SYSTEM AND PROCESS ASSESSMENT RESEARCH LABORATORY

SPAR Lab

Civil, Architectural and Environmental Engineering • 103/104-E Butler-Carlton Hall

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

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MISSOURI S&T

Outline of This Presentation

- The Smart Rock Monitoring Concept
- Design and Prototyping
- Localization and Effectiveness
- Field Test Demonstration
- Concluding Remarks

THE SMART ROCK MONITORING CONCEPT

- **Two Application Scenarios**
  - **Scour Depth**
    - ✓ ***Deposits at a bridge pier or abutment are washed away to form a scour hole with unknown location and depth.***

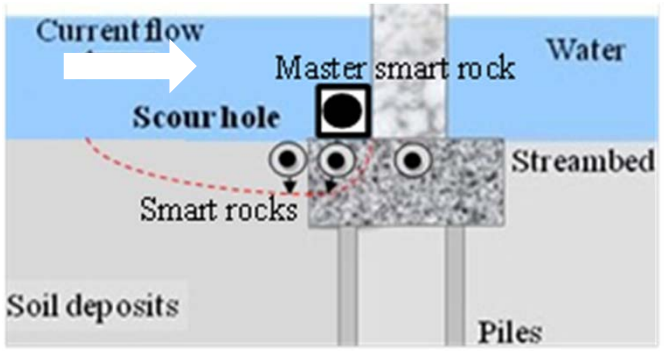


Fig. 1 Maximum Scour Depth Monitoring

  - **Countermeasure Effectiveness**
    - ✓ ***Move of rocks leads to the loss of a rip-rap countermeasure for bridge scour protection.***

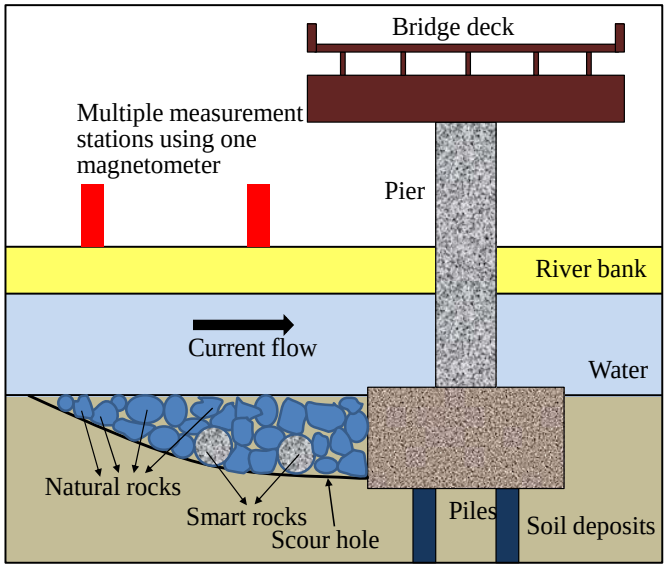


Fig. 2 Scour Countermeasure Monitoring

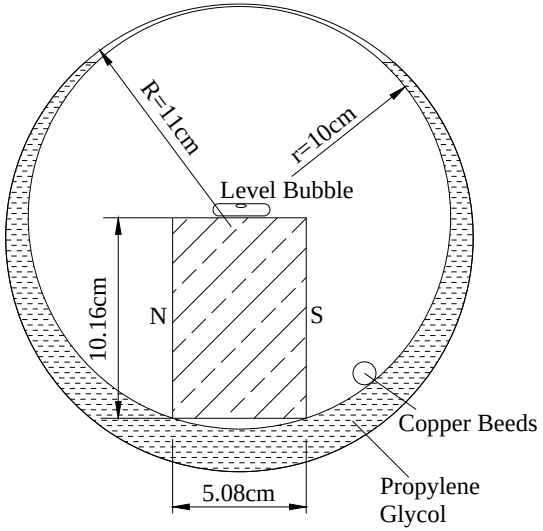
DESIGN AND PROTOTYPING

- **Arbitrarily Oriented System *(AOS)***
  - ✓ ***Monitored along the river bank or on the bridge deck***
  - ✓ ***Most complicated in smart rock localization***

AOS Model of Smart Rocks

DESIGN AND PROTOTYPING

- **Automatically Pointing-South System *(APSS)***
  - ✓ ***Monitored along the river bank***
  - ✓ ***Measurement station located in South or North pole of the magnet***
  - ✓ ***Rapid convergence and high accuracy of APSS location***
  - ✓ ***However, easily affected by ferromagnetic substances***



