5.445
Q_{27}	8.04	-3.05	-0.58	5.178
Q_{28}	7.99	-1.55	-0.66	5.371
Q_{30}	8.65	-0.66	-0.76	5.635
Q_{31}	8.32	0.28	-0.73	5.284
Predicted AOS Location	9.93	-2.21	-1.56	
Measured AOS Location	10.05	-2.28	-1.48	N/A
Component Location Error	-0.12	0.06	-0.08	
Total SRSS Error				0.15 m

Table 4.4. Predicted and measured location of the AOS: M3_{AOS}

Location of Sensor Head	X_i (m)	Y_i (m)	Z_i (m)	$B_{Ti}^{(M)}$ (10^4 nT)
Q_9	10.94	-2.07	-0.67	5.265
Q_{12}	10.67	-3.16	-0.68	5.466
Q_{13}	12.03	-4.40	-0.75	5.210
Q_{14}	11.28	-4.17	-0.65	5.381
Q_{15}	10.44	-3.83	-0.65	5.715
Q_{17}	12.19	-5.82	-0.49	5.139
Q_{18}	11.22	-6.36	-0.51	5.075
Q_{19}	10.57	-7.12	-0.55	5.299
Q_{20}	9.82	-2.72	-0.65	5.493
Q_{21}	9.41	-3.88	-0.76	6.251
Q_{23}	8.31	-4.22	-0.51	5.936
Q_{25}	7.75	-4.59	-0.87	5.952
Q_{26}	7.32	-4.06	-0.74	5.664
Q_{27}	8.04	-3.05	-0.56	5.540
Predicted AOS Location	9.51	-5.52	-1.86	
Measured AOS Location	9.58	-5.58	-1.84	NA
Component Location Error	-0.06	0.06	-0.02	
Total SRSS Error				0.09 m

4.6.3. APSS localization

Table 4.5 gives the measured coordinate (X, Y, Z) and the total magnetic field intensity ($B_{Ti}^{(M)}$) at 18 sensor points when the APSS is located at M1, which was compared with the predicted location using the measured coordinates of sensor points. Table 4.6 and Table 4.7 provide similar results when the APSS is located at M2 and M3. Similar to the AOS case, the prediction location error of the magnet ranges from 8.5 cm to 18 cm. Once again, this range of errors is small compared with the size of smart rocks, demonstrating satisfactory accuracy in smart rock localization for bridge scour monitoring.

Table 4.5. Predicted and measured location of the APSS: M1_{APSS}

Location of Sensor Head	X_i (m)	Y_i (m)	Z_i (m)	$B_{Ti}^{(M)}$ (10^4 nT)
Q_1	10.88	2.20	-0.52	5.812
Q_2	11.43	1.48	-0.42	5.695
Q_3	12.37	1.48	-0.55	5.181
Q_4	12.04	0.59	-0.45	4.972
Q_5	12.70	-0.16	-0.48	4.989
Q_6	11.87	-0.54	-0.56	4.797
Q_7	11.45	-1.21	-0.58	4.973
Q_8	10.17	-1.84	-0.68	5.213
Q_9	10.94	-2.07	-0.69	5.206
Q_{10}	12.12	-1.66	-0.67	5.094
Q_{20}	9.82	-2.72	-0.67	5.300
Q_{28}	7.99	-1.55	-0.66	5.146
Q_{29}	9.22	-1.48	-0.66	5.103
Q_{30}	8.65	-0.66	-0.76	4.891
Q_{31}	8.32	0.28	-0.73	4.949
Q_{32}	7.71	1.01	-0.60	5.119
Q_{33}	8.81	1.49	-0.69	5.524
Q_{34}	9.46	2.32	-0.41	5.642
Predicted APSS Location	10.25	0.45	-1.35	
Measured APSS Location	10.33	0.30	-1.41	NA
Component Location Error	-0.08	0.15	0.06	
Total SRSS Error				0.18 m

Table 4.6. Predicted and measured location of the APSS: M2_{APSS}

Location of Sensor Head	X_i (m)	Y_i (m)	Z_i (m)	$B_{Ti}^{(M)}$ (10^4 nT)
Q_4	12.04	0.59	-0.45	5.218
Q_5	12.70	-0.16	-0.48	5.173
Q_6	11.87	-0.54	-0.56	5.289
Q_7	11.45	-1.21	-0.58	5.485
Q_{10}	12.12	-1.66	-0.67	5.097
Q_{11}	11.99	-3.08	-0.59	4.924
Q_{13}	12.03	-4.40	-0.77	5.171
Q_{14}	11.28	-4.17	-0.67	5.188
Q_{15}	10.44	-3.83	-0.67	5.137
Q_{16}	11.40	-5.22	-0.69	5.332
Q_{21}	9.41	-3.88	-0.78	5.382
Q_{23}	8.31	-4.22	-0.53	5.475
Q_{25}	7.75	-4.59	-0.89	5.707
Q_{26}	7.32	-4.06	-0.76	5.473
Q_{27}	8.04	-3.05	-0.58	5.134
Q_{28}	7.99	-1.55	-0.66	5.233
Q_{30}	8.65	-0.66	-0.76	5.535
Q_{31}	8.32	0.28	-0.73	5.277
Predicted APSS Location	9.96	-2.20	-1.43	
Measured APSS Location	10.05	-2.28	-1.47	NA
Component Location Error	-0.09	0.08	0.04	
Total SRSS Error				0.13 m

Table 4.7. Predicted and measured location of the APSS: M3_{APSS}

Location of Sensor Head	X_i (m)	Y_i (m)	Z_i (m)	$B_{Ti}^{(M)}$ (10^4 nT)
Q_9	10.94	-2.07	-0.66	5.277
Q_{11}	11.99	-3.08	-0.56	5.242
Q_{12}	10.67	-3.16	-0.67	5.520
Q_{13}	12.03	-4.40	-0.74	5.253
Q_{14}	11.28	-4.17	-0.64	5.493
Q_{15}	10.44	-3.83	-0.64	5.879
Q_{16}	11.40	-5.22	-0.66	5.311
Q_{17}	12.19	-5.82	-0.48	5.161
Q_{18}	11.22	-6.36	-0.50	5.117
Q_{19}	10.57	-7.12	-0.54	5.245

Table 4.7. Predicted and measured location of the APSS: M3_{APSS} (Cont'd)

Location of Sensor Head	X_i (m)	Y_i (m)	Z_i (m)	$B_{Ti}^{(M)}$ (10^4 nT)
Q_{20}	9.82	-2.72	-0.64	5.516
Q_{21}	9.41	-3.88	-0.75	6.373
Q_{23}	8.31	-4.22	-0.50	5.920
Q_{25}	7.75	-4.59	-0.86	5.835
Q_{26}	7.32	-4.06	-0.73	5.609
P_{27}	8.04	-3.05	-0.55	5.520
Predicted APSS Location	9.53	-5.52	-1.85	
Measured APSS Location	9.58	-5.58	-1.82	N/A
Component Location Error	-0.05	0.06	-0.03	
Total SRSS Error				0.08 m

4.7. Summary

In this section, the localization algorithms for a single smart rock with an AOS, APSS and APUS, respectively, and the localization algorithm for two smart rocks with an APUS each were developed through a minimization of the SRSS error in the prediction of smart rock location(s). The algorithms for a single AOS or APSS smart rock were validated when the AOS and APSS were deployed at the bridge site of US Highway 63 over the Gasconade River. The algorithms for a single APUS smart rock or two APUS smart rocks will be validated at three bridge sites in Section 5.

The total magnetic field consists of the magnetic field generated by a permanent magnet inside the smart rock, the Earth and any other ferromagnetic substances such as the steel reinforcement in bridge piers and deck. The mathematic model of the magnetic field for the magnet is known. However, the distribution of the combined Earth and other ferromagnetic substances referred as the non-uniform ambient magnetic field is unknown. Therefore, a custom-built device named AMFOD was developed and prototyped to detect the orientation and a G858 magnetometer was used to measure the intensity of the ambient magnetic field.

The experimental field test at the bridge site of US Highway 63 over the Gasconade River was designed and carried out to demonstrate the localization procedure and validate the localization algorithm for the AOS and APSS. The results showed that the localization errors were small compared to the size of smart rocks and the achieved accuracy for smart rock localization satisfactorily met the design requirements. The known orientation of the APSS made the localization process and procedure greatly simplified, thus a better choice than the AOS in practical applications.

5. FIELD IMPLEMENTATION OF SMART ROCKS AT THREE BRIDGE SITES

In this section, the smart rock technology proposed and developed in Sections 2-4 is further validated at three bridge sites for the measurement of scour depth and for the detection of rip-rap effectiveness. The three bridge sites tested are Highway 1 over the Waddell Creek (Br. No. 36-0065) in California, I-44W Highway over the Roubidoux Creek (Br. No. L0093) and US Highway 63 over the Gasconade River (Br. No. A3760) in Missouri.

In Section 4, the localization algorithms were validated with field measurements from a river bank. The three components of the AMF due to the effect of the Earth and bridge pier/deck were obtained at all measurement points from the specially-designed AMFOD device. However, it is impractical to use the AMFOD device from the river bank as it is submerged under water during a flood event. In this section, all measurements are taken from the bridge deck. To generate strong magnetic fields in vertical direction, the smart rocks with an APUS each, designed in Section 2 for the three bridge sites, are deployed around scour critical piers. Furthermore, a test crane that can be installed on a truck and moves on the bridge deck is designed and manufactured to support the magnetometer sensor above water for measurements as close to the deployed smart rocks as possible.

5.1. 3-axis Flux Magnetometer and Test Apparatus

The three components of the AMF and the total magnetic field are measured with a newly-acquired digital 3-axis magnetometer instead of the G858 magnetometer and the AMFOD device used in Section 4. A direct measurement of the three components of a magnetic field with the new magnetometer increases the operation efficiency and the accuracy of localization in bridge applications. The magnetic field intensity can also be graphically viewed on a computer screen with the special software to go with the new magnetometer. This capability allows a real time check on the quality of measured data during tests at bridge sites.

5.1.1. The 3-axis flux magnetometer

A digital 3-axis magnetometer system as shown in Figure 5.1, manufactured by STL Systemtechnik Ludwig GmbH in Konstanz, Germany, was used for this study. It is composed of a digital sensor DM050, a three-channel coax Ethernet hub, a 50 m coax cable for power and data transmission, and a notebook with STL GradMag software installed for full control of measurement, data acquisition and graphical display. The DM050 is a precision magnetometer with 0.002 nT resolution, less than 0.06 nT/√Hz noise and a field range of ±1 mT. It measures three orthogonal field components at a maximum sample rate of 10 kHz. The software also offers the total field as an additional virtual channel. Typical sources of errors due to axis misalignment, scaling, offset and phase are eliminated to the greatest extent possible with a digital signal conditioning strategy. The software offers full control over all system features and real-time monitoring of data and data documentation greatly improves the efficiency of field data analysis and display.

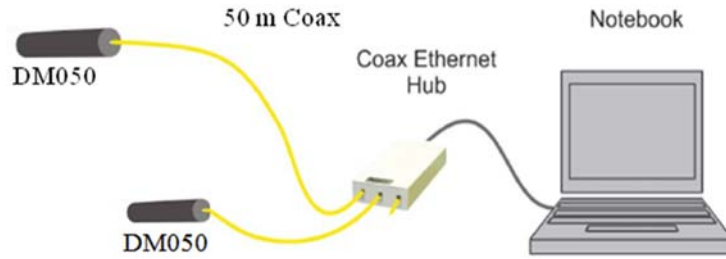


Figure 5.1. The STL digital 3-axis flux magnetometer system.

5.1.2. The lightweight test crane

In the design of a new frame to facilitate field tests, the following factors were taken into account: stiffness, lightweight, ease in installation, rapid assembling, and cost effectiveness. The frame must be sufficiently stiff to minimize the wind-induced disturbance on measurement during field tests. As shown in Figure 5.2, the frame mainly consists of four components: 1 to 4. Comp.1 is a lower horizontal bar that supports a sensor head for the measurement of magnetic field intensities and two non-magnetic prisms for the coordinate determination of a sensor head. Comp. 2 is a vertical rod that allows proper access to the measurement points as close to the water surface as possible in field application. Comp. 3 is an upper horizontal bar that functions as an outrigger to support the vertical rod. Comp. 4 is a forklift that, once installed on a trailer, allows three directional movements of the sensor head. Finally, Comp. 5 represents balanced weights as needed.

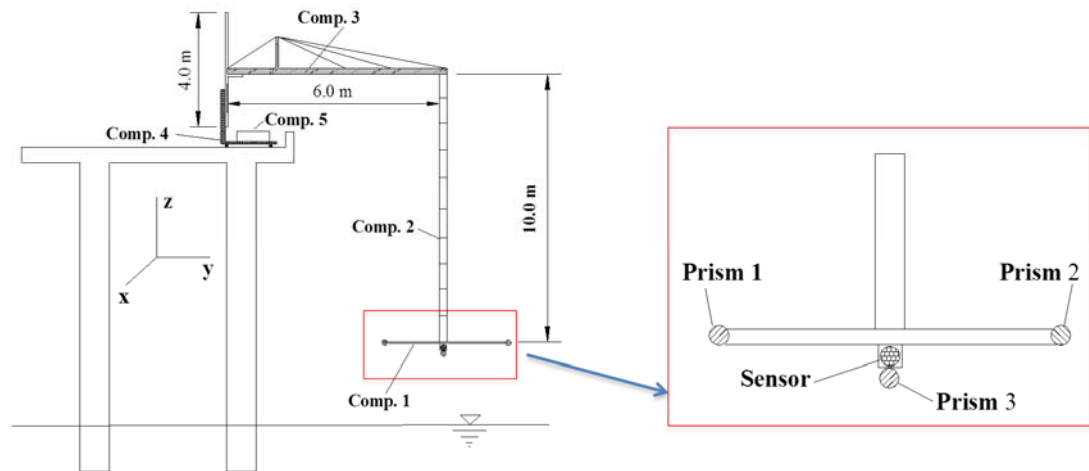


Figure 5.2. Schematic view of a test crane.

Comp.1 is made of carbon fiber that has a low density of 1800 kg/m^3 and a high modulus of elasticity of 240 GPa compared to other non-magnetic materials. Comp. 2 is made of modular carbon fiber tubes (1 m in length) that are designed to minimize flexural deformation and resist potential vibration caused by the wind load. The standard tubes can be connected to any required length in field application. Comp. 3 is made of aluminum alloy with a density of $2700\text{-}2810 \text{ kg/m}^3$ and a modulus of elasticity of 71 GPa . A balanced weight is applied as needed to ensure that Comp.3 remains horizontal during tests. All the components can be rapidly assembled at a test site. The forklift can

be installed on a trailer and pulled by a truck. It is operated manually in this study but could be automatically controlled as needed from a remote site in the future. The test crane is most appropriate for a bridge deck that is less than 10 m above water. The outrigger can laterally extend up to 5 m from the bridge deck. The forklift allows a vertical movement of up to 4 m. The test crane can move any distance as needed along the traffic direction.

5.2. I-44W Roubidoux Creek Bridge, MO

The I-44W Roubidoux Creek Bridge (No. L0039) in Waynesville, MO, was used as the first test site to validate the performance of a smart rock. The bridge is a ten-span, steel-girder structure to support two lanes of westbound traffic on Interstate 44. As shown in Figure 5.3, Pier 7 is located in the main flow of the channel. The downstream side of Pier 7 is scour critical. Three series of field tests were carried out in different seasons to validate the localization algorithm and understand the accumulated movement of a smart rock between flood events or during normal water flow.

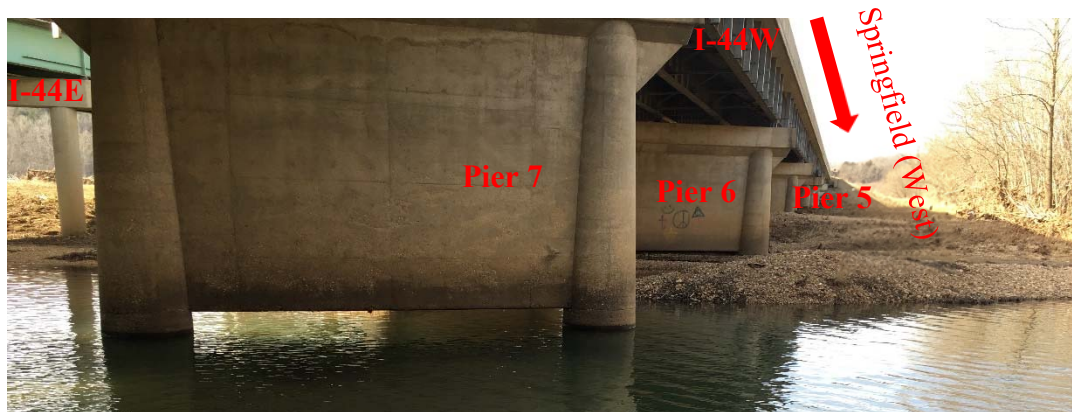


Figure 5.3. The overview of I-44W Roubidoux Creek Bridge.