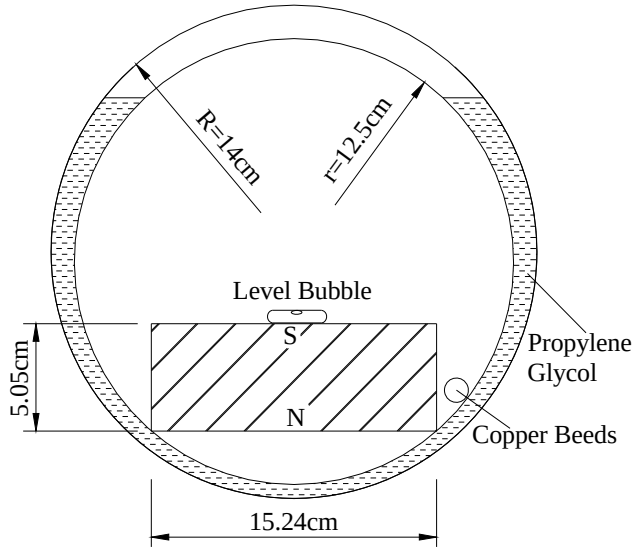
(a) Schematic View

(b) Prototype Smart Rock

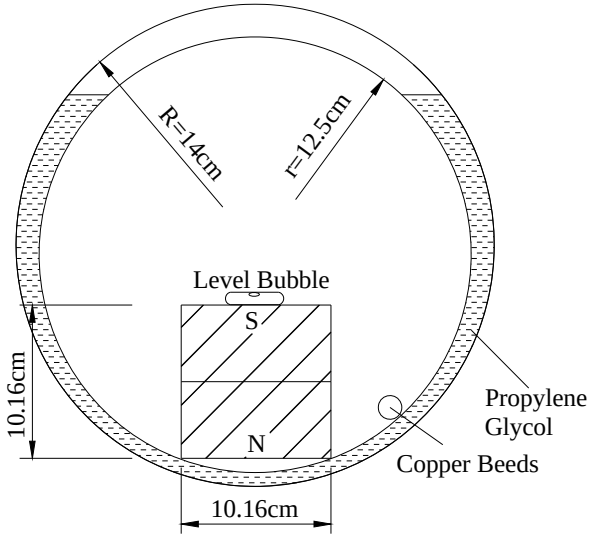
APSS Model of Smart Rocks

DESIGN AND PROTOTYPING

- **Automatically Pointing-Up System (APUS)**
  - ✓ ***Automatically Pointing to Upward System (APUS)***
  - ✓ ***Measurement apparatus set on the bridge deck***
  - ✓ ***Gravity-orientated direction, reduces the degree of freedom, less effect by ferromagnetic substance***



(a) One N45 Magnet



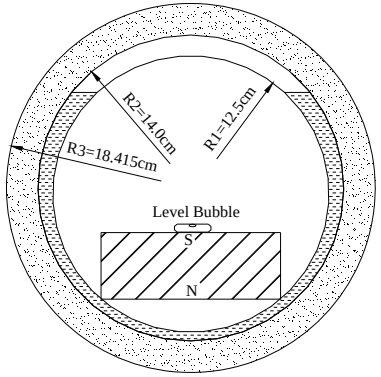
(b) Two N42 Magnets

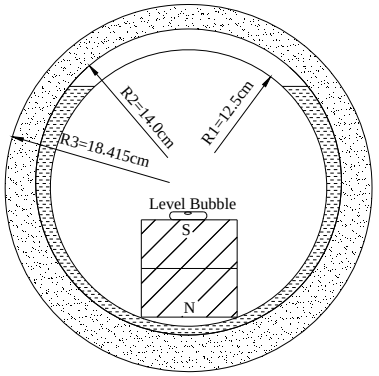
(b) Prototype Smart Rock

DESIGN AND PROTOTYPING

- **Concrete Encasement and Fabrication**
  - ***36.83-cm-diameter mold with a concrete density of 1495 kg/m^3***
  - ***Fabrication process***

One N45 Magnet





Two Stacked N42 Magnet

1. Mix fiber concrete

2. Place APUS inside a mold

3. Fill the mold with concrete

4. Cure the concrete in water for 14 days

LOCALIZATION AND EFFECTIVENESS

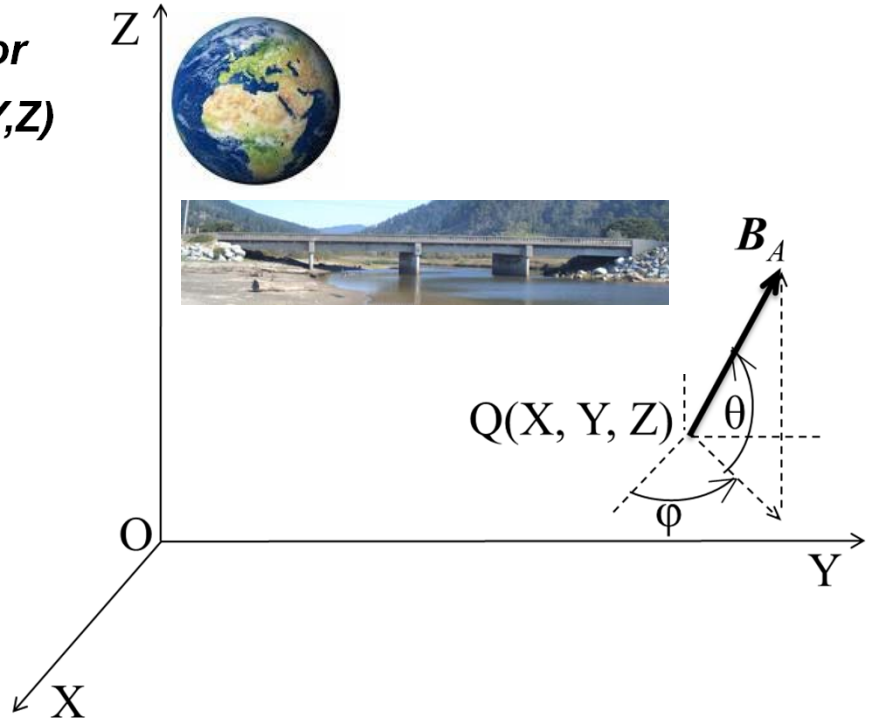
- **Ambient Magnetic Field at Q Station in Absolute XYZ Coordinate System**
  - ✓ ***Ambient Ferromagnetic Substances***
  - ✓ ***B_A, Ambient Magnetic Field Vector at a Measurement station, Q (X,Y,Z)***
  - ✓ ***Three components of B_A:***

$$B_{XA} = B_A \cos\theta \cos\varphi$$

$$B_{YA} = B_A \cos\theta \sin\varphi$$

$$B_{ZA} = B_A \sin\theta$$

  - ✓ ***B_A, measured by magnetometer***
  - ✓ **θ (0, π) and φ θ (0, 2π) measured by an orientation device**