5.2.1. Test setup and layout

As shown in Figure 5.4(a, b), the test crane and the magnetic field measurement system are set up on the bridge shoulder near Bent 7. A total station was set on ground near Bent 8 to survey the smart rock and the magnetometer sensor head as ground true coordinate data. Its position was used as the origin of a Cartesian coordinate system O-XYZ with X-, Y-, and Z-axes oriented in transverse, longitudinal (traffic direction), and vertical (upward) directions, respectively, following the right-hand rule. The smart rock, SR1, was deployed around Pier 7. The test crane was fixed on a flatbed trailer towed by a truck. The magnetometer sensor mounted on the test crane was extended down from the bridge deck to measure the total magnetic field near the smart rock. Prism 3 mounted below the sensor as shown in Figure 5.4(d) was used to represent the coordinate of each measurement point. Prisms 1 and 2 were fixed at two ends of the horizontal bar of the test crane to ensure that the bar was in parallel with the X axis. The measurement points in XOY plane were selected as the cross points in Mesh 1 as shown in Figure 5.4(a). They were translated into the corresponding forklift locations on the bridge deck as illustrated in Figure 5.4(c). Through the test crane, the longitudinal, transverse and vertical positions

of the measurement points corresponded to Stop (S1-S3) and Path (P1 and P2) of the trailer on the bridge deck as well as Elevation (E1-E7). Therefore, each truck stop and forklift elevation is uniquely defined by a designation of SrPsEt where r, s, and t are three integers. For each SrPsEt, the coordinate of the magnetometer sensor and the magnetic field were measured simultaneously.

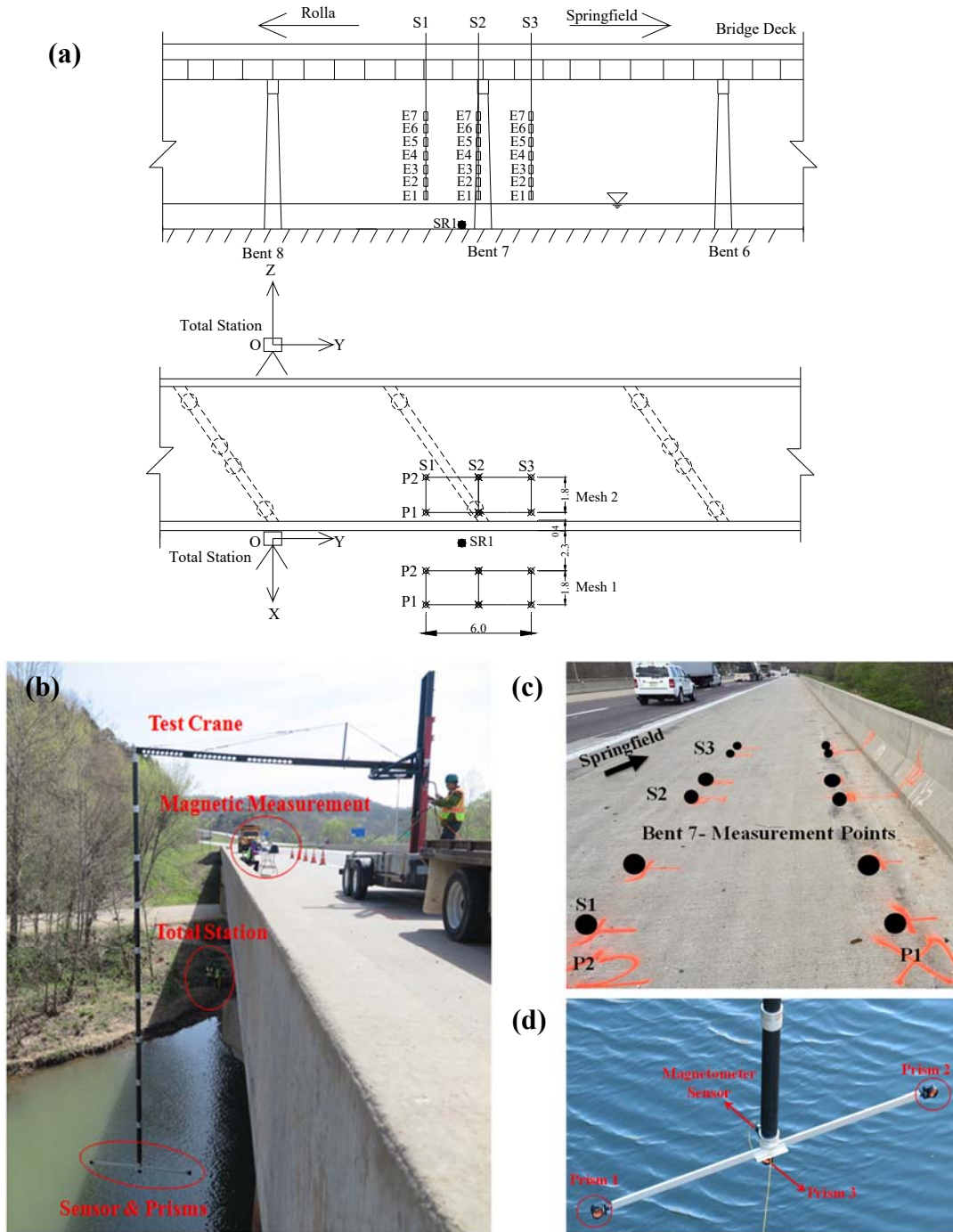


Figure 5.4. I-44W Roubidoux Creek bridge: (a) planning (unit: m), (b) test setup, (c) forklift positions, and (d) sensor and prisms locations.

5.2.2. Test procedure

Three series of field tests were conducted following the same procedure in eight steps. Each step is described in detail below.

(1) *Set the O-XYZ coordinate system.* As shown in Figure 5.5, a total station was set up near Bent 8 for its line of sight to the magnetometer sensor. The center of the total station, Point O, is designated as the origin of the coordinate system. The Y-axis was selected to be the longitudinal (traffic) direction of the straight bridge deck, pointing to Springfield, MO. The X-axis is perpendicular to the Y-axis, pointing to downstream in the horizontal plane. The Z-axis is pointing up. A permanent point A (Benchmark) on Pier 9 was surveyed during each of three series of field tests for cross reference between any two series.

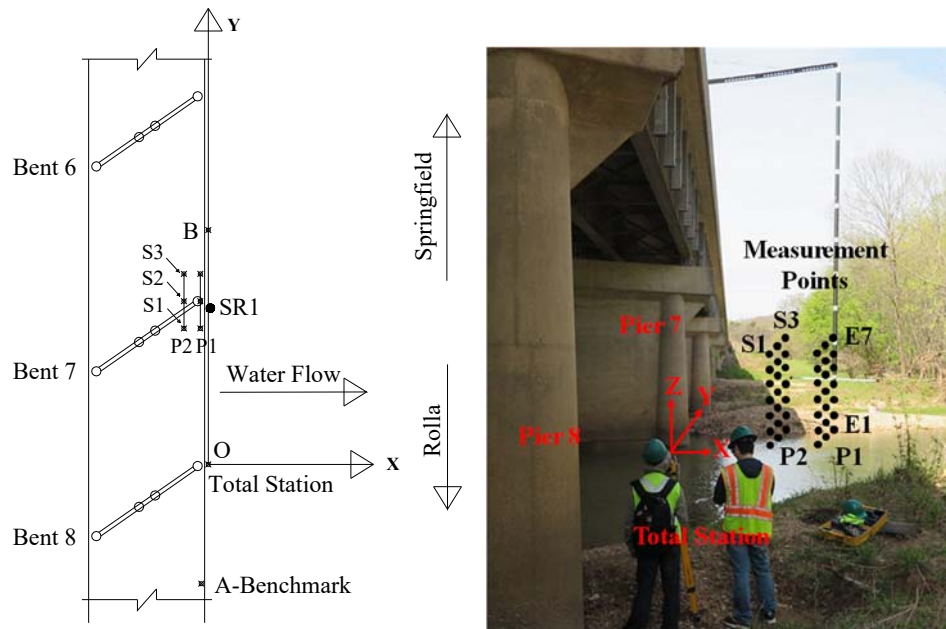


Figure 5.5. Selection of the Cartesian coordinate system.

(2) *Assemble the test crane.* As shown in Figures 5.4(b), the forklift was first set and tied to a flatbed trailer. The horizontal aluminum arm was then attached to the forklift. Next, nine carbon fiber tubes with 1.0 m each were attached to the aluminum arm one by one. Finally, the horizontal bar was connected at the bottom carbon tube.

(3) *Set up the STL digital magnetometer.* As shown in Figure 5.4(b), the magnetometer sensor for magnetic field measurement and three prisms for coordinate measurement were attached to the lower bar. The sensor was connected to a laptop computer with an Ethernet cable via an interface called mini Ethernet box. The laptop computer includes special software for sensor control and measurement. The sensor and the computer were charged by two batteries, respectively.

(4) *Measure the AMF.* The AMF is generated by the Earth and nearby ferromagnetic objects. It was measured prior to the deployment of a smart rock during the first field test. As indicated in Figure 5.4(a, b, d), the trailer ran two paths (X coordinates) on the bridge deck and three stops (Y coordinates). At each stop, seven elevations (Z

coordinates) were selected by moving up and down the horizontal aluminum arm of the test crane by 0.3 m. Figure 5.5(b) illustrates all the measurement points in space. Figure 5.6 (a) illustrates one stop when the two rear tires of the trailer were parked at the marked location and the forklift was positioned at P2S3. At each stop, measurements (both coordinate and magnetic field intensity) were taken at seven elevations in Z direction. Therefore, a total of 42 measurements were taken following the measurement sequence as indicated in Figure 5.6(b).

(5) *Deploy or inspect the smart rock and measure its coordinate.* During the first series of field tests, a smart rock (SR1) with two stacked N42 magnets in the APUS configuration as shown in Figure 5.7 was deployed around the downstream side of Pier 7 as indicated in Figure 5.8(a). The smart rock was transported in a boat from the river bank and deployed at the predetermined site as shown in Figure 5.8(b). The smart rock can be observed near Pier 7 with a connection rope floated on the water surface.

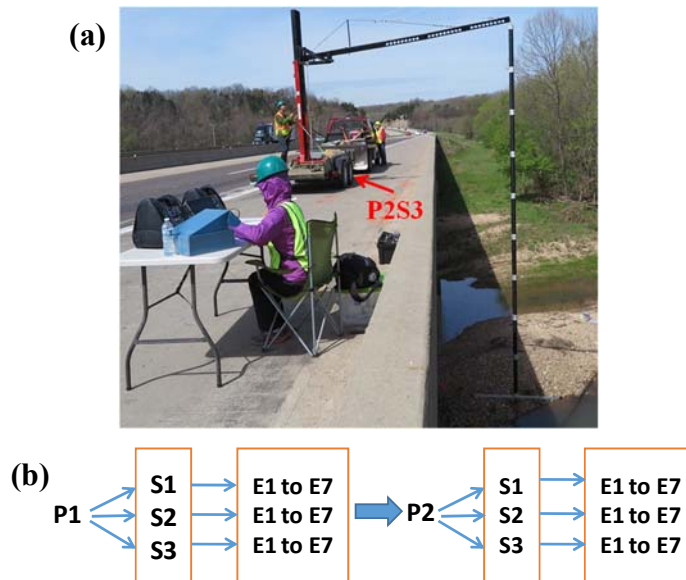


Figure 5.6. A snapshot of field measurement: (a) test crane located at P2S3 and (b) measurement point sequence.

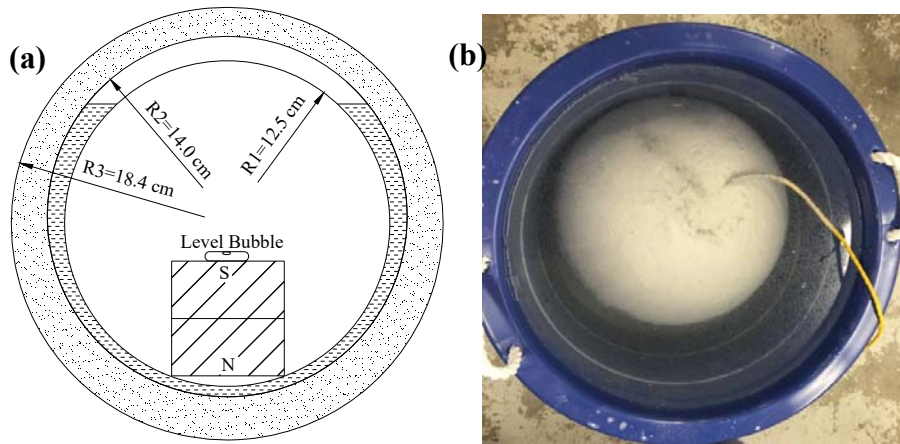


Figure 5.7. The APUS: (a) schematic view and (b) cast in smart rock.

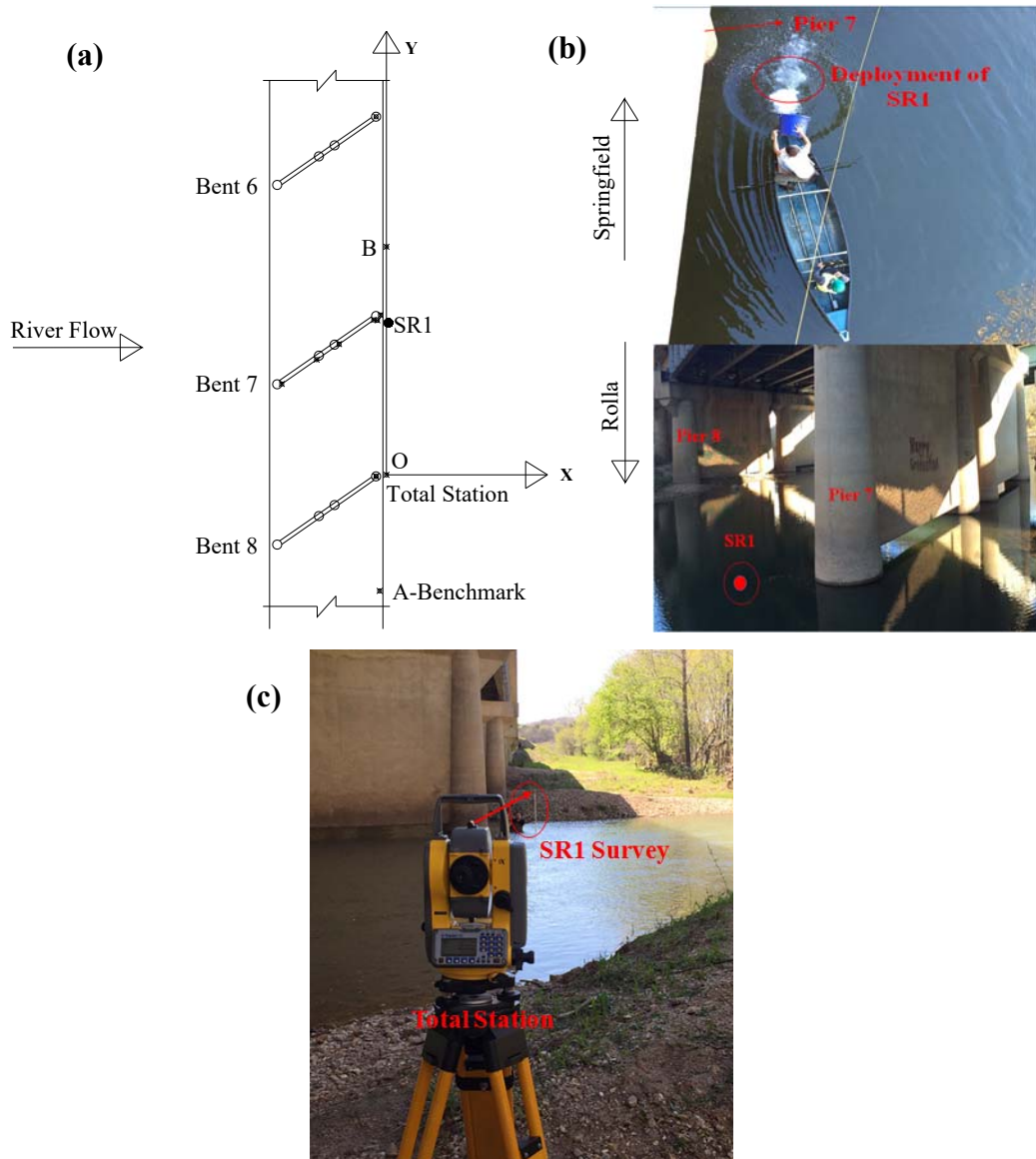


Figure 5.8. Application of smart rock SR1: (a) location, (b) deployment, and (c) survey.

During the second series of field tests, the smart rock, SR1, was inspected to ensure that it was rolled to the bottom of the scour hole around Pier 7. Indeed, it was found to have slightly moved from the original position when deployed during the first series of field tests.

During the third series of field tests, the smart rock, SR1, continued to be inspected to ensure that it remained in the scour hole around Pier 7. It was found to have slightly moved back to the original position during the first series of field tests.

As illustrated in Figure 5.8(c), the coordinates of the smart rock during all three series of field tests were measured with a total station through the prism placed on top of the smart rock. These measured coordinates served as ground truth data in smart rock localization and validation.

(6) *Measure the total magnetic field.* After the deployment of the smart rock

during the first series of field tests, the total magnetic field combining the effects of the smart rock and the AMF was measured following the same procedure as used for the AMF measurement. During the second and third series of field tests, the total magnetic field was measured at 42 points around Pier 7 with the same measurement sequence as shown in Figure 5.6(b).

(7) *Measure the time-varying AMF for reference.* The Earth's magnetic field and the magnetization of nearby ferromagnetic substances may change over time. To take this factor into account in the localization process of the smart rock, the time-varying property of the AMF was characterized. Bent 5 is over 60 m away from Bent 7 and its surrounding magnetic field is not affected by the presence of the smart rock. Thus, Pier 5 (identical to Pier 7) was selected as a reference site for a study of potential change of the AMF over time. One permanent point, P_5 represented by $(-1.02, 85.22, 0.44)$ coordinates, was marked on Pier 5 as a reference for other nearby measurement points. To further separate the Earth's and others' magnetic fields, six measurement points, P_{5-1} , P_{5-2} , P_{5-3} , P_{5-4} , P_{5-5} , and P_{5-6} , were selected at the top of orange markers as shown in Figure 5.9. The magnitude of the AMF for each point was measured by a scalar magnetometer G858. Note that Point P_{5-6} represented by $(15.43, 88.55, 0.53)$ coordinates is far away from Pier 5 and its magnetic field is not affected by the presence of Pier 5. It was selected during the first series of field tests as a reference location for the Earth magnetic field intensity since the magnetic field intensities within 1 m of Point P_{5-6} changed little. These measurements indicated little influence from the bridge pier or deck. Therefore, the measurement at Point P_{5-6} represents the Earth's magnetic field only. Continuing measurements at Point P_{5-6} shed light on any potential change of the Earth magnetic field between various field visits.

(8) *Map the riverbed profile.* The 999ci HD KVD SI Combo/900 Series - Side sonar imaging instrument from Humminbird™ Sonar as shown in Figure 5.10(a) was used to map the riverbed profile in the studied area. The transmission and reflection of acoustic wave were used to complete the HD side and down imaging. The side imaging can pick up any structures, timbers, wrecks, falling logs and fishes in the covered underwater area. The included GPS chart plotting with built-in Humminbird ContourXD map and Ethernet networking capabilities provides the altitude and latitude coordinates corresponding to each mapping.

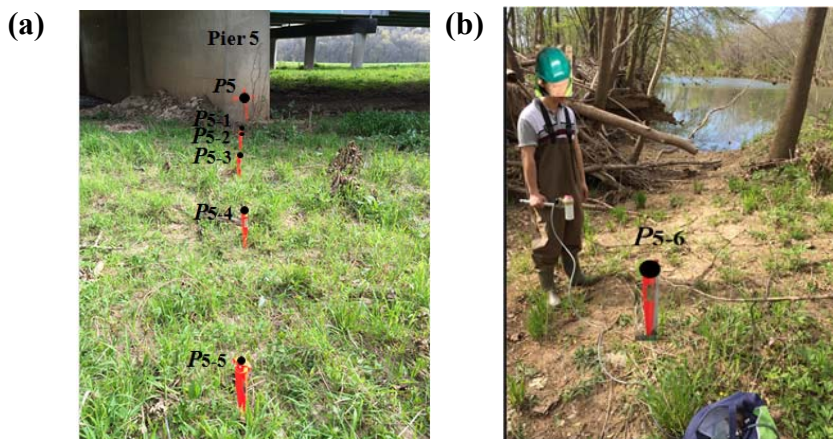


Figure 5.9. Time-varying ambient magnetic field measurement near Pier 5.

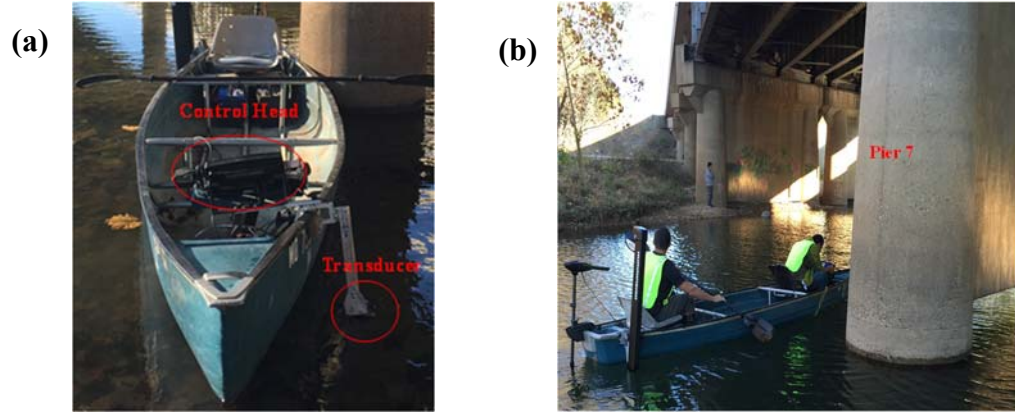


Figure 5.10. Sonar installed on a boat for riverbed profiling: (a) setup and (b) operation.

As shown in Figure 5.10(a), the sonar transducer was fixed on one side of the boat and adjusted to ensure it was below the boat. The control head of the sonar connected to the transducer was operated to map the riverbed profile and the location of the smart rock. Along the water flow, the boat first passed as close to the studied pier as possible, as shown in Figure 5.10(b), to collect clear information about the pier, and then made additional parallel runs gradually moving far away from the pier to map the riverbed.

5.2.3. Test results and discussion

To date, three series of field tests have been completed at this bridge site. Both rock positioning accuracy and movement trend are discussed below.

5.2.3.1 First series of field tests

The first series of tests were carried out on November 6, 2015. Table 5.1 summarizes the coordinates of 42 measurement points, the AMF intensities prior to smart rock deployment, and the total intensities after deployment of the smart rock SR1. The coefficient $k = 86521 \text{ nT.m}^3$ for two stacked N42 magnets was calculated from the maximum residual flux density. The three components of the magnetic field were measured using the 3-axis digital magnetometer sensor oriented in parallel with the X-, Y-, and Z-axis.

Table 5.1. Coordinates and intensities from the first series of field tests

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			Total Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{AX}^{(M)}$	$B_{AY}^{(M)}$	$B_{AZ}^{(M)}$	$B_T^{(M)}$	
E1	3.85	21.79	-1.00	2.278	0.102	-4.891	5.322	
E2	3.82	21.61	-0.70	2.241	0.174	-4.900	5.335	
E3	3.81	21.63	-0.41	2.242	0.223	-4.895	5.345	
S1P1	E4	3.81	21.67	-0.12	2.244	0.237	-4.891	5.354
	E5	3.79	21.56	0.19	2.241	0.232	-4.891	5.362
	E6	3.79	21.51	0.49	2.287	0.335	-4.867	5.369
	E7	3.83	21.55	0.80	2.263	0.240	-4.878	5.370

Table 5.1. Coordinates and intensities from the first series of field tests (Cont'd)

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			Total Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{AX}^{(M)}$	$B_{AY}^{(M)}$	$B_{AZ}^{(M)}$	$B_T^{(M)}$	
S1P2	E1	2.07	21.87	-0.99	2.278	0.167	-4.893	5.327
	E2	2.06	21.78	-0.72	2.278	0.167	-4.893	5.372
	E3	2.06	21.81	-0.40	2.246	0.280	-4.911	5.407
	E4	2.00	21.67	-0.10	2.245	0.286	-4.918	5.437
	E5	2.07	21.70	0.19	2.240	0.271	-4.929	5.458
	E6	2.08	21.63	0.47	2.246	0.293	-4.938	5.470
	E7	2.08	21.61	0.78	2.250	0.324	-4.948	5.490
S2P1	E1	3.84	24.51	-1.00	2.247	0.216	-4.873	5.288
	E2	3.83	24.50	-0.74	2.256	0.248	-4.861	5.296
	E3	3.81	24.42	-0.39	2.241	0.254	-4.862	5.307
	E4	3.79	24.32	-0.11	2.288	0.279	-4.835	5.318
	E5	3.80	24.39	0.18	2.237	0.280	-4.855	5.327
	E6	3.80	24.37	0.47	2.248	0.271	-4.848	5.334
	E7	3.79	24.29	0.78	2.235	0.279	-4.851	5.342
S2P2	E1	2.07	24.57	-1.00	2.295	0.441	-4.798	5.258
	E2	2.01	24.45	-0.71	2.285	0.493	-4.785	5.323
	E3	2.04	24.49	-0.40	2.268	0.568	-4.781	5.359
	E4	2.04	24.48	-0.11	2.233	0.524	-4.819	5.387
	E5	2.03	24.40	0.19	2.233	0.496	-4.837	5.417
	E6	1.96	24.20	0.50	2.224	0.519	-4.856	5.438
	E7	2.08	24.30	0.80	2.230	0.555	-4.866	5.445
S3P1	E1	3.84	27.69	-1.03	2.149	0.225	-4.899	5.320
	E2	3.84	27.67	-0.74	2.154	0.240	-4.895	5.323
	E3	3.79	27.59	-0.41	2.158	0.269	-4.891	5.326
	E4	3.84	27.58	-0.12	2.175	0.253	-4.884	5.327
	E5	3.84	27.55	0.19	2.186	0.274	-4.873	5.331
	E6	3.85	27.52	0.47	2.178	0.258	-4.878	5.334
	E7	3.84	27.45	0.76	2.176	0.339	-4.869	5.334
S3P2	E1	2.13	27.59	-1.02	2.084	0.523	-4.928	5.326
	E2	2.11	27.30	-0.72	2.089	0.529	-4.927	5.336
	E3	2.04	27.21	-0.41	2.108	0.545	-4.920	5.345
	E4	2.04	27.31	-0.12	2.105	0.537	-4.927	5.359
	E5	2.03	27.26	0.19	2.128	0.536	-4.925	5.375
	E6	2.09	27.36	0.47	2.153	0.579	-4.912	5.388
	E7	2.08	27.30	0.76	2.170	0.688	-4.898	5.400

Given the coordinates, AMF intensities, and total intensities at various measurement points in Table 5.1, the coordinate of the smart rock can be determined from the localization algorithm as discussed in Section 4.2.3. The predicted coordinate is

presented in Table 5.2 and compared with the measured coordinate from the total station. It can be seen from Table 5.2 that a prediction error of 0.26 m was determined. The prediction error mainly occurred in Y coordinate likely because the measurement bar was inaccurately placed on top of the smart rock with 0.368 m in diameter.

Table 5.2. Predicted and measured location of the smart rock

Test Date	Predicted Coordinate			Measured Coordinate			SRSS Prediction Error (m)
	X_M (m)	Y_M (m)	Z_M (m)	X_M (m)	Y_M (m)	Z_M (m)	
11/06/15 (1 st)	0.06	23.49	-3.03	0.09	23.24	-3.04	0.26
04/14/16 (2 nd)	0.55	24.38	-3.21	0.37	24.60	-3.38	0.33
10/20/16 (3 rd)	0.00	22.73	-2.59	0.00	22.63	-2.87	0.30

5.2.3.2 Second series of field tests

The second series of field tests were carried out on April 14, 2016. They followed the same protocol as used during the first series of field tests. The coordinate system set up during these tests was slightly translated from that used during the first series of tests. It was transformed to the first coordinate system through the benchmark A on Pier 9.

The Earth's magnetic field intensity was measured using a magnetometer G858 at Point P_{5-6} near Pier 5. It was $51,760\text{ nT}$ during the first series of tests and $52,120\text{ nT}$ during the second series of tests, which indicates a 0.7% increase in magnetic field intensity of the Earth. By comparing the Earth's magnetic field intensity from the first series of tests with that of the AMF intensity in Table 5.1, the magnetic field resulting from the steel reinforcement near Bent 7 is less than $2,700\text{ nT}$ or 5.3% of the Earth's field intensity. The steel reinforcement is magnetized in the Earth's magnetic field. The secondary magnetic field generated by the reinforcement is approximately correlated with the Earth's magnetic field, both varying over time as a result of the direct or indirect effect of solar wind. Therefore, the AMF during the second series of tests was compensated for the Earth magnetic field change by approximately increasing the AMF from the first series of tests by 0.7% . Table 5.3 summarizes the coordinates, the adjusted AMF intensities, and the total intensities at various measurement points from the second series of field tests.

Table 5.3. Coordinates and intensities from the second series of field tests

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			Total Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{AK}^{(M)}$	$B_{AY}^{(M)}$	$B_{AZ}^{(M)}$	$B_T^{(M)}$	
E1	3.83	21.77	-1.00	2.294	0.102	-4.925	5.375	
E2	3.82	21.66	-0.71	2.256	0.175	-4.935	5.385	
E3	3.80	21.61	-0.41	2.258	0.225	-4.929	5.395	
S1P1	E4	3.80	21.65	-0.12	2.260	0.239	-4.926	5.404
	E5	3.76	21.51	0.18	2.257	0.234	-4.925	5.409
	E6	3.79	21.56	0.47	2.303	0.337	-4.901	5.416
	E7	3.81	21.53	0.79	2.279	0.242	-4.912	5.419

Table 5.3. Coordinates and intensities from the second series of field tests (Cont'd)

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			Total Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{AX}^{(M)}$	$B_{AY}^{(M)}$	$B_{AZ}^{(M)}$	$B_T^{(M)}$	
S1P2	E1	3.83	24.54	-1.00	2.263	0.218	-4.908	5.318
	E2	3.87	24.42	-0.74	2.271	0.250	-4.895	5.342
	E3	3.80	24.40	-0.40	2.257	0.256	-4.896	5.361
	E4	3.75	24.34	-0.13	2.304	0.281	-4.869	5.375
	E5	3.82	24.37	0.19	2.252	0.282	-4.889	5.385
	E6	3.78	24.34	0.47	2.264	0.273	-4.882	5.393
	E7	3.75	24.23	0.77	2.251	0.281	-4.885	5.396
S2P1	E1	3.85	27.66	-1.02	2.164	0.227	-4.933	5.339
	E2	3.84	27.62	-0.73	2.169	0.242	-4.929	5.347
	E3	3.75	27.57	-0.42	2.173	0.271	-4.925	5.355
	E4	3.84	27.50	-0.12	2.190	0.254	-4.918	5.362
	E5	3.85	27.58	0.19	2.201	0.276	-4.907	5.367
	E6	3.83	27.54	0.47	2.193	0.260	-4.912	5.372
	E7	3.85	27.49	0.77	2.191	0.342	-4.903	5.374
S2P2	E1	2.05	21.86	-1.00	2.294	0.168	-4.928	5.405
	E2	2.07	21.72	-0.72	2.294	0.168	-4.928	5.433
	E3	2.06	21.88	-0.42	2.261	0.281	-4.945	5.456
	E4	2.08	21.68	-0.11	2.261	0.288	-4.953	5.476
	E5	2.07	21.62	0.19	2.256	0.273	-4.964	5.493
	E6	2.06	21.61	0.47	2.261	0.296	-4.973	5.509
	E7	2.07	21.62	0.78	2.265	0.326	-4.982	5.522
S3P1	E1	2.07	24.55	-0.99	2.311	0.444	-4.832	5.590
	E2	2.01	24.41	-0.71	2.301	0.497	-4.818	5.580
	E3	2.07	24.43	-0.41	2.284	0.572	-4.814	5.571
	E4	2.08	24.46	-0.11	2.249	0.527	-4.853	5.560
	E5	2.09	24.47	0.20	2.249	0.499	-4.871	5.547
	E6	2.09	24.20	0.49	2.239	0.523	-4.890	5.544
	E7	2.09	24.32	0.79	2.245	0.559	-4.900	5.539
S3P2	E1	2.14	27.57	-1.01	2.099	0.526	-4.963	5.372
	E2	2.13	27.32	-0.72	2.104	0.532	-4.962	5.392
	E3	2.06	27.23	-0.40	2.123	0.549	-4.955	5.411
	E4	2.04	27.37	-0.12	2.120	0.541	-4.962	5.427
	E5	2.05	27.25	0.18	2.143	0.540	-4.959	5.442
	E6	2.11	27.31	0.47	2.168	0.583	-4.947	5.455
	E7	2.04	27.28	0.76	2.185	0.693	-4.932	5.467

As shown in Table 5.2, the prediction error in rock positioning during the second series of tests was 0.33 m, which is nearly 30% higher than that during the first series of tests. The higher level of prediction error was likely attributed to the less accurate AMF.