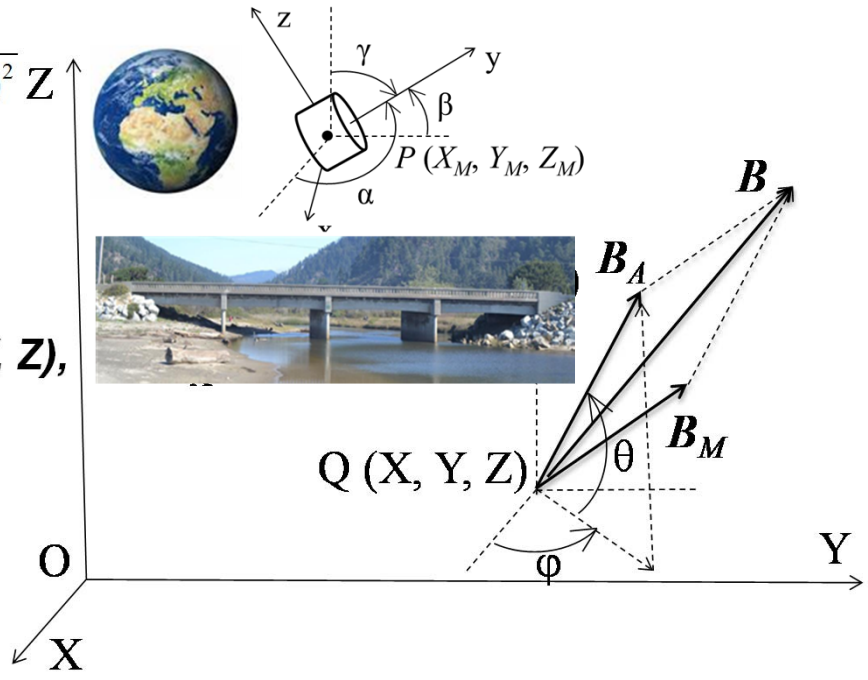


LOCALIZATION AND EFFECTIVENESS

- **Total Magnetic Field at Q Station in Absolute XYZ Coordinate System**
  - ✓ ***Total Magnetic field intensity:***

$$B = \sqrt{(B_{XM} + B_{XA})^2 + (B_{YM} + B_{YA})^2 + (B_{ZM} + B_{ZA})^2}$$

  - ✓ ***B = B (B_A, θ, φ, k, X_M, Y_M, Z_M, α, β, γ, X, Y, Z) at a Measurement station, Q (X,Y,Z)***
  - ✓ **Given *k, θ , φ and B_A at each (X, Y, Z), B = B (X_M, Y_M, Z_M, α, β, γ)***
  - ✓ **Magnet's effect:**



$$\begin{pmatrix} B_{XM} \\ B_{YM} \\ B_{ZM} \end{pmatrix} = \mathbf{T}^{-1} \begin{pmatrix} k3xy/r^5 \\ k(2y^2 - x^2 - z^2)/r^5 \\ k3zy/r^5 \end{pmatrix}$$

$$\mathbf{T} = \begin{bmatrix} \cos\beta\cos\gamma & \cos\beta\sin\gamma & -\sin\beta \\ \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\cos\beta \\ \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\cos\beta \end{bmatrix}$$

LOCALIZATION AND EFFECTIVENESS

- **Localization Algorithm**
  - **Unknown Orientation**
    - ✓ ***SRSS error between predicted intensity*** $B_i^{(P)}$ ***and the measured intensity*** $B_i^{(M)}$ ***,***

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

$$\frac{\partial J(X_M, Y_M, Z_M, \alpha, \beta, \gamma)}{\partial X_M} = 0 \qquad \frac{\partial J(X_M, Y_M, Z_M, \alpha, \beta, \gamma)}{\partial Y_M} = 0$$

$$\frac{\partial J(X_M, Y_M, Z_M, \alpha, \beta, \gamma)}{\partial Z_M} = 0 \qquad \frac{\partial J(X_M, Y_M, Z_M, \alpha, \beta, \gamma)}{\partial \alpha} = 0$$

$$\frac{\partial J(X_M, Y_M, Z_M, \alpha, \beta, \gamma)}{\partial \beta} = 0 \qquad \frac{\partial J(X_M, Y_M, Z_M, \alpha, \beta, \gamma)}{\partial \gamma} = 0$$

  - **Known Orientation *(α=0, β=0, and γ=0)***

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

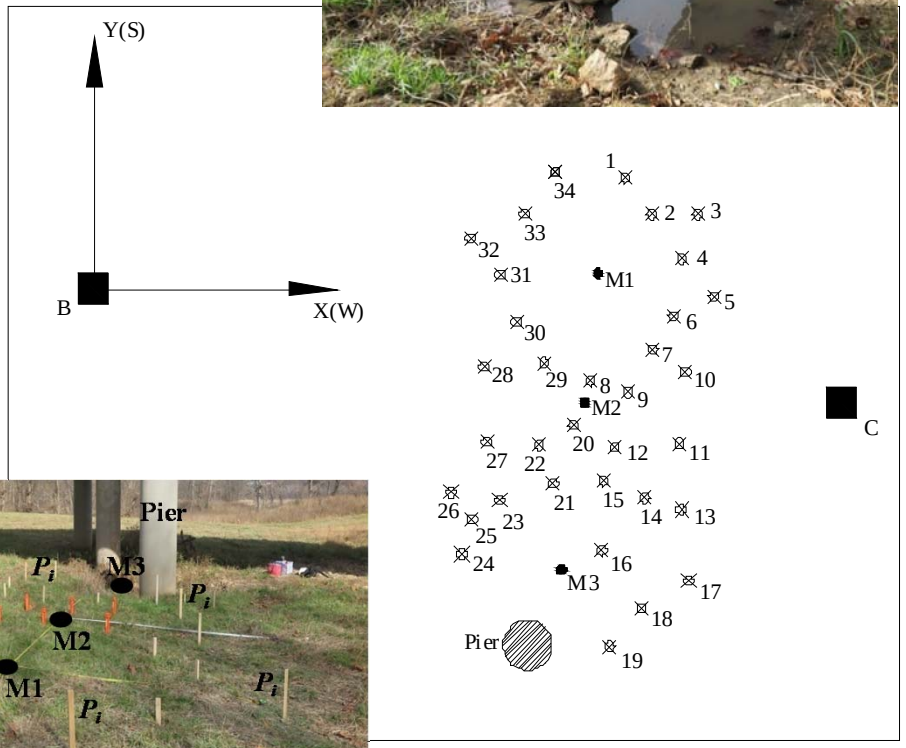
$$\frac{\partial J(X_M, Y_M, Z_M)}{\partial Y_M} = 0 \qquad \frac{\partial J(X_M, Y_M, Z_M)}{\partial Z_M} = 0 \qquad \frac{\partial J(X_M, Y_M, Z_M)}{\partial X_M} = 0$$