Nevertheless, a prediction error of 0.33 m is still much less than 0.5 m , a target accuracy set forth for engineering application.

5.2.3.3 Third series of field tests

The third series of tests were carried out on October 20, 2016. These tests also followed the same test protocol as established during the first series of field tests. The coordinate system set up during the third series of tests was also transformed to the first coordinate system through the benchmark A on Pier 9. Similarly, the Earth's magnetic field intensity was measured using a magnetometer G858 at Point P_{5-6} near Pier 5. It was $51,761\text{ nT}$ during the first series of tests and $52,021\text{ nT}$ during the third series of tests, which indicates a 0.5% increase in magnetic field intensity. Following the same compensation analysis for the Earth's magnetic field change as used during the second series of field tests, the AMF during the third series of tests was estimated by increasing the AMF during the first series of tests by 0.5% . Similar to Tables 5.1 and 5.3, Table 5.4 summarizes the coordinates, the adjusted AMF intensities, and the total intensities at various measurement points for the third series of field tests.

Table 5.4. Coordinates and intensities from the third series of field tests

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			Total Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{AX}^{(M)}$	$B_{AY}^{(M)}$	$B_{AZ}^{(M)}$	$B_T^{(M)}$	
S1P1	E1	3.81	21.77	-0.93	2.290	0.102	-4.915	5.350
	E2	3.82	21.63	-0.68	2.252	0.175	-4.925	5.365
	E3	3.78	21.37	-0.32	2.253	0.224	-4.920	5.381
	E4	3.81	21.35	-0.10	2.256	0.238	-4.916	5.395
	E5	3.74	21.23	0.28	2.252	0.233	-4.915	5.403
	E6	3.79	21.36	0.50	2.298	0.336	-4.892	5.408
	E7	3.81	21.35	0.88	2.274	0.241	-4.902	5.413
S1P2	E1	3.76	24.09	-0.94	2.258	0.217	-4.898	5.308
	E2	3.78	24.09	-0.72	2.267	0.249	-4.886	5.327
	E3	3.76	24.05	-0.33	2.253	0.256	-4.886	5.343
	E4	3.77	24.08	-0.01	2.300	0.281	-4.859	5.358
	E5	3.77	24.07	0.20	2.248	0.281	-4.879	5.369
	E6	3.77	24.06	0.49	2.259	0.272	-4.872	5.379
	E7	3.76	23.97	0.87	2.246	0.280	-4.875	5.386
S2P1	E1	3.73	27.21	-0.94	2.160	0.226	-4.924	5.358
	E2	3.77	27.20	-0.71	2.165	0.241	-4.919	5.362
	E3	3.79	27.17	-0.33	2.168	0.270	-4.915	5.366
	E4	3.78	27.20	-0.12	2.186	0.254	-4.908	5.370
	E5	3.78	27.21	0.27	2.197	0.276	-4.898	5.374
	E6	3.76	27.14	0.48	2.189	0.260	-4.903	5.378
	E7	3.69	27.05	0.78	2.187	0.341	-4.893	5.380

Table 5.4. Coordinates and intensities from the third series of field tests (Cont'd)

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			Total Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{X_i}^{(M)}$	$B_{Y_i}^{(M)}$	$B_{Z_i}^{(M)}$	$B_i^{(M)}$	
S2P2	E1	2.06	21.14	-0.93	2.289	0.167	-4.918	5.400
	E2	2.08	21.16	-0.71	2.289	0.167	-4.918	5.437
	E3	2.06	21.14	-0.32	2.257	0.281	-4.936	5.469
	E4	2.02	20.91	-0.01	2.256	0.288	-4.943	5.497
	E5	2.04	21.09	0.28	2.251	0.272	-4.954	5.519
	E6	2.06	21.06	0.48	2.257	0.295	-4.963	5.535
	E7	2.12	21.12	0.87	2.261	0.325	-4.972	5.540
S3P1	E1	2.09	23.91	-0.92	2.306	0.443	-4.822	5.349
	E2	2.09	23.83	-0.70	2.296	0.496	-4.809	5.428
	E3	2.14	23.90	-0.32	2.279	0.571	-4.805	5.445
	E4	2.14	23.89	-0.11	2.244	0.526	-4.843	5.471
	E5	2.15	23.88	0.28	2.244	0.498	-4.862	5.487
	E6	2.11	23.85	0.50	2.235	0.522	-4.880	5.510
	E7	2.14	23.88	0.88	2.241	0.558	-4.890	5.515
S3P2	E1	2.07	27.03	-0.94	2.095	0.525	-4.953	5.376
	E2	2.14	27.06	-0.71	2.100	0.531	-4.952	5.390
	E3	2.10	26.96	-0.33	2.118	0.548	-4.945	5.402
	E4	2.16	27.08	-0.02	2.116	0.540	-4.952	5.417
	E5	2.13	27.07	0.27	2.139	0.539	-4.950	5.430
	E6	2.10	27.01	0.50	2.164	0.582	-4.937	5.448
	E7	2.08	26.83	0.77	2.181	0.691	-4.922	5.457

As shown in Table 5.2, the prediction error in rock positioning during the third series of tests was 0.30 m , which is nearly 16% higher than that during the first series of tests. The higher level of prediction error was also attributed to the less accurate AMF. Nevertheless, a prediction error of 0.30 m is still acceptable in engineering application.

5.2.4. Smart rock movement and scour depth

The predicted and the measured coordinates of the smart rock obtained from the first, second and third series of tests, as listed in Table 5.2, were used to calculate the displacement of the smart rock and thus scour depth increment between two consecutive tests. The three displacement components (ΔX_M , ΔY_M , ΔZ_M) and the total displacement as well as the difference between the predicted and measured displacements are presented in Table 5.5. To relate the movement of the smart rock to the evolution of the riverbed, three-dimensional contour maps were created in ArcGIS based on the riverbed survey data collected with the sonar and the total station during the second and third series of field tests. The riverbed contours and their corresponding measured positions of the smart rock in the scour hole around Pier 7 are illustrated in Figures 5.11(a) and 5.11(b) from the second and third site visits. The initial position of the smart rock during the first series of field tests is also included in Figure 5.11(a).

Table 5.5. Prediction accuracy of smart rock movement

Displacement	1st to 2 nd series of tests				2 nd to 3 rd series of tests			
	ΔX_M (m)	ΔY_M (m)	ΔZ_M (m)	Total (m)	ΔX_M (m)	ΔY_M (m)	ΔZ_M (m)	Total (m)
Predicted	0.49	0.89	-0.18	1.04	-0.55	-1.65	0.62	1.85
Measured	0.28	1.37	-0.34	1.44	-0.37	-1.97	0.51	2.06
Difference	0.21	-0.47	0.16	-0.40	-0.19	0.32	0.11	-0.21

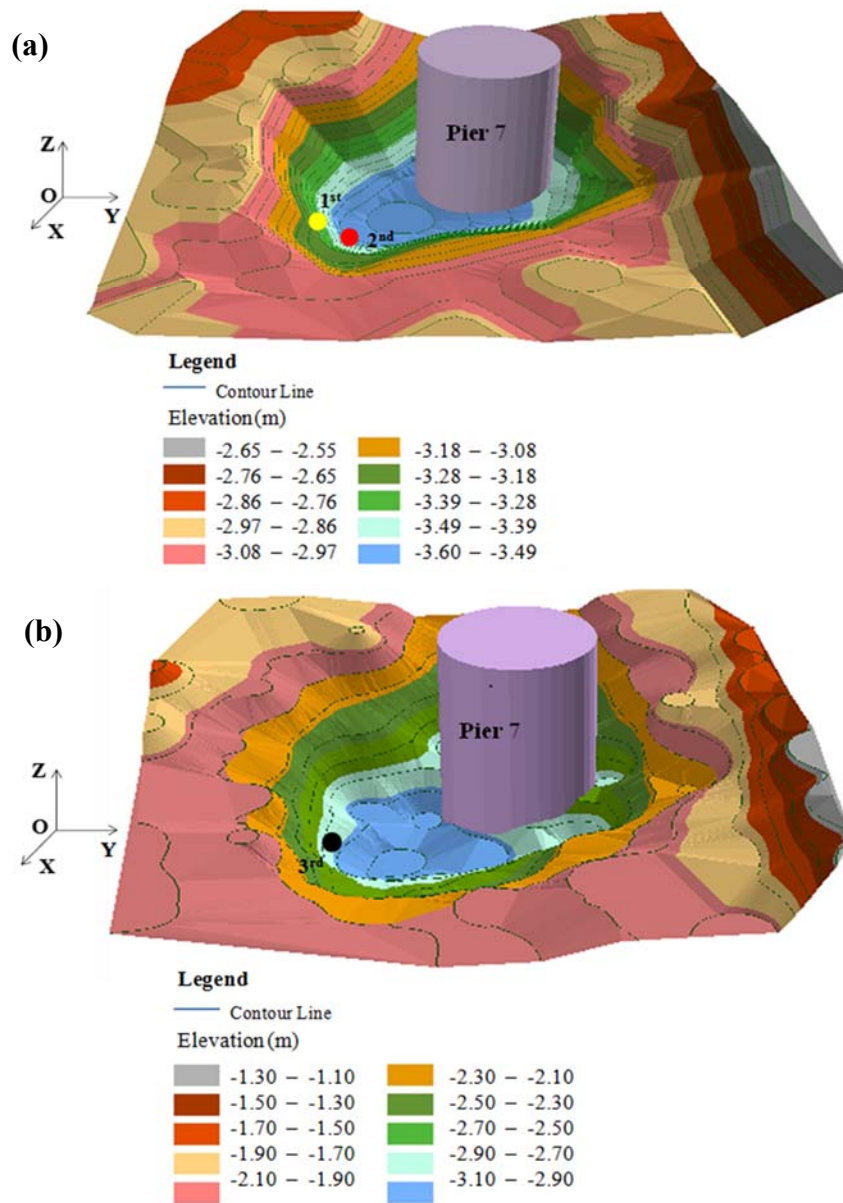


Figure 5.11. The smart rock movement in the scour hole around Pier 7: (a) the second field test and (b) the third field test.

From the first to second series of tests, the predicted and measured total displacements are 1.04 m and 1.44 m , respectively. They are differed by 0.4 m . The maximum component displacement error of 0.47 m occurred in Y-direction or traffic direction. As explained previously, this error is likely attributed to the potentially misplaced measurement bar in the process of coordinate measurement of the smart rock. Nevertheless, both the component and total displacement errors are less than 0.5 m , a level of accuracy acceptable in engineering application. It is also important to note that the predicted and measured movement directions of the smart rock are all consistent. In particular, the smart rock was settled down by 0.18 m (prediction) or 0.34 m (measurement), which likely occurred during the December 27, 2015 flood between the two series of field tests.

From the second to third series of tests, the predicted and measured total displacements are 1.85 m and 2.06 m , respectively. They are differed by 0.21 m . The maximum component displacement error of 0.32 m also came from Y-direction because of the main error from actual location measurement and other factors discussed in the prediction error of localization. Nevertheless, both the component and total displacement errors are within the acceptable range in application. Between the second and third series of tests, the smart rock moved upward in Z direction by 0.51 m and away from Pier 7 in Y direction by 1.97 m . These movements may result from the change of the scour hole in shape and deposits refilling between the two series of tests. For instance, when the bottom of a scour hole becomes nearly flat, the smart rock can be moved up against a slow slope.

5.3. State Hwy1 Waddell Creek Bridge, CA

The State Highway 1 Bridge (No. 36-0065) over the Waddell Creek, approximately 27 km north of the City of Santa Cruz, CA, was used as the second test site to validate the performance of smart rocks. As shown in Figure 5.12, the bridge is a four-span, continuous reinforced concrete T-girder structure, supporting two lanes of two-way traffic on California Highway 1. The upstream of the bridge is a small creek formed between low mountains while the downstream of the bridge is only a few hundreds of meters away from the Pacific Ocean. The bridge site is exposed to a complex hydraulic condition, combining the strong water flow from the mountains during flood seasons and the strong current from the Pacific Ocean during high tides. As a result, the embankment around South Abutment 1 (closer to Santa Cruz) experienced severe erosion extending from the channel bank from the upstream. Since the California Department of Transportation (Caltrans) already protected Abutment 1 with rocks, Abutment 1 was used as a validation site of potentially detecting the rip-rap effectiveness with a smart rock. Similarly, the pier at Bent 2 was considered by Caltrans as scour critical and thus used as a validation site for scour depth monitoring with two smart rocks. To date, two series of field tests were carried out to validate the localization and movement of the smart rocks driven by flood events or normal water flow.

During the first series of field tests, one smart rock with two stacked magnets in the APUS configuration was placed among a few widely spaced natural rocks at the toe of rip-rap measures around Abutment 1 for rip-rap effectiveness monitoring. Two additional smart rocks were placed on the surface of the riverbed near Bent 2 for bridge scour monitoring.



Figure 5.12. State Highway 1 Bridge over Waddell Creek, CA.

During the second series of field tests, the three smart rocks deployed previously were found to have been washed away likely due to the strong tide waves from the Pacific Ocean occurred in March 2016. Therefore, two new smart rocks were deployed again near Bent 2 to validate the localization algorithms for one or two smart rocks. During the second visit, however, the smart rocks were buried into the riverbed such that the top of the smart rocks was flush with the riverbed with the intent of making the smart rocks difficult to be washed away.

5.3.1. Planning for the first series of field tests

All tests were conducted near South Abutment 1 on the Santa Cruz side and the pier at Bent 2 of the four-span bridge as shown in Figure 5.13(a, b). A total station was set near North Abutment 5 on the San Francisco side to measure the coordinates (location) of three smart rocks and the magnetometer sensor as ground truth data. The center of the total station was used as the origin of a Cartesian coordinate system O-XYZ with X-, Y-, and Z- axes oriented transversely (upstream to downstream direction), longitudinally (south bound traffic direction), and vertically (upward direction).

Two smart rocks, designated as SR1 and SR2, were deployed on two sides of the Bent 2 in far and near distances, respectively. The third smart rock, SR3, placed in the gap of rip-rap rocks around South Abutment 1. The magnetometer sensor mounted on the test crane was extended down from the bridge deck for measurement of the AMF and the total magnetic field with the smart rocks placed at three locations. Prism 3 mounted below the sensor was used to represent the location of each measurement point. The measurement points in XOY plane are shown in Figure 5.13(a) as the cross points of Mesh 1 for Abutment 1 and Mesh 3 for Bent 2. The sensor points in Mesh 1 and Mesh 3 were translated to Mesh 2 and Mesh 4 on the bridge deck for corresponding positions of the forklift as displayed in Figure 5.13(c). These forklift positions were represented as four Paths (P1, P2, P3 and P4) and three Stops (S1, S2 and S3) on each path. For each stop on a path, seven elevations denoted as E1, E2, E3, E4, E5, E6 and E7 with equal spacing of 0.3 m were positioned for field measurements. Therefore, a total of 84 measurements were taken for SR3 around Abutment 1 and for SR1 & SR2 around Bent 2.

The step-by-step test procedure for the Waddell Creek Bridge, CA, is the same as that used for the I-44W Roubidoux Creek Bridge, MO, except that the time-varying AMF for reference is not analyzed since no smart rock movement is calculated. Only main different features specific to the Waddell Creek Bridge are discussed below. A permanent point on the concrete pedestal at the top and upstream/east side of south abutment was selected as the benchmark for this bridge site. As shown in Figure 5.14, the total station

was set at Point O on the north end of the bridge such that Y-axis along the traffic (longitudinal) direction to Santa Cruz is parallel to the tangential line of bridge railing closest to Point A, X-axis is perpendicular to the Y-axis and pointing to downstream/west in the horizontal plane, and Z-axis is pointing up according to the right hand rule.