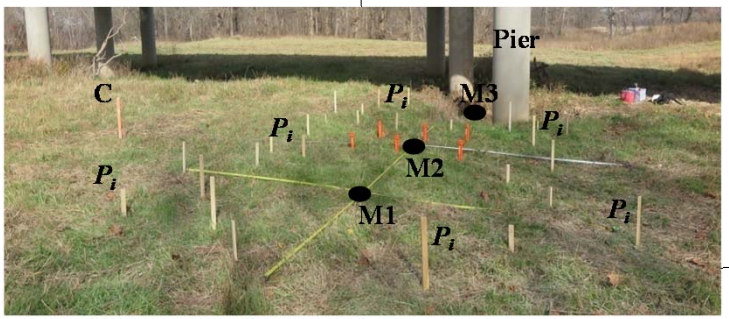
LOCALIZATION AND EFFECTIVENESS

- **Experimental Validation Procedure**
  - **Before a smart rock is deployed, the ambient magnetic field of the Earth and environmental effects was evaluated at each measurement point either by a scalar magnetometer and an orientation device or by a three-component magnetometer.**
  - **After the smart rock is deployed, the total magnetic field of the magnet and the ambient field was measured with the same magnetometer at various points around the smart rock.**
  - **The coordinates of measurement points were surveyed by a total station – a survey instrument.**
  - **The intensity and coordinate measurements at six or more stations allowed the determination of the smart rock's location.**

LOCALIZATION AND EFFECTIVENESS

- **Experimental Validation**
  - ***Test Setup***
    - ✓ ***A scour experienced pier***
    - ✓ ***Three Locations M1, M2, and M3 for AOS and APSS***
    - ✓ ***Total 34 measurement points***
    - ✓ ***Total Station at Point B to survey coordinates of three smart rocks' locations and 34 sensor positions***
    - ✓ ***MFDD was set at the 34 points to measure the angles of θ and φ***





LOCALIZATION AND EFFECTIVENESS

- **Experimental Validation**
  - **Test Results ($M3_{APSS}$)**

Location of Sensor Head	X(m)	Y(m)	Z(m)	$B_i^{(M)}$ (nT)
P9	10.940	-2.065	-0.657	52766
P11	11.991	-3.082	-0.558	52422
P12	10.670	-3.162	-0.670	55203
…	…	…	…	…
P20	9.822	-2.717	-0.635	55164
P21	9.413	-3.877	-0.748	63734
P23	8.313	-4.215	-0.501	59204
P25	7.750	-4.591	-0.858	58350
P26	7.315	-4.055	-0.726	56087
P27	8.043	-3.046	-0.553	55198
Predicted APSS Location $M3_{APSS}$	**9.527**	**-5.520**	**-1.850**	N/A
Measured APSS Location $M3_{APSS}$	**9.576**	**-5.584**	**-1.822**	
Location Prediction Error for $M3_{APSS}$	**-0.049**	**0.064**	**-0.028**	
SRSS Error in Coordinate	0.085m			

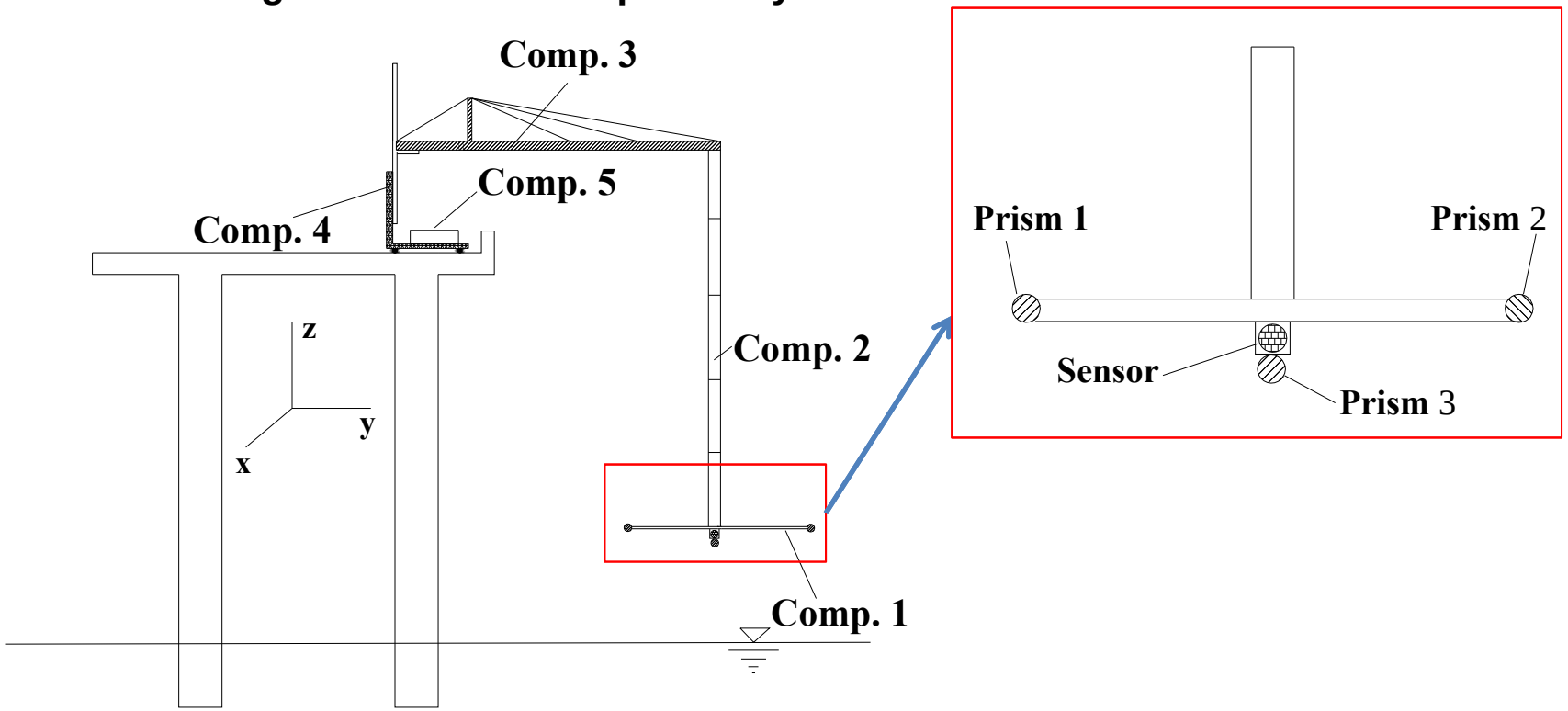
LOCALIZATION AND EFFECTIVENESS

- **Experimental Validation**
  - **Test Results ($M3_{AOS}$)**

Location of Sensor Head	X(m)	Y(m)	Z(m)	$B_i^{(M)}$ (nT)
P9	10.940	-2.065	-0.667	52651
P12	10.670	-3.162	-0.680	54660
P13	12.031	-4.399	-0.745	52095
…	…	…	…	…
P20	9.822	-2.717	-0.645	54929
P21	9.413	-3.877	-0.758	62508
P23	8.313	-4.215	-0.511	59364
P25	7.750	-4.591	-0.868	59523
P26	7.315	-4.055	-0.736	56642
P27	8.043	-3.046	-0.563	55399
Predicted AOS Location $M3_{AOS}$	9.514	-5.519	-1.860	N/A
Measured AOS Location $M3_{AOS}$	9.576	-5.584	-1.837	
Location Prediction Error for $M3_{AOS}$	-0.062	0.065	-0.023	
SRSS Error in Coordinate	0.093m			

FIELD TEST DEMONSTRATION

- **Test "Crane" Design**
  - **Lightweight, easy installation, rapid assembling, and cost effectiveness**
  - **Minimal wind-induced disturbance**
  - **Non-magnetic materials in proximity to the sensor**

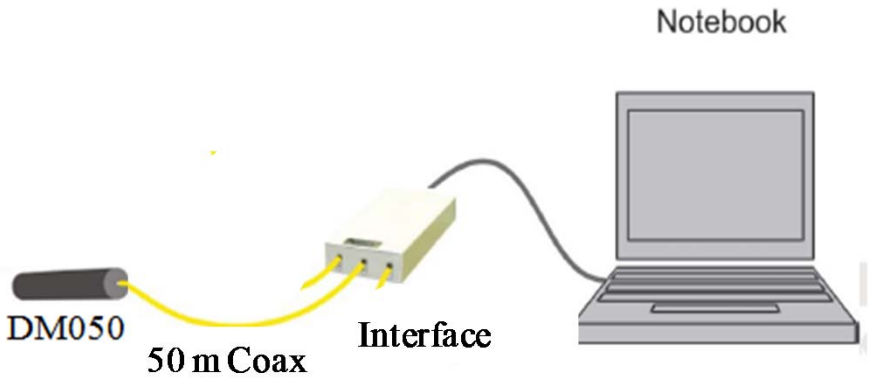


FIELD TEST DEMONSTRATION

- **Test "Crane" Prototype/Product**

FIELD TEST DEMONSTRATION

- **Three-axis Flux Digital Magnetometer (STL)**
  - **Manufactured by Systemtechnic Ludwig GmBH, Konstanz, Germany**
  - **STL DM050: measure X-, Y- and Z- component and total field**
  - **50 meters Coax cable for power and data transmission**
  - **Interface : Coax Ethernet Hub for connection of up to 3 magnetometers**
  - **STL GradMag software installed in a Notebook for full controlling of measurement, data acquisition and viewer**
  - **Field range: ±1,000,000nT**
  - **Resolution: 0.002nT**
  - **Maximum sample rate: 1**