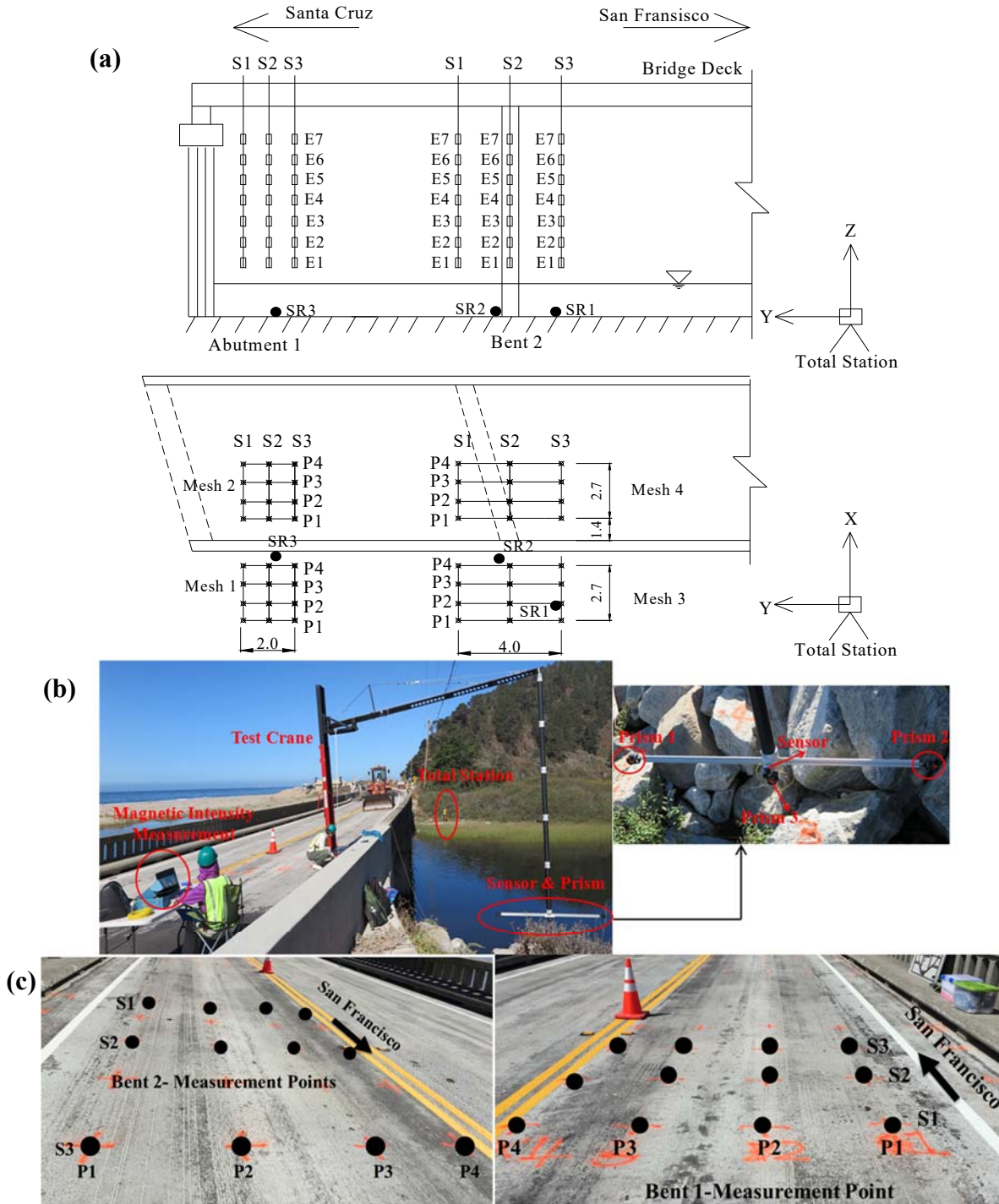


Figure 5.13. Waddell Creek bridge – first series of tests: (a) planning (unit: m), (b) test setup, and (c) forklift positions.

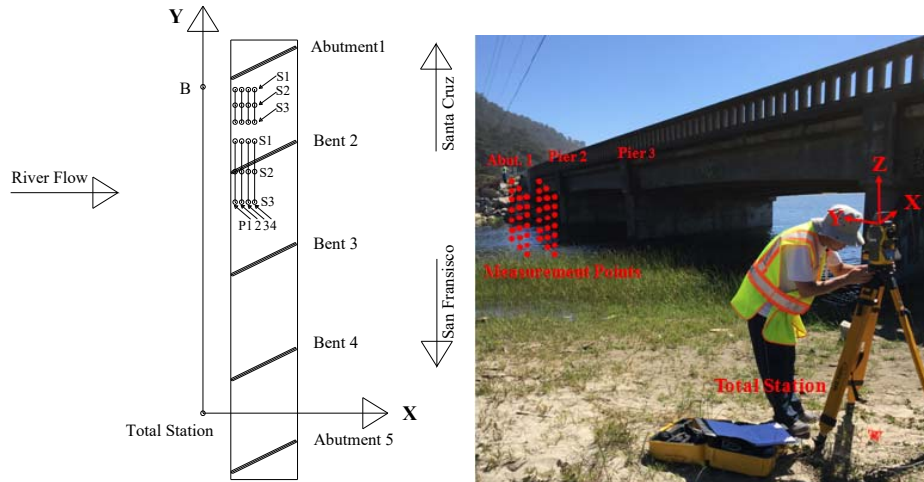


Figure 5.14. Selection of the coordinate system.

As shown in Figure 5.13(b), the test crane was directly set on the bridge deck. The forklift on four wheels with brakes was first placed on the bridge deck. The horizontal aluminum arm was then installed and five 1.0-m long carbon fiber tubes were assembled. Finally, the horizontal bar with three prisms and sensor attached was connected to the bottom tube. It was found during the tests that moving the forklift from one location to another on the sloped bridge deck proved cumbersome in some cases. During wind gusts, stability and safety of the forklift could be a concern.

The AMF was measured prior to deployment of the smart rocks. The forklift was first parked at S1P1 near south Abutment 1 and the horizontal arm of the test crane was moved up or down between E1 and E7 for simultaneous measurements of the coordinate and intensity at each elevation. The forklift was then moved to S1P2, S1P3 and S1P4 for successive measurements along X axis. It was further moved to S2 and S3 lines along Y axis to repeat the same measurements along X direction as those in S1 line. The same sequence and steps were followed near Bent 2 to complete the measurements along S1, S2 and S3 lines, respectively, as illustrated in Figure 5.15.

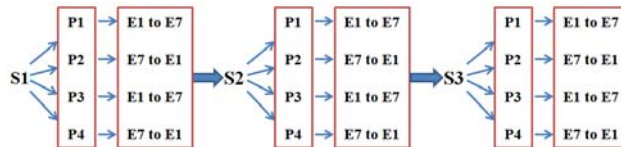


Figure 5.15. Sequence for AMF measurements.

Three smart rocks with the APUS, as shown in Figure 5.7, were deployed as indicated in Figure 5.16 before the total magnetic field was measured. As shown in Figure 5.16(a), SR1 and SR2 were located on the north and south sides of Bent 2 for scour monitoring and SR3 between two rocks near the south abutment for rip-rap effectiveness monitoring. The three smart rocks were individually transported in a boat and dropped at the predetermined sites as indicated in Figure 5.16(b). As illustrated in Figure 5.16(c), SR3 in shallow water can be clearly seen from the bridge deck, SR2 close to the bottom of the scour hole can be barely seen when the water is calm, and SR1 farther away from Bent 2 with a connection rope floated on the water surface can be

located as well. The deployed smart rocks were surveyed for their coordinates from the total station through the placement of a prism on top of each smart rock.

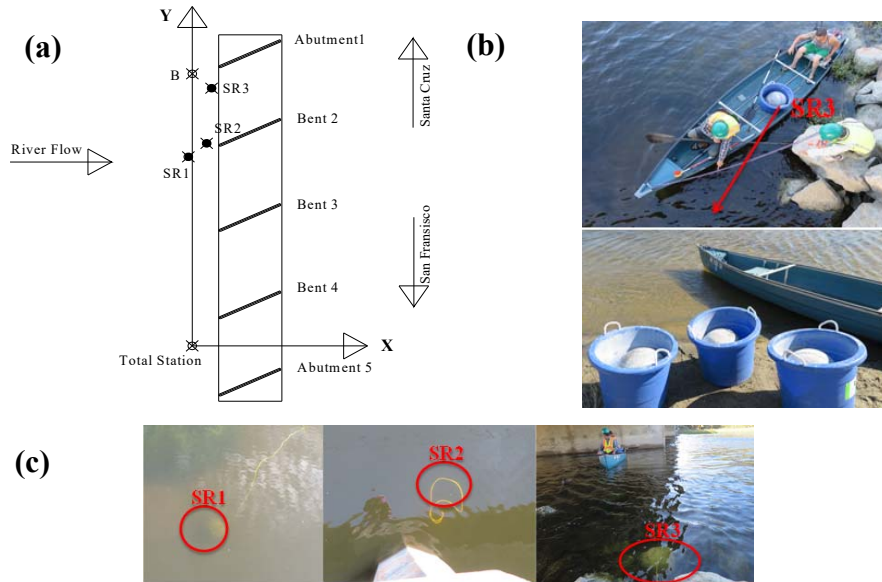


Figure 5.16. Application of three smart rocks: (a) locations, (b) SR3 deployment, and (c) top views.

After the deployment of smart rocks, the total magnetic field from the smart rocks, the Earth, and the nearby ferromagnetic objects was measured following the same procedure as used for the ambient magnetic field measurements except that only six elevations were considered in Z direction for all points near the south abutment. Therefore, a total of 72 and 84 measurements were taken around the south abutment for SR3 and around Bent 2 for SR1 and SR2, respectively.

5.3.2. Planning for the second series of field tests

The spherical smart rock SR3 deployed previously near the south abutment had no interlock with nearby natural rocks. It was witnessed by a Caltrans engineer to have been washed away due to strong tide waves. Heavier and polyhedral smart rocks are recommended for rip-rap effectiveness monitoring in the future.

Therefore, the second series of field tests were focused on the localization of smart rocks near Bent 2. Since the previously deployed smart rocks SR1 and SR2 cannot be located near the bridge, they were assumed to have also been washed away. As a result, two same smart rocks, also named SR1 and SR2, were deployed near Bent 2 again. During the second series of tests, however, the smart rocks were buried in the riverbed to increase their resistance to strong water current. Specifically, the top of each smart rock is approximately flush with the riverbed. The test layout was also changed and simplified as shown in Figure 5.17 based on the experience gained from the first series of field tests. The test crane as shown in Figure 5.17(c) was fixed on a flatbed trailer towed by a truck. Through the test crane, the measurement points at the location of the sensor (cross points of Mesh 1) were translated to the corresponding forklift locations (cross points of Mesh 2) represented by two paths (P1 and P2) and seven stops (S1 to S7) on the bridge deck, as

depicted in Figure 5.17(d). For each stop on two path of the trailer, seven elevations denoted as E1 to E7 with equal spacing of 0.3 m were considered for magnetic field measurements. Therefore, a total of 98 measurements were taken around Bent 2 in order to locate the two smart rocks.

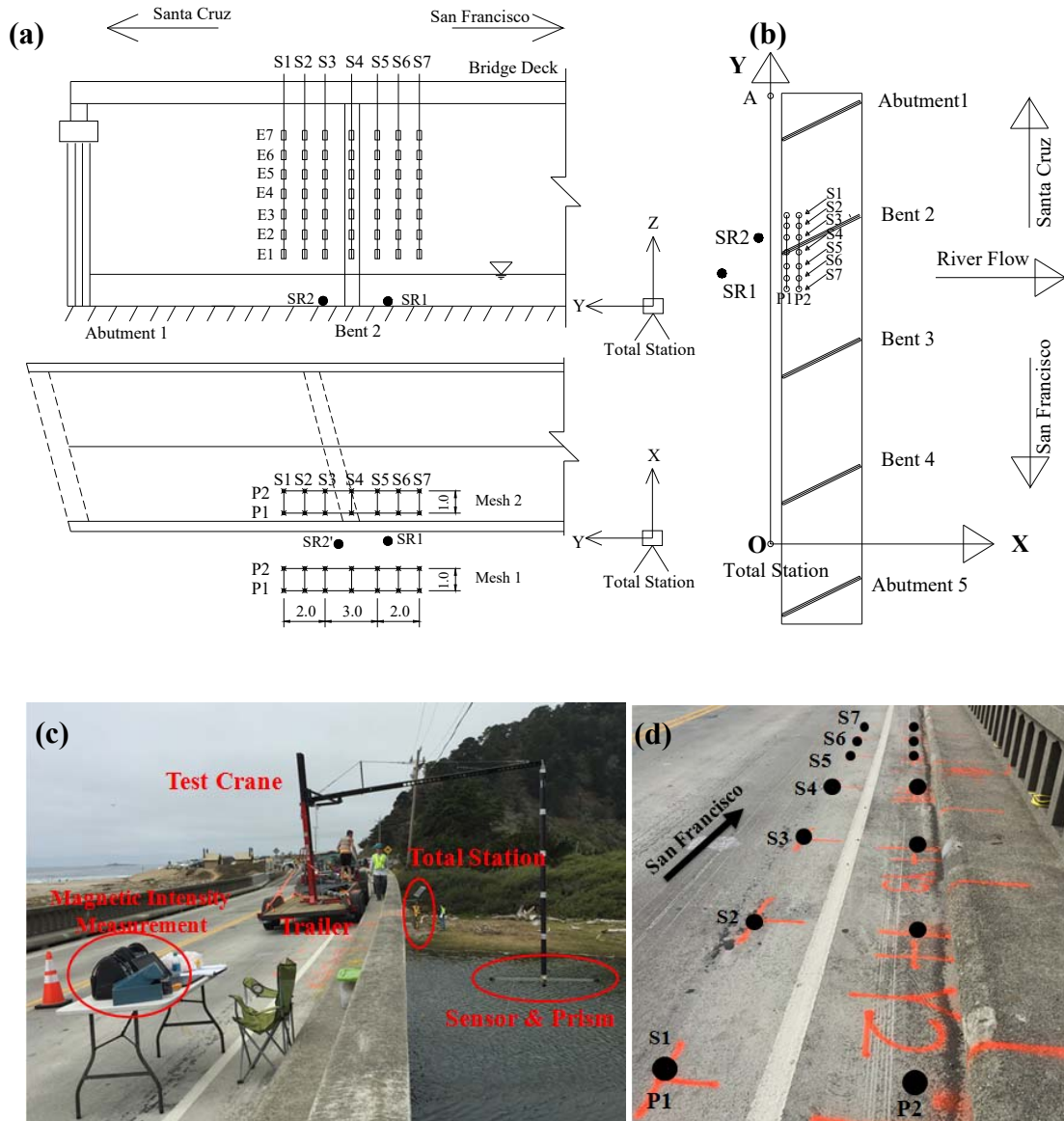


Figure 5.17. Waddell Creek bridge - second series of tests: US63 Bridge site: (a) planning (unit: m), (b) test setup, and (c) forklift positions.

The second series of field tests followed the same procedure as used during the first series of tests except that the two smart rocks, SR1 and SR2 on the north and south side of Bent 2, were deployed at different times with the total magnetic field measurements taken in between. The AMF was first measured following the sequence as shown in Figure 5.18. After the deployment of SR1, the total magnetic field with one smart rock was then measured along two paths P1 and P2 with three stops S4, S5 and S7

at 39 points. After the deployment of SR2, the total magnetic field with two smart rocks as depicted in Figure 5.19 was next measured along the two paths with seven stops at 91 points. Finally, SR2 was moved to a new position represented by SR2' and the total magnetic field was measured again at points P1S2, P1S3, P1S5, P1S6, P2S1, P2S3, P2S5, and P2S7 for a total of 52 measurements.

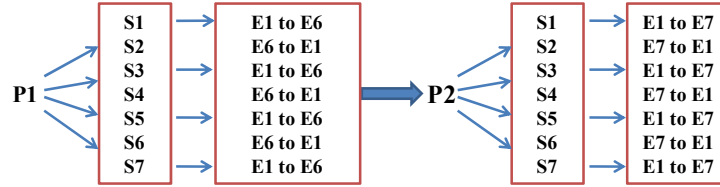


Figure 5.18. Sequence for AMF measurement during the second series of field tests.

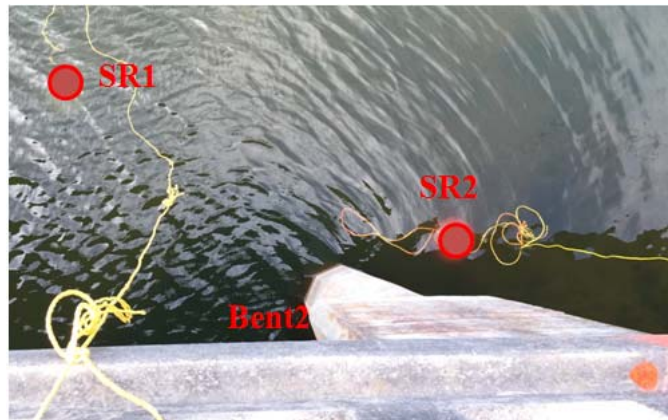


Figure 5.19. Deployed smart rocks: SR1 and SR2 during the second series of tests.