FIELD TEST DEMONSTRATION

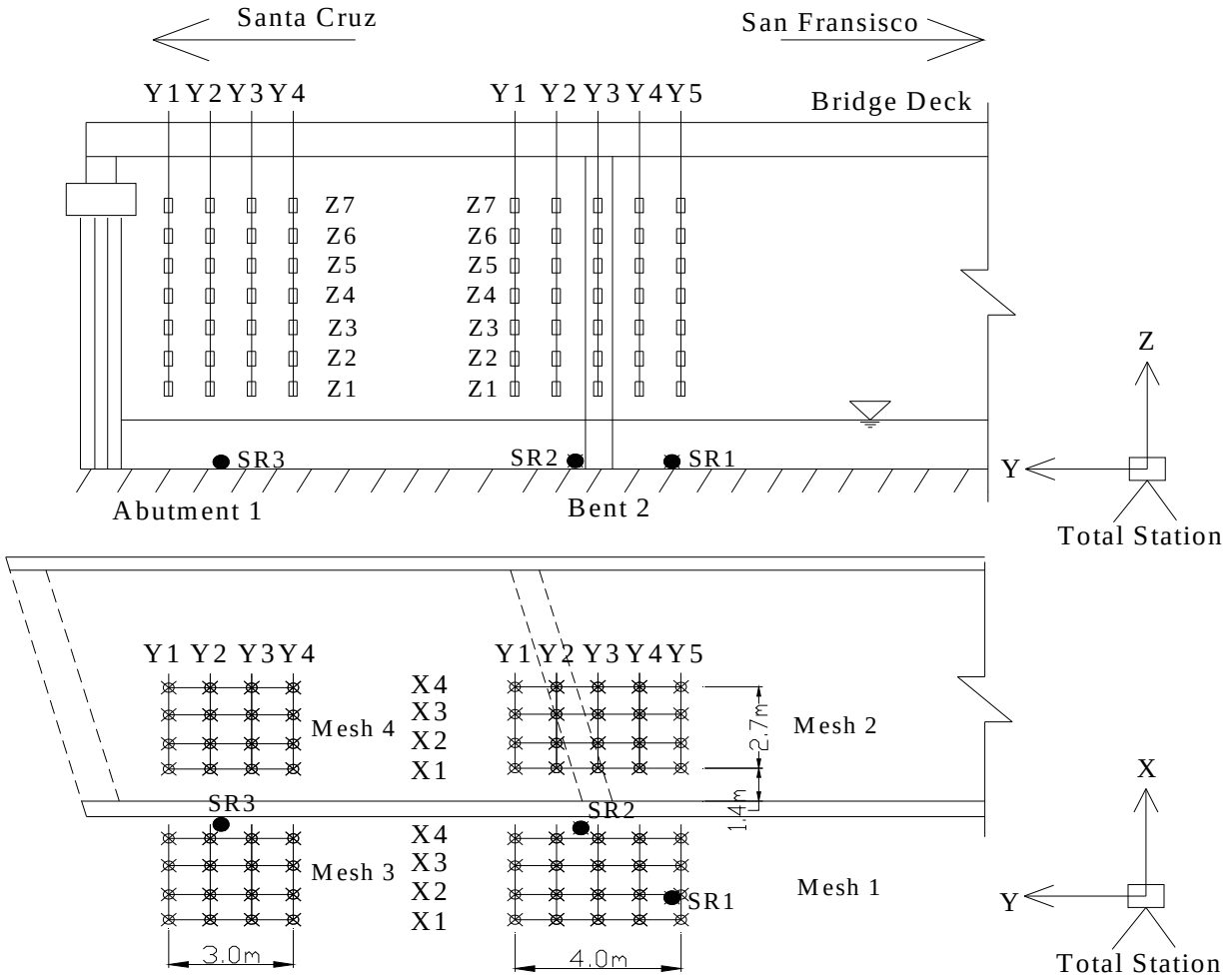
- **HWY1 Waddell Creek Bridge, CA**

FIELD TEST DEMONSTRATION

- **Setup and Layout on Bridge Deck**
- **Test Procedure**
  - **Set a Cartesian Coordinate System**
  - **Ambient Magnetic Field Measurement**
  - **Deployment of Smart Rocks**
  - **Measurement of the Total Magnetic Field**
- **Results from Bridge Deck Measurements**

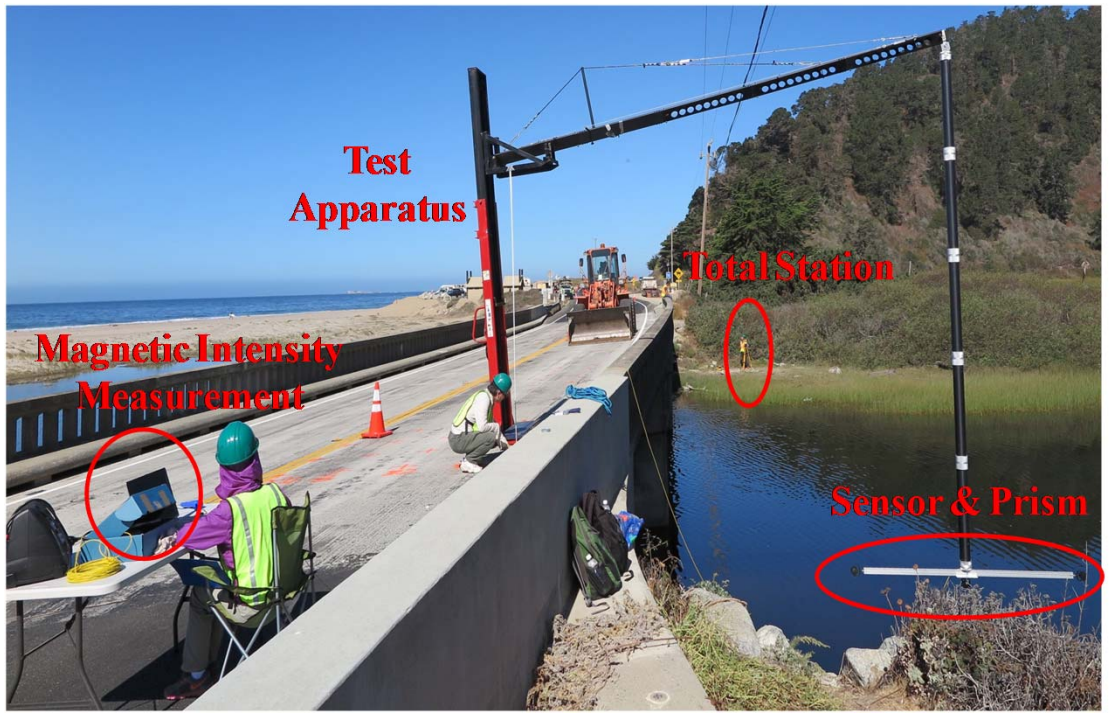
FIELD TEST DEMONSTRATION

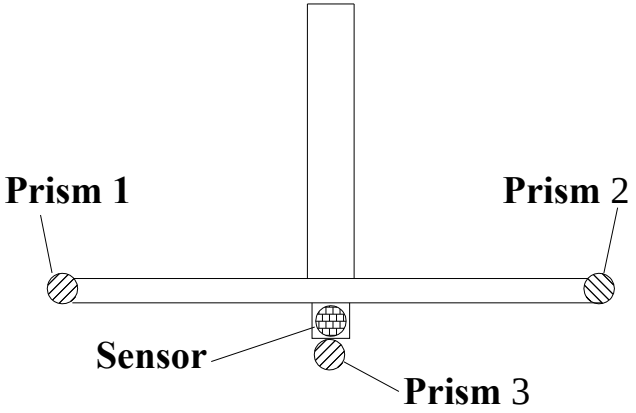
- **Measurement Station Layout on Bridge Deck**