5.3.3. Test results and discussion

During the first series of field tests, the localization of the SR3 deployed near the south abutment was conducted. During the second series of field tests, the localizations of a single smart rock SR1 deployed on the north side of Bent 2 and then two smart rocks, SR1 and SR2, were conducted.

5.3.3.1 Field tests near the south abutment

Table 5.6 summarizes the coordinates of 18 measurement points near the south abutment, the AMF intensities, and the total Intensities after deployment of the smart rock SR3. The coefficient $k = 86,521 \text{ nT}\cdot\text{m}^3$ for two stacked N42 magnets was calculated from the maximum residual flux density. The three components of the AMF ($B_{AX}^{(M)}$, $B_{AY}^{(M)}$, $B_{AZ}^{(M)}$) and the total magnetic field $B_T^{(M)}$ were directly measured from the 3-axis flux magnetometer in which three directions marked on the sensor were placed in parallel with the three axes of the O-XYZ coordinate system. Therefore, the magnitude of the total magnetic field and the three components of the AMF were substituted into the localization algorithm of one smart rock to determine the coordinates of the smart rock SR3. The predicted location of the smart rock SR3 is included in Table 5.7.

Table 5.6. Coordinates and intensities for SR3 location

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			SR3&AMF Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{AX}^{(M)}$	$B_{AY}^{(M)}$	$B_{AZ}^{(M)}$	$B_T^{(M)}$	
P2S1	E1	0.66	42.26	-0.94	-1.868	-0.982	-4.001	4.583
	E2	0.69	42.29	-0.64	-1.867	-0.974	-4.012	4.600
	E3	0.70	42.30	-0.32	-1.865	-0.980	-4.017	4.607
	E4	0.70	42.25	-0.03	-1.866	-0.975	-4.024	4.606
	E5	0.75	42.25	0.28	-1.872	-0.974	-4.024	4.604
	E6	0.77	42.35	0.57	-1.866	-0.989	-4.023	4.599
P3S1	E1	1.69	42.29	-1.14	-1.824	-0.971	-3.997	5.139
	E2	1.75	42.30	-0.84	-1.828	-0.966	-4.018	5.019
	E3	1.68	42.25	-0.54	-1.840	-0.969	-4.031	4.871
	E4	1.69	42.27	-0.25	-1.851	-0.969	-4.044	4.804
	E5	1.71	42.28	0.06	-1.871	-0.959	-4.052	4.758
	E6	1.74	42.28	0.37	-1.888	-0.968	-4.051	4.726
P4S1	E1	2.34	42.39	-1.09	-1.641	-1.080	-4.026	5.758
	E2	2.34	42.37	-0.89	-1.656	-1.063	-4.059	5.490
	E3	2.38	42.34	-0.59	-1.676	-1.055	-4.084	5.219
	E4	2.38	42.29	-0.28	-1.697	-1.062	-4.105	5.043
	E5	2.42	42.34	0.02	-1.732	-1.059	-4.121	4.940
	E6	2.44	42.33	0.32	-1.771	-1.078	-4.123	4.888

Table 5.7 compares the predicted and measured coordinates (X_M, Y_M, Z_M) of the smart rock SR3. It can be observed that the largest error in Z coordinate is 29 cm as a result of significant swing of the sensor caused by the strong wind during the tests. The SRSS prediction error of three components is 36 cm , which is small in comparison with the error limit of half a meter.

Table 5.7. Predicted and measured location of smart rock SR3

	X_M (m)	Y_M (m)	Z_M (m)
Predicted Coordinate	2.79	41.30	-2.82
Measured Coordinate	2.71	41.10	-2.53
Component Error	0.08	0.20	-0.29
Total SRSS Error	0.36 m		

5.3.3.2 Field tests near Bent 2

Table 5.8 summarizes the coordinates of 39 measurement points near Bent 2, the AMF intensities prior to any smart rock deployment, and the total intensities after deployment of the smart rock SR1. The three components of the AMF and the total magnetic field were directly measured from the 3-axis magnetometer sensor oriented in parallel with the X-, Y-, and Z-axis.

Table 5.8. Coordinates and intensities for SR1 location

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			SR1&AMF Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{X'}^{(M)}$	$B_{Y'}^{(M)}$	$B_{Z'}^{(M)}$	$B_T^{(M)}$	
P1S4	E1	-2.88	29.26	-1.50	-2.087	-0.956	-4.032	4.597
	E2	-2.87	29.29	-1.21	-2.085	-0.955	-4.045	4.619
	E3	-2.85	29.33	-0.91	-2.096	-0.962	-4.050	4.639
	E4	-2.82	29.37	-0.61	-2.093	-0.967	-4.057	4.655
	E5	-2.81	29.40	-0.32	-2.097	-0.971	-4.061	4.668
	E6	-2.80	29.41	0.00	-2.102	-1.006	-4.053	4.677
P1S5	E1	-2.89	27.66	-1.51	-2.095	-0.909	-4.030	4.486
	E2	-2.87	27.68	-1.21	-2.091	-0.928	-4.042	4.506
	E3	-2.84	27.72	-0.92	-2.100	-0.940	-4.047	4.532
	E4	-2.82	27.74	-0.60	-2.100	-0.958	-4.053	4.561
	E5	-2.80	27.76	-0.31	-2.107	-0.948	-4.061	4.586
	E6	-2.78	27.78	0.00	-2.106	-0.969	-4.062	4.611
P1S7	E1	-2.84	25.29	-1.50	-2.110	-0.868	-4.029	4.581
	E2	-2.81	25.34	-1.19	-2.104	-0.880	-4.043	4.564
	E3	-2.79	25.39	-0.90	-2.112	-0.890	-4.050	4.558
	E4	-2.77	25.41	-0.59	-2.110	-0.914	-4.056	4.563
	E5	-2.75	25.46	-0.31	-2.116	-0.909	-4.064	4.574
	E6	-2.74	25.46	0.01	-2.115	-0.937	-4.065	4.588
P2S4	E1	-1.94	29.14	-1.51	-2.196	-0.946	-3.993	4.615
	E2	-1.92	29.22	-1.21	-2.207	-0.981	-4.002	4.654
	E3	-1.91	29.28	-0.91	-2.224	-1.004	-4.007	4.685
	E4	-1.89	29.30	-0.62	-2.240	-1.005	-4.014	4.707
	E5	-1.86	29.32	-0.31	-2.255	-0.998	-4.019	4.722
	E6	-1.86	29.34	-0.02	-2.267	-0.997	-4.018	4.731
	E7	-1.83	29.37	0.28	-2.278	-1.002	-4.010	4.735
P2S5	E1	-1.93	27.64	-1.52	-2.164	-0.903	-4.006	4.203
	E2	-1.91	27.66	-1.21	-2.185	-0.898	-4.023	4.318
	E3	-1.89	27.70	-0.91	-2.199	-0.927	-4.032	4.437
	E4	-1.88	27.73	-0.62	-2.215	-0.924	-4.043	4.437
	E5	-1.84	27.76	-0.32	-2.243	-0.924	-4.043	4.579
	E6	-1.84	27.78	-0.01	-2.259	-0.912	-4.046	4.626
	E7	-1.82	27.85	0.27	-2.275	-0.948	-4.033	4.660
P2S7	E1	-1.86	25.19	-1.50	-2.193	-0.854	-3.985	4.408
	E2	-1.83	25.19	-1.20	-2.212	-0.849	-4.004	4.408
	E3	-1.81	25.24	-0.91	-2.224	-0.851	-4.021	4.431
	E4	-1.79	25.26	-0.60	-2.237	-0.857	-4.033	4.471
	E5	-1.77	25.30	-0.31	-2.255	-0.860	-4.039	4.507
	E6	-1.77	25.31	-0.01	-2.270	-0.872	-4.041	4.546
	E7	-1.74	25.39	0.27	-2.282	-0.903	-4.035	4.575

Given the coordinates, AMF intensities, and total intensities at various measurement points in Table 5.8, the coordinate of the smart rock can be predicted as shown in Table 5.9 from the localization algorithm. By comparing the predicted coordinate with that measured from the total station, also listed in Table 5.9, a SRSS coordinate error of 0.27 m was determined. The prediction error mainly occurred in X coordinate likely because the measurement points on two close paths were not distributed well and the measurement bar was inaccurately placed on top of the smart rock with 0.368 m in diameter. Nevertheless, the prediction error of 0.27 m is less than 0.5 m , a target rock positioning accuracy set forth for engineering application.

Table 5.9. Predicted and measured location of smart rock SR1

	X_{M1} (m)	Y_{M1} (m)	Z_{M1} (m)
Predicted Coordinate	-0.43	27.21	-3.13
Measured Coordinate	-0.20	27.17	-3.26
Component Error	-0.23	0.05	0.13
Total SRSS Error	0.27 m		

Table 5.10 summarizes the coordinates, the AMF intensities, and the total intensities after deployment of the two smart rocks SR1 and SR2 at 91 measurement points near Bent 2 and the 52 total intensities after the smart rock SR2 was moved to a new position, designated as smart rock SR2'. The 52 measurement points were selected from the 91 points due to the limited time available to cover the area of two smart rocks.

Given $k = 86,521\text{ nT}\cdot\text{m}^3$ for the two stacked N42 magnets and the coordinates, the AMF intensities, and the total intensities at various measurement points in Table 5.10, the coordinates of the two smart rocks SR1 and SR2 can be predicted as shown in Table 5.11 from the localization algorithm. Similarly, the predicted locations of the two smart rock of SR1 and SR2' were also evaluated as listed in Table 5.12. The predicted coordinates were compared with their corresponding ground truth data obtained from the total station. The prediction errors in component and SRSS total are also included in Tables 5.11 and 5.12 accordingly.

Table 5.10. Coordinates and intensities for SR1 and SR2 or SR2' locations

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			SR1&SR2&AMF Intensity (10^4 nT)	SR1&SR2'&AMF Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{X_i}^{M}$	$B_{Y_i}^{M}$	$B_{Z_i}^{M}$	B_i^M	B_i^M	
P1S1	E1	-2.92	33.04	-1.52	-2.114	-0.954	-4.036	4.545	
	E2	-2.90	33.06	-1.21	-2.112	-0.967	-4.042	4.576	
	E3	-2.88	33.09	-0.91	-2.112	-0.994	-4.043	4.605	
	E4	-2.86	33.11	-0.60	-2.116	-0.994	-4.046	4.629	NA
	E5	-2.84	33.17	-0.32	-2.121	-1.013	-4.043	4.648	
	E6	-2.83	33.20	-0.01	-2.122	-1.011	-4.045	4.662	

Table 5.10. Coordinates and Intensities for SR1 and SR2 or SR2' locations (Cont'd)

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			SR1&SR2&AMF Intensity (10^4 nT)	SR1&SR2'&AMF Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{X_i}^{(M)}$	$B_{Y_i}^{(M)}$	$B_{Z_i}^{(M)}$	$B_r^{(M)}$	$B_r^{(M)}$	
P1S1	E1	-2.92	33.04	-1.52	-2.114	-0.954	-4.036	4.545	
	E2	-2.90	33.06	-1.21	-2.112	-0.967	-4.042	4.576	
	E3	-2.88	33.09	-0.91	-2.112	-0.994	-4.043	4.605	
	E4	-2.86	33.11	-0.60	-2.116	-0.994	-4.046	4.629	NA
	E5	-2.84	33.17	-0.32	-2.121	-1.013	-4.043	4.648	
	E6	-2.83	33.20	-0.01	-2.122	-1.011	-4.045	4.662	
P1S2	E1	-2.90	31.97	-1.52	-2.105	-0.992	-4.029	4.471	4.493
	E2	-2.88	32.00	-1.21	-2.099	-0.991	-4.042	4.527	4.519
	E3	-2.86	32.06	-0.91	-2.105	-0.982	-4.049	4.577	4.544
	E4	-2.84	32.08	-0.61	-2.106	-0.992	-4.053	4.617	4.566
	E5	-2.82	32.11	-0.32	-2.108	-1.012	-4.052	4.645	4.584
	E6	-2.80	32.10	0.00	-2.109	-1.037	-4.047	4.666	4.593
P1S3	E1	-2.86	30.70	-1.51	-2.088	-0.965	-4.037	4.361	4.442
	E2	-2.85	30.70	-1.21	-2.087	-1.000	-4.040	4.451	4.478
	E3	-2.83	30.74	-0.92	-2.089	-1.027	-4.041	4.525	4.512
	E4	-2.81	30.77	-0.61	-2.092	-1.025	-4.048	4.585	4.541
	E5	-2.79	30.80	-0.32	-2.097	-1.026	-4.051	4.628	4.565
	E6	-2.77	30.83	-0.02	-2.101	-1.045	-4.043	4.655	4.583
P1S4	E1	-2.82	29.15	-1.53	-2.087	-0.956	-4.032	4.321	
	E2	-2.82	29.13	-1.22	-2.085	-0.955	-4.045	4.391	
	E3	-2.79	29.17	-0.93	-2.096	-0.962	-4.050	4.455	
	E4	-2.78	29.19	-0.60	-2.093	-0.967	-4.057	4.516	NA
	E5	-2.75	29.23	-0.32	-2.097	-0.971	-4.061	4.562	
	E6	-2.74	29.23	-0.01	-2.102	-1.006	-4.053	4.597	
P1S5	E1	-2.78	27.46	-1.52	-2.095	-0.909	-4.030	4.305	4.295
	E2	-2.76	27.47	-1.22	-2.091	-0.928	-4.042	4.336	4.333
	E3	-2.73	27.50	-0.92	-2.100	-0.940	-4.047	4.379	4.373
	E4	-2.72	27.52	-0.62	-2.100	-0.958	-4.053	4.429	4.418
	E5	-2.71	27.57	-0.32	-2.107	-0.948	-4.061	4.474	4.457
	E6	-2.69	27.61	-0.02	-2.106	-0.969	-4.062	4.518	4.495
P1S6	E1	-2.73	26.33	-1.51	-2.097	-0.854	-4.038	4.378	4.337
	E2	-2.71	26.37	-1.21	-2.088	-0.872	-4.053	4.371	4.338
	E3	-2.69	26.42	-0.91	-2.097	-0.876	-4.060	4.389	4.359
	E4	-2.67	26.45	-0.61	-2.106	-0.893	-4.063	4.420	4.391
	E5	-2.64	26.48	-0.33	-2.109	-0.912	-4.067	4.454	4.425
	E6	-2.64	26.48	-0.01	-2.106	-0.931	-4.070	4.494	4.461

Table 5.10. Coordinates and Intensities for SR1 and SR2 or SR2' locations (Cont'd)

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			SR1&SR2&AMF Intensity (10^4 nT)	SR1&SR2'&AMF Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{X_i}^{(M)}$	$B_{Y_i}^{(M)}$	$B_{Z_i}^{(M)}$	$B_r^{(M)}$	$B_r^{(M)}$	
P1S7	E1	-2.84	25.29	-1.50	-2.110	-0.868	-4.029	4.505	
	E2	-2.81	25.34	-1.19	-2.104	-0.880	-4.043	4.490	
	E3	-2.79	25.39	-0.90	-2.112	-0.890	-4.050	4.490	NA
	E4	-2.77	25.41	-0.59	-2.110	-0.914	-4.056	4.498	
	E5	-2.75	25.46	-0.31	-2.116	-0.909	-4.064	4.511	
	E6	-2.74	25.46	0.01	-2.115	-0.937	-4.065	4.530	
P2S1	E1	-1.94	33.08	-1.52	-2.167	-0.951	-4.024	4.561	4.535
	E2	-1.94	33.14	-1.23	-2.176	-0.973	-4.033	4.622	4.573
	E3	-1.92	33.20	-0.92	-2.190	-0.994	-4.038	4.672	4.608
	E4	-1.89	33.21	-0.62	-2.203	-0.995	-4.045	4.710	4.637
	E5	-1.88	33.25	-0.33	-2.224	-0.996	-4.044	4.736	4.661
	E6	-1.86	33.25	-0.02	-2.236	-0.984	-4.046	4.753	4.674
	E7	-1.84	33.30	0.26	-2.253	-0.984	-4.036	4.758	4.679
P2S2	E1	-1.93	32.04	-1.51	-2.232	-0.976	-3.980	4.525	
	E2	-1.91	32.05	-1.22	-2.247	-0.997	-3.990	4.645	
	E3	-1.89	32.08	-0.92	-2.260	-1.000	-4.001	4.725	
	E4	-1.87	32.10	-0.62	-2.278	-1.010	-4.005	4.775	NA
	E5	-1.85	32.15	-0.33	-2.293	-1.006	-4.007	4.801	
	E6	-1.84	32.16	-0.02	-2.310	-0.998	-4.004	4.810	
	E7	-1.81	32.25	0.27	-2.319	-1.005	-3.994	4.805	
P2S3	E1	-1.93	30.96	-1.51	-2.209	-0.966	-3.983	4.506	4.400
	E2	-1.91	31.00	-1.20	-2.219	-0.963	-4.001	4.696	4.491
	E3	-1.89	31.05	-0.92	-2.234	-0.967	-4.012	4.799	4.565
	E4	-1.86	31.07	-0.61	-2.248	-0.970	-4.019	4.850	4.620
	E5	-1.85	31.11	-0.33	-2.267	-0.978	-4.018	4.865	4.657
	E6	-1.83	31.12	-0.01	-2.278	-0.988	-4.014	4.860	4.679
	E7	-1.80	31.16	0.28	-2.291	-0.991	-4.003	4.845	4.686
P2S4	E1	-1.95	29.27	-1.51	-2.186	-0.946	-3.993	4.283	
	E2	-1.93	29.27	-1.21	-2.197	-0.981	-4.002	4.451	
	E3	-1.92	29.32	-0.92	-2.214	-1.004	-4.007	4.576	
	E4	-1.90	29.34	-0.61	-2.230	-1.005	-4.014	4.660	NA
	E5	-1.87	29.38	-0.32	-2.245	-0.998	-4.019	4.716	
	E6	-1.86	29.39	-0.02	-2.257	-0.997	-4.018	4.744	
	E7	-1.85	29.43	0.28	-2.268	-1.002	-4.010	4.758	