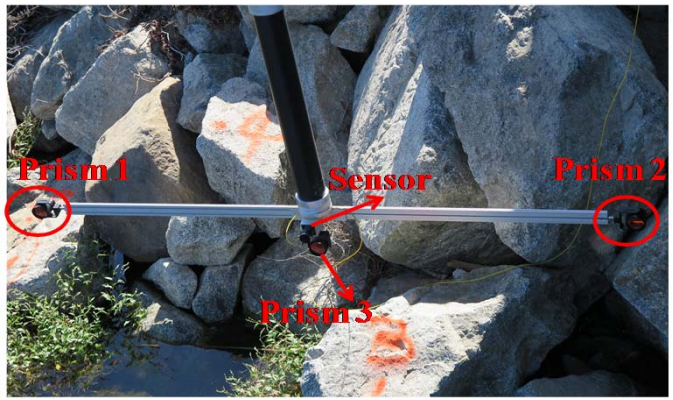


FIELD TEST DEMONSTRATION

- **Test Setup and Layout**

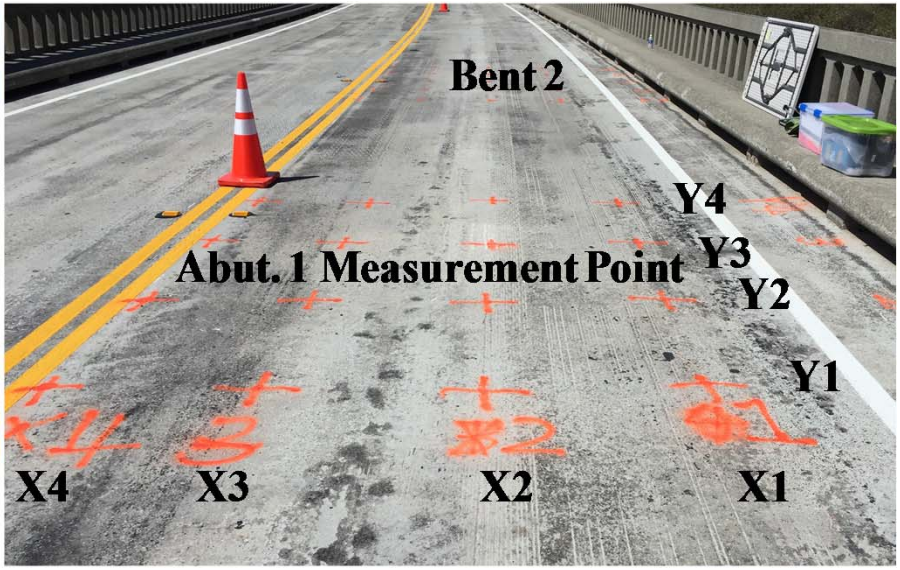






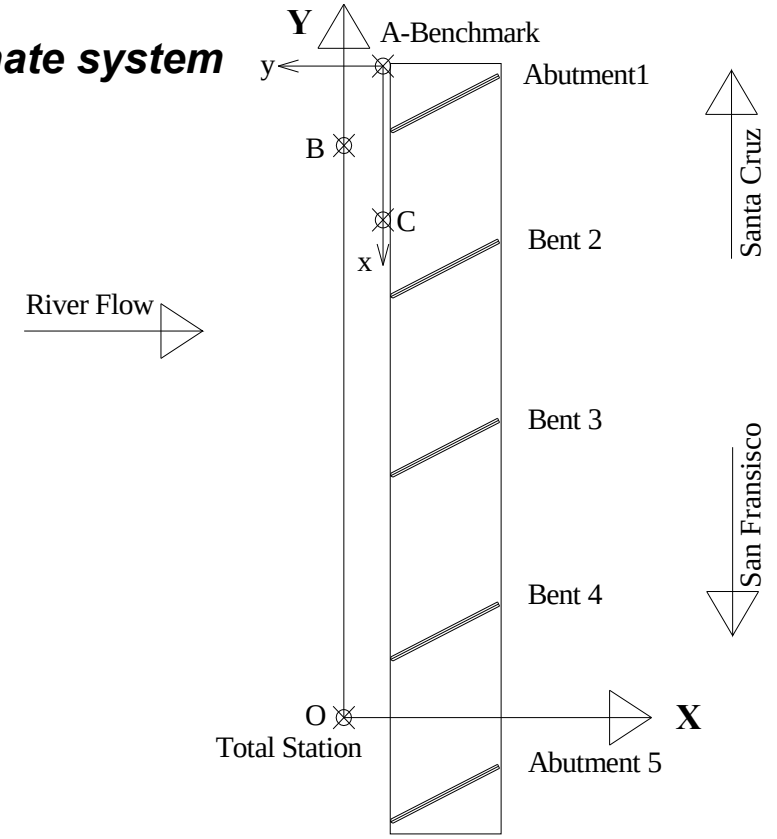
FIELD TEST DEMONSTRATION

- **Test Set up and Layout**
  - **Measurement Points Layout on the Bridge Deck**



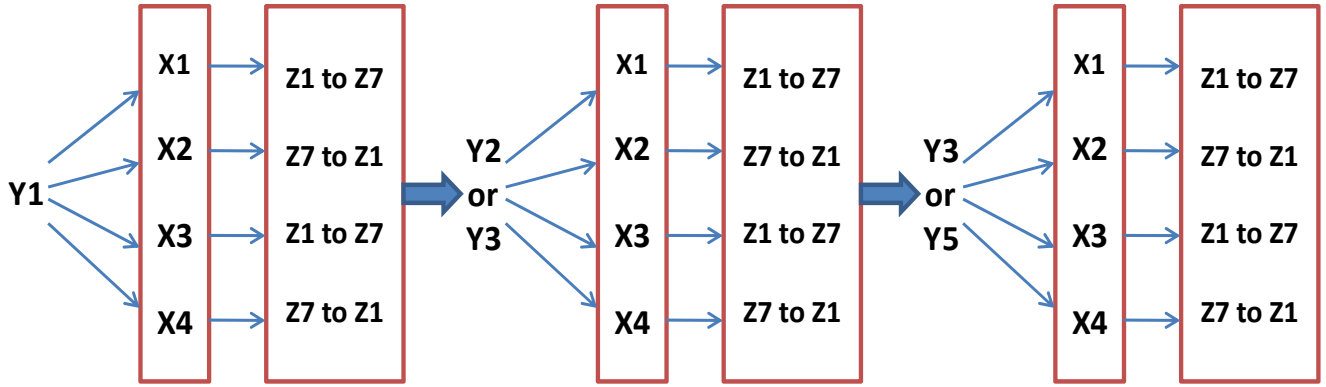
FIELD TEST DEMONSTRATION

- **Test Procedure**
  - **Set a Cartesian coordinate system O-XY**
    - ✓ ***Point A- Permanent Benchmark***
    - ✓ ***Total station at Point A to set coordinate system as A-xy***
    - ✓ ***Survey Point B and O under A-xy coordinate system***
    - ✓ ***Set up total station at Point O to determine the final coordinate O-XY***