Table 5.10. Coordinates and Intensities for SR1 and SR2 or SR2' locations (Cont'd)

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			SR1&SR2&AMF Intensity (10^4 nT)	SR1&SR2'&AMF Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{XA}^{(M)}$	$B_{YA}^{(M)}$	$B_{ZA}^{(M)}$	$B_r^{(M)}$	$B_r^{(M)}$	
P2S5	E1	-1.94	27.66	-1.52	-2.154	-0.903	-4.006	4.022	4.107
	E2	-1.93	27.70	-1.21	-2.175	-0.898	-4.023	4.176	4.229
	E3	-1.91	27.75	-0.92	-2.189	-0.927	-4.032	4.308	4.335
	E4	-1.89	27.77	-0.61	-2.205	-0.924	-4.043	4.414	4.421
	E5	-1.87	27.79	-0.33	-2.233	-0.924	-4.043	4.498	4.492
	E6	-1.84	27.80	-0.01	-2.249	-0.912	-4.046	4.564	4.542
	E7	-1.82	27.85	0.27	-2.265	-0.948	-4.033	4.613	4.587
P2S6	E1	-1.91	26.42	-1.51	-2.158	-0.877	-3.999	3.979	
	E2	-1.88	26.43	-1.21	-2.177	-0.885	-4.015	4.065	
	E3	-1.86	26.46	-0.92	-2.194	-0.917	-4.023	4.177	
	E4	-1.85	26.49	-0.62	-2.215	-0.927	-4.031	4.289	NA
	E5	-1.82	26.54	-0.33	-2.231	-0.924	-4.038	4.383	
	E6	-1.81	26.52	-0.01	-2.248	-0.913	-4.044	4.464	
	E7	-1.78	26.57	0.27	-2.268	-0.926	-4.037	4.522	
P2S7	E1	-1.86	25.12	-1.51	-2.183	-0.854	-3.985	4.344	4.288
	E2	-1.84	25.18	-1.21	-2.202	-0.849	-4.004	4.342	4.280
	E3	-1.82	25.22	-0.91	-2.214	-0.851	-4.021	4.369	4.313
	E4	-1.80	25.25	-0.61	-2.227	-0.857	-4.033	4.408	4.357
	E5	-1.77	25.27	-0.32	-2.245	-0.860	-4.039	4.452	4.402
	E6	-1.75	25.28	-0.01	-2.260	-0.872	-4.041	4.496	4.447
	E7	-1.73	25.32	0.28	-2.272	-0.903	-4.035	4.529	4.483

Table 5.11. Predicted and measured locations of two smart rocks SR1 & SR2

	SR1			SR2		
	X_{M1} (m)	Y_{M1} (m)	Z_{M1} (m)	X_{M2} (m)	Y_{M2} (m)	Z_{M2} (m)
Predicted Coordinate	0.50	26.85	-2.54	-0.90	30.28	-3.78
Measured Coordinate	-0.20	27.17	-3.26	-0.40	30.55	-3.07
Component Error	0.70	-0.32	0.72	-0.51	-0.22	-0.71
Total SRSS Error	1.05 m			0.90 m		

It can be calculated from the measured coordinates of SR1 and SR2 in Table 5.11 that SR1 and SR2 were spaced by 3.40 m . The SRSS prediction errors were determined to be 1.05 m and 1.18 m for the prediction of SR1 and SR2 locations, respectively. The errors in Y coordinate were smaller than those in X and Z coordinate. likely because the measurement points covered a large area of the two smart rocks in Y direction (7 m) and a small area in X direction (1 m) and Z direction (1.5 m). In addition, most measurement points were positioned on one side of the smart rocks in X and Z directions. As discussed

in Sections 3 and 4, the more uniformly distributed the measurement points are around a smart rock, the more accurate the localization of the smart rock.

The smart rock SR2 was moved to SR2' by 1.01 m towards the pier, and SR1 and SR2' were spaced by 3.34 m based on the measured coordinates in Tables 5.11 and 5.12. The SRSS location prediction errors were determined to be 1.07 m and 1.54 m for SR1 and SR2', respectively. While the prediction error for SR1 together with smart rock SR2 versus SR2' is close, the location error for SR2' is significantly higher than that for SR2 mainly because the number of measurement points was reduced from 91 to 52. Indeed, by comparing Table 5.12 with Table 5.11, it can be found that the increase in prediction error from SR2 to SR2' location mainly occurred in Y direction, which is from -0.22 m to 1.23 m . The APUS in SR2' may be slightly affected by steel reinforcement in the pier.

Table 5.12. Predicted and measured locations of two smart rocks SR1 & SR2'

	SR1			SR2'		
	X_{M1} (m)	Y_{M1} (m)	Z_{M1} (m)	X_{M2} (m)	Y_{M2} (m)	Z_{M2} (m)
Predicted Coordinate	0.36	26.78	-2.44	0.19	31.64	-4.05
Measured Coordinate	-0.20	27.17	-3.26	0.59	30.41	-3.21
Component Error	0.56	-0.39	0.82	-0.40	1.23	-0.84
Total SRSS Error	1.07 m			1.54 m		

Figure 5.20 displays the measured locations of smart rocks SR1, SR2, and SR2' on the upstream riverbed profile near Bent 2. The three-dimensional contour map was created in ArcGIS based on the riverbed survey data collected with the sonar and the total station in the Cartesian coordinate system O-XYZ. It can be seen that the smart rock SR2' was moved closer to the pier and settled down to the scour hole around the pier. It is noted that one smart rock SR1 alone can be tracked as it moves over time as demonstrated at the I-44W Roubidoux Creek Bridge site in Missouri.

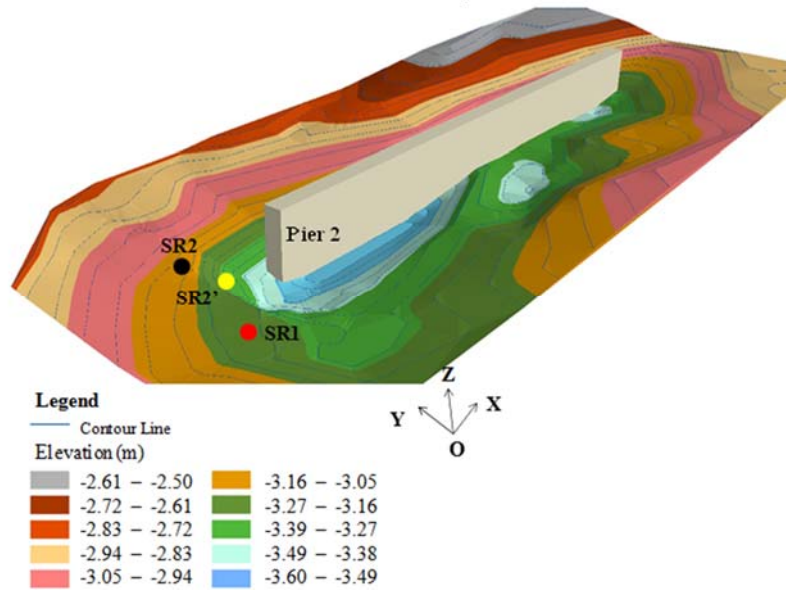


Figure 5.20. Two smart rock locations near the scour hole around Bent 2.

5.4. US63 Hwy Gasconade River Bridge

The US63 Bridge (No. A3760) over the Gasconade River located approximately 9 km southeast of Vienna in Maries County, MO, was used as the third test site to validate the performance of a smart rock. As shown in Figure 5.21, the bridge is a 12-span continuous reinforced concrete-girder structure to support two lanes of two-way traffic on US Highway 63. Pier 4 is located in the main channel of water flow and potentially subjected to severe contraction scour and local scour during flood events.



Figure 5.21. The US Highway 63 Gasconade River Bridge.

5.4.1. Test setup and layout

To date, two field tests were carried out in different seasons to validate the localization algorithm of one smart rock. Both were conducted near Bent 4 with one lane of the roadway closed for operation safety. Figure 5.22 shows the overall test plan and setup at the US63 bridge site. The test crane with an attached sensor head of the 3-axis digital magnetometer was mounted on a flatbed trailer towed by a truck. The trailer was parked on the bridge deck at three stops (S1, S2 and S3 with 4.5 m equal spacing) along each of the two paths (P1 and P2 with 2 m spacing). For each stop, seven elevations (E1 to E7 with 0.3 m equal spacing) were considered for magnetic field measurements. Therefore, a total of 42 measurements were taken near Bent 4 in order to locate the smart rock SR1. A total station was used to survey the smart rock and the magnetometer sensor for ground truth coordinate data.

5.4.2. Test procedure

The step-by-step test procedure is the same as that for the I-44 Roubidoux Creek Bridge, MO. The exception to that procedure is that the time-varying AMF for reference is not analyzed since no smart rock movement is calculated. As such, only key different features about the US63 Gasconade River Bridge, MO, are discussed below.

As shown in Figure 5.22, the total station was set near Bent 1 on the Jefferson City side of the bridge for its line of sight to the magnetometer sensor. The center of the total station, Point O, was selected as the origin of a global coordinate system O-XYZ. The Y-axis was set along the south-bound traffic direction towards Rolla, MO. Perpendicular to the Y-axis in horizontal plane, the X-axis pointed to the upstream of the River. The Z-axis pointed upward according to the right-hand rule.

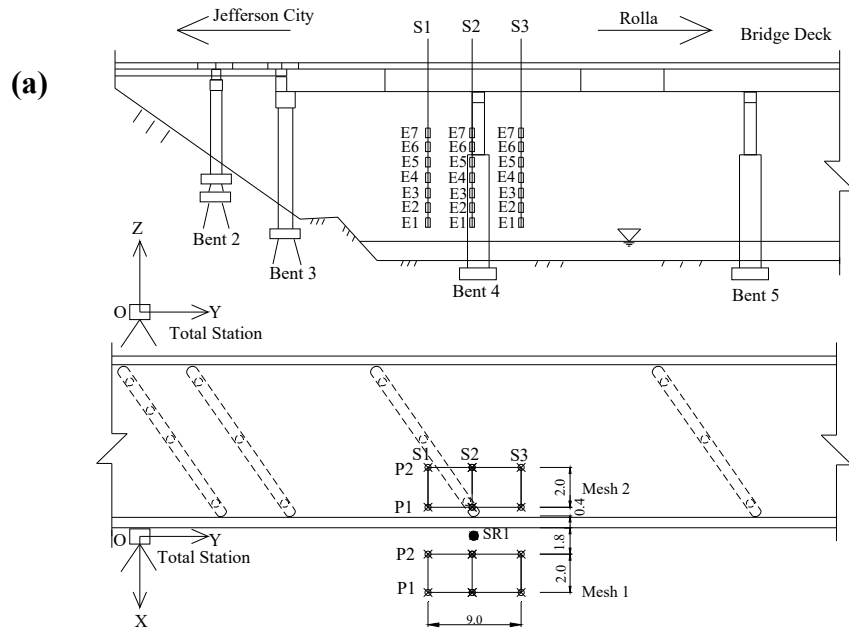


Figure 5.22. US63 Bridge site: (a) planning (unit: m), and (b) test setup.

The AMF was measured prior to the deployment of the smart rock, following the (path, stop, elevation) sequence as shown in Figure 5.23. At each stop, measurements were taken at seven elevations for both coordinate and magnetic field intensity. Note that one forklift position on the bridge deck is related to seven sensor positions by moving the forklift up and down as indicated in Figure 5.22(b).

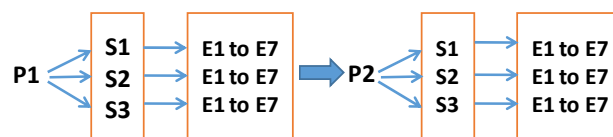


Figure 5.23. Measurement sequence.

During the first series of tests, one smart rock SR1 with one N45 magnet in the APUS configuration as shown in Figure 5.24 was dropped from the bridge deck into water around the upstream side of Bent 4 for maximum scour depth monitoring. The smart rock was tied to a rope and lowered down from the bridge deck to the river bottom at the predetermined area as indicated in Figure 5.25. Due to strong water current at the time, it was determined to be unsafe to ride a small boat around the deployed smart rock and get its location measured with the total station. During the second series of field tests, it was found that the smart rock deployed previously was washed away during the December 2015 flood. Thus, another smart rock SR1 (identical to the previous one) was deployed. During the second series of field tests, however, the smart rock was buried in the riverbed such that the top of the smart rock was flush with the riverbed surface to make it more stable under strong current. After the deployment of the smart rock, the total magnetic field combining the effects of the smart rock and the AMF was measured following the same sequence as used for AMF measurement, as shown in Figure 5.23.

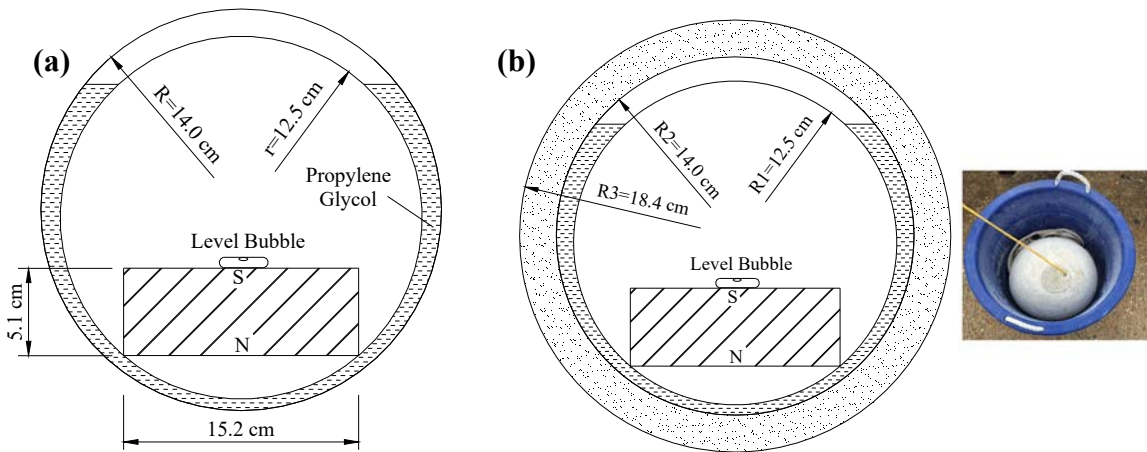


Figure 5.24 Smart rock SR1: (a) schematic view and (b) prototype.

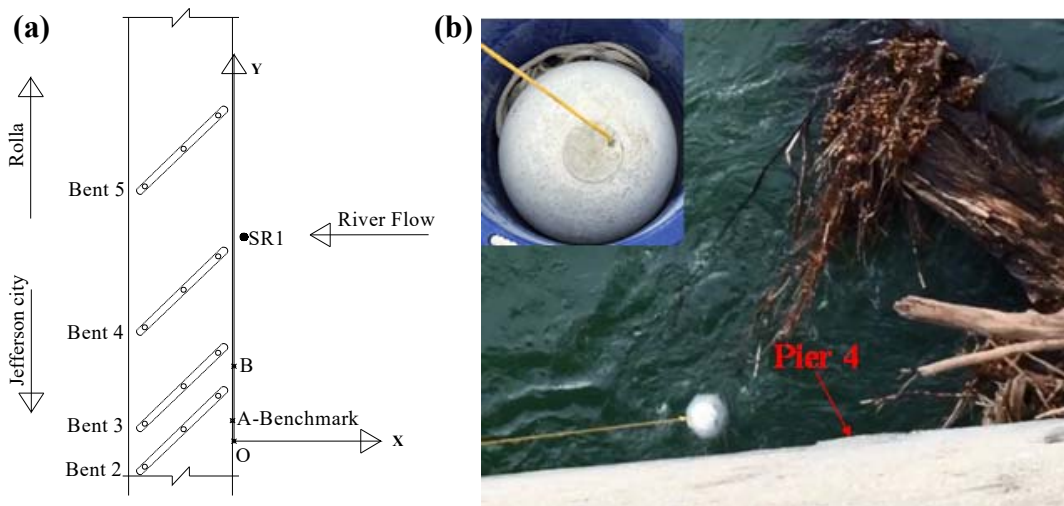


Figure 5.25 Smart rock SR1: (a) location and (b) deployment.

5.4.3. Test results and discussion

The first series of field tests were carried out on December 11, 2015. Since the ground truth data of the smart rock was not available, the location prediction error cannot be evaluated. The second series of field tests were performed on October 18, 2016. The measured coordinates, ambient and total magnetic fields are summarized in Table 5.13.

The localization algorithm as discussed in Section 4.2.3 was used to locate the smart rock based on the measured coordinates of measurement points, AMF intensities, and the total magnetic field intensities as well as $k=101,770 \text{ nT}\cdot\text{m}^3$ that was calculated from the maximum residual flux density of a N45 magnet. The predicted and measured coordinates of the smart rock SR1 are compared in Table 5.14.

Table 5.13. Coordinates and magnetic field intensities at measurement points

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			Total Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{AX}^{(M)}$	$B_{AY}^{(M)}$	$B_{AZ}^{(M)}$	$B_T^{(M)}$	
P1S1	E1	-3.06	64.04	-11.35	-1.605	-0.557	-4.767	5.093
	E2	-3.12	64.02	-11.02	-1.601	-0.536	-4.766	5.085
	E3	-3.10	64.06	-10.75	-1.630	-0.548	-4.750	5.079
	E4	-3.11	64.02	-10.43	-1.626	-0.525	-4.750	5.072
	E5	-3.10	64.03	-10.13	-1.629	-0.514	-4.744	5.066
	E6	-3.09	64.04	-9.82	-1.635	-0.520	-4.735	5.058
	E7	-3.11	64.06	-9.56	-1.646	-0.508	-4.726	5.052
P1S2	E1	-3.25	68.53	-11.42	-1.676	-0.667	-4.685	5.052
	E2	-3.29	68.56	-11.09	-1.644	-0.663	-4.691	5.046
	E3	-3.27	68.59	-10.82	-1.705	-0.692	-4.662	5.041
	E4	-3.26	68.50	-10.50	-1.710	-0.673	-4.660	5.035
	E5	-3.26	68.53	-10.21	-1.696	-0.733	-4.649	5.031
	E6	-3.27	68.54	-9.90	-1.681	-0.667	-4.660	5.025
	E7	-3.29	68.54	-9.61	-1.731	-0.651	-4.642	5.018
P1S3	E1	-3.10	73.07	-11.51	-1.754	-0.801	-4.625	5.016
	E2	-3.10	72.94	-11.14	-1.774	-0.781	-4.617	5.012
	E3	-3.11	72.98	-10.88	-1.771	-0.730	-4.621	5.008
	E4	-3.12	73.00	-10.55	-1.794	-0.736	-4.608	5.004
	E5	-3.13	73.00	-10.26	-1.797	-0.758	-4.598	5.000
	E6	-3.13	73.00	-9.97	-1.790	-0.746	-4.597	4.996
	E7	-3.13	73.04	-9.67	-1.827	-0.744	-4.580	4.992
P2S1	E1	-1.26	64.13	-11.31	-1.633	-0.513	-4.739	5.089
	E2	-1.29	64.13	-10.99	-1.651	-0.496	-4.730	5.078
	E3	-1.28	64.10	-10.69	-1.648	-0.470	-4.730	5.068
	E4	-1.31	64.08	-10.39	-1.654	-0.456	-4.724	5.057
	E5	-1.27	64.14	-10.11	-1.654	-0.490	-4.712	5.047
	E6	-1.26	64.11	-9.82	-1.626	-0.404	-4.726	5.038
	E7	-1.27	64.14	-9.51	-1.658	-0.445	-4.699	5.027

Table 5.13. Coordinates and magnetic field intensities at measurement points (Cont'd)

Measurement Point	Coordinate (m)			AMF Intensity (10^4 nT)			Total Intensity (10^4 nT)	
	X_i	Y_i	Z_i	$B_{AX}^{(M)}$	$B_{AY}^{(M)}$	$B_{AZ}^{(M)}$	$B_T^{(M)}$	
P2S2	E1	-0.97	68.69	-11.36	-1.717	-0.672	-4.621	5.019
	E2	-1.14	68.70	-11.08	-1.719	-0.620	-4.624	5.012
	E3	-1.16	68.68	-10.77	-1.726	-0.645	-4.611	5.002
	E4	-1.16	68.64	-10.48	-1.731	-0.672	-4.598	4.993
	E5	-1.15	68.61	-10.17	-1.738	-0.629	-4.597	4.982
	E6	-1.14	68.64	-9.86	-1.735	-0.608	-4.594	4.974
	E7	-1.16	68.63	-9.58	-1.752	-0.565	-4.587	4.963
P2S3	E1	-1.18	73.00	-11.46	-1.750	-0.757	-4.573	4.962
	E2	-1.17	72.93	-11.13	-1.778	-0.693	-4.565	4.956
	E3	-1.20	73.00	-10.86	-1.765	-0.702	-4.559	4.948
	E4	-1.21	72.98	-10.55	-1.777	-0.727	-4.542	4.940
	E5	-1.18	72.97	-10.26	-1.795	-0.682	-4.535	4.933
	E6	-1.21	72.99	-9.96	-1.784	-0.698	-4.526	4.924
	E7	-1.21	72.94	-9.64	-1.778	-0.672	-4.522	4.917

Table 5.14. Predicted and measured location of smart rock SR1

Coordinate	X_M (m)	Y_M (m)	Z_M (m)
Predicted	0.15	66.30	-17.71
Measured	0.41	66.02	-17.46
Component Error	-0.26	0.28	0.25
SRSS Total Error	0.46 m		

Figure 5.26 shows both the measured (M_SR1) and the predicted (P_SR1) locations on the three-dimensional contour map of the riverbed in the coordinate system O-XYZ. The prediction error in rock positioning was 0.46 m , which is less than the error limit of 0.5 m for engineering application. This level of error is much larger than that at other bridge sites mainly because of high elevation of the Gasconade River Bridge and thus a measurement distance of up to 8 m .

5.5. Summary

In this section, the smart rock technology developed and validated in Sections 2 to 4 was applied and further validated at three bridge sites (one in California and two in Missouri) for monitoring of scour depth or rip-rap effectiveness. The smart rocks with an APUS configuration were deployed around the scour critical pier or abutment. Their location and movement were evaluated based on a localization algorithm using the measured ambient (three components) and total magnetic fields at various measurement points around the smart rocks. All measurements were taken on the bridge deck using a commercial digital 3-axis magnetometer. A custom-designed test crane was built to support the magnetometer sensor, and mounted on a flatbed trailer to facilitate the field

measurement above water at close distance to the deployed smart rock. A total station was used to survey the deployed smart rocks and measurement points for ground truth coordinate data that are used to evaluate the accuracy of the predicted smart rock locations.

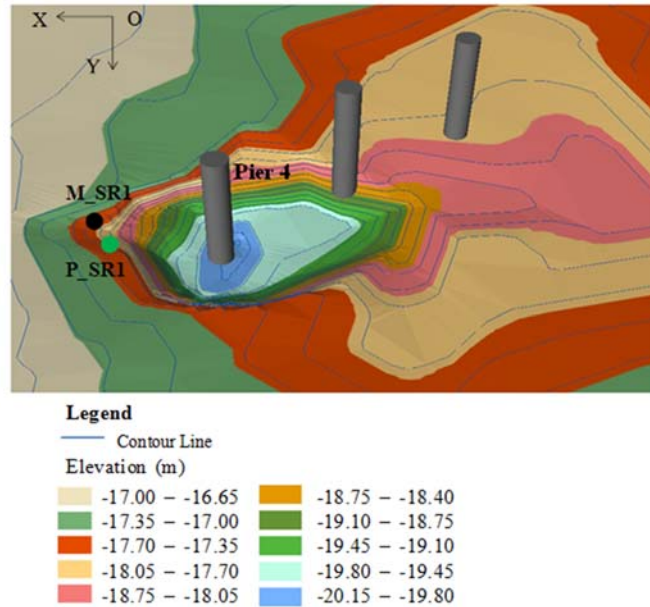


Figure 5.26. The measured and predicted smart rock locations on the riverbed profile.

The localization of single smart rocks deployed at the three bridge sites was successful with a prediction error of less than 0.5 m , a target rock positioning accuracy set forth for engineering application. However, the localization error for two smart rocks deployed at the Highway 1 Waddell Creek Bridge site exceeded 1 m , which is unsatisfactory in application. When placed in close distance, e.g., 3.4 m , individual smart rocks were difficult to identify and locate.

The smart rock movement was discussed only at the I-44 Roubidoux Creek Bridge site based on the available field measurements in different seasons. The predicted displacements were in general agreement with the ground truth data. The prediction error was likely caused by a potentially misplaced measurement bar in the process of smart rock survey.

The spherical smart rock directly placed between rip-rap rocks on the abutment embankment of the Waddell Creek Bridge was unstable due to lack of interlock with the natural rocks. They were washed away during high tide waves from the Pacific Ocean. Smart rocks directly placed on top of the riverbed at the Waddell Creek Bridge and US63 Gasconade River Bridge sites were also washed away due to high tides and the December 27, 2015, flood, respectively. Additional smart rocks were thus deployed for future monitoring by making the top of the smart rocks flush with the riverbed surface.

6. CONCLUSIONS AND FUTURE WORK

6.1. Main Findings from the Overall Project

In this report, a novel smart rock technology with embedded magnet(s) has been developed for the monitoring of bridge scour and rip-rap effectiveness, and demonstrated at three bridge sites. Once properly designed, a smart rock functions like a field agent deployed around a bridge pier for rock positioning, and rolls to the bottom of a scour hole around the bridge pier. The position of the rock can be transformed to the maximum scour depth that is critical in bridge design and maintenance. The change in smart rock position can also be indicative of the disassembling process of a rip-rap mitigation measure. Therefore, a smart rock can also be referred to as a “scour and movement sensor” for scour depth measurement and rip-rap effectiveness monitoring.

The key technical challenge is to locate the smart rock before, during, and after a flood event. To address this challenge, three types of smart rocks with Arbitrarily Oriented System (AOS), Automatically Pointing South System (APSS), and Automatically Pointing Upward System (APUS) were developed and characterized in an open field and at a bridge site. Several localization algorithms were formulated based on the minimization of an objective error function between the predicted and measured magnetic field intensities. Based on extensive test data and localization analysis, the following main conclusions can be drawn:

- (1) The first model of smart rock with an AOS configuration was developed by directly embedding a magnet into concrete encasement. It is small in size and easy to fabricate, but less efficient in computational time to determine the arbitrary orientation of the embedded magnet. This model is not recommended for practical application.
- (2) The second model of smart rock with an APSS configuration was developed by making a magnet free to rotate like a compass needle so that the magnet is always oriented in approximate alignment with the geographic south of the Earth. This model simplifies the process of rock localization with the known magnet orientation. To locate the APSS effectively and accurately, a sufficient number of measurements should be taken along the extension of the south and north poles of the magnet since the field intensity at two poles is twice as much as that at equators. Thus, the APSS is most desirable when measured at river banks.
- (3) The third model of smart rock with an APUS configuration was developed by making the south pole of a magnet point upward with unbalanced weights, which is most desirable when measurements are taken from the bridge deck in bridge scour monitoring. In comparison with the APSS, the gravity-controlled APUS (e.g. orientation) is less affected by steel reinforcement and other ferromagnetic substances when deployed in proximity of a bridge pier, thus improving the accuracy of rock localization.
- (4) For the purpose of rock localization, the effective measurement distance of a cylinder magnet depends on the maximum residual flux density and volume of the magnet and its relation with the measurement station. The larger the flux density and/or the volume, the stronger the magnetic field generated by the magnet and the further the measurement distance for effective magnetic field

intensity. For a cylindrical magnet (N42), the most sensitive and reliable measurement distance ranges from 1.5 m to 7.5 m .

- (5) The localization errors for smart rocks with AOS and APSS configurations at the open field site were less than 10 cm , which is quite accurate and satisfactory. Their localization errors in the open river bank area near a bridge pier at the Gasconade River Bridge site were between 10 cm and 20 cm . In addition to potential non-collocation of the measurement point, the magnetometer sensor, and the AMFOD device, the APSS may be subjected to a small rotation of the magnet in the ambient magnetic field particularly when placed near the bridge pier.
- (6) In comparison with the APSS, the gravity-controlled APUS is not affected by the presence of steel reinforcement in nearby bridge piers in application. The smart rocks with the APUS were implemented around scour critical piers of the three bridges. A single smart rock was successfully located with an accuracy of less than 0.5 m , a target set forth with bridge engineers. However, the localization of two smart rocks led to a prediction error of over 1.0 m . This is mainly attributed to the non-optimal selection and distribution of measurement points due to physical limits, and the error in ground truth data for the location of smart rocks underwater.
- (7) At the I-44W Roubidoux Creek Bridge site, the prediction errors of one smart rock with the APUS were less than 35 cm based on three series of field tests in different seasons. The reasons for the errors may include the influence of passing vehicles during intensity measurements, the non-collocation of measurement points and the sensor head as a result of wind induced movement, and the potentially-misplaced bar in the process of acquiring ground truth location of the smart rock.
- (8) At the State Hwy1 Waddell Creek Bridge site, the smart rock deployed around the south abutment was located with a prediction error of 0.36 m mainly due to wind induced movement of the sensor. The single smart rock deployed near Bent 2 was located with a prediction error of 0.27 cm , which was less than the diameter of the smart rock and acceptable for engineering application.
- (9) At the US Hwy63 Gasconade River Bridge site, the smart rock deployed in the upstream of Bent 4 was located with a prediction error of 0.46 m , which is still acceptable for engineering application. The larger error at this particular site was largely because this bridge is much higher than the other two bridges and the measurement points are farther away from the deployed smart rock.

6.2. Future Work

Although the potential of the smart rock technology has been successfully demonstrated to certain extent in an open field and at three bridge sites, this project represents the first study of smart rock implementation. For practical applications, several improvements can be made in the following directions:

- (1) The spherical smart rocks with 0.368 m in diameter and a density of 1495 kg/m^3 deployed at three bridge sites were designed based on the critical velocity of water flow. The rocks directly placed on the riverbed at the State Hwy1 Waddell Creek Bridge and the US Hwy63 Gasconade River Bridge

sites were washed away due to tidal waves from the Pacific Ocean in California and the December 27, 2015, flood in Missouri, respectively. For the monitoring of rip-rap effectiveness, a polyhedral shape of smart rocks is recommended since it can provide the interlock with other natural rocks in the rip-rap measure. For the measurement of scour depth, spherical rocks may be embedded in deposits to ensure their top is flush with the riverbed surface and increase their resistance to water current. More studies to derive accurate hydraulics data at bridge sites are needed to improve the design of smart rocks.

- (2) The custom-built crane used to facilitate the field tests for measurements at close distance to the deployed smart rocks has been demonstrated to be effective. However, assembling such a crane takes more than one hour and its operation requires lane closure on the bridge deck. The awkward crane also limits the number of measurement points in application. Therefore, future research is directed to the development of a mobile platform with an unmanned aerial vehicle (UAV) so that measurements can be taken above water in the vicinity of bridge piers without interrupting traffic on the bridge. The effects of the UAV on the magnetic field and the operation speed on the measured data need to be investigated.
- (3) Using a total station to survey smart rocks and magnetometer sensors for their coordinates is viable during field tests but not conducive in terms of efficiency and accuracy. A high accuracy positioning system that is integrated into the smart rocks and magnetometer sensors would be desirable.
- (4) The Earth's magnetic field and the secondary field of magnetized ferromagnetic substances at and around a bridge change over time. After smart rocks have been deployed near the bridge, the time-varying measurements can no longer be taken accurately. Therefore, a well-calibrated mathematic model of the ambient magnetic field at the bridge site was highly desirable so that the time-varying magnetic field can be simulated consistently and accurately.

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