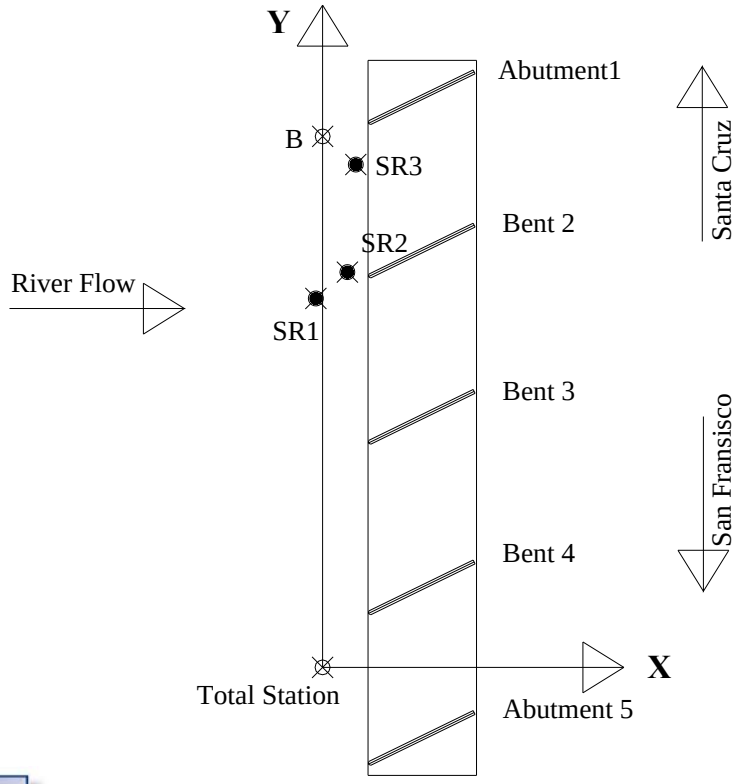
FIELD TEST DEMONSTRATION

- **Test Procedure**
  - **Measure the Ambient Magnetic Field**
    - ✓ ***Magnetic field from Earth and ambient ferromagnetic constructions***
    - ✓ ***Conduct before deployment of the smart rock***
    - ✓ ***Abutment 1 Measurement: Y1, Y2, Y3 along Y axis, X1, X2, X3, X4 along X axis, and Z1,Z2, ..., Z7 along Z axis, total 84 points.***
    - ✓ ***Bent 2 Measurement: Y1, Y3, Y5 along Y axis, X1, X2, X3, X4 along X axis, and Z1,Z2, ..., Z7 along Z axis, total 84 points.***
    - ✓ ***Measurement points sequence:***



FIELD TEST DEMONSTRATION

- **Test Procedure**
  - **Deploy Three Smart Rocks**
    - ✓ ***Smart Rock 1 (SR1) & Smart Rock 2 (SR2) around Bent 2***
    - ✓ ***Smart Rock 3 (SR3) around Abutment 1***

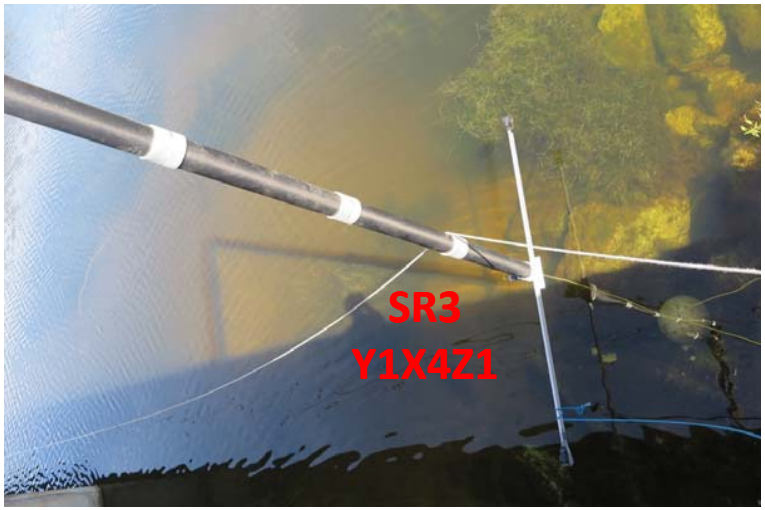


FIELD TEST DEMONSTRATION

- **Test Procedure**
  - **Deploy Three Smart Rocks**

FIELD TEST DEMONSTRATION

- **Test Procedure**
  - **Measure the Total Magnetic Field Intensity**
    - ✓ ***Magnetic field from both smart rock and AMF.***
    - ✓ ***Abutment 1 Measurement: Y1, Y2, Y3 along Y axis, X1, X2, X3, X4 along X axis, and Z1,Z2, ..., Z6 along Z axis, total 72 points.***
    - ✓ ***Bent 2 Measurement: Y1, Y3, Y5 along Y axis, X1, X2, X3, X4 along X axis, and Z1,Z2, ..., Z7 along Z axis, total 84 points.***
    - ✓ ***Measurement points sequence same as that of AMF.***



FIELD TEST DEMONSTRATION

- **Test Results**
  - **Coordinates and Intensities at Measurement Points around Abutment 1**

		Measurement Points Coordinate (m)			N42 Magnet Factor ($nT.m^3$)	AMF Intensity (nT)				SR3 & AMF Intensity (nT)			
		X_i	Y_i	Z_i	K	B_{XA}	B_{YA}	B_{ZA}	B_A	B_X	B_Y	B_Z	B
Y1X2	Z1	0.656	42.259	-0.942	86521	-18675	-9823	-40007	45230	-17485	-6252	-41897	45828
	…	…	…	…	…	…	…	…	…	…	…	…	…
	Z6	0.768	42.345	0.573	86521	-18661	-9888	-40226	45433	-19943	-7237	-40802	45988
Y1X3	Z1	1.693	42.293	-1.141	86521	-18243	-9707	-39974	45000	-13343	-8111	-48963	51393
	…	…	…	…	…	…	…	…	…	…	…	…	…
	Z6	1.736	42.275	0.366	86521	-18878	-9675	-40509	45727	-19475	-7190	-42452	47256
Y1X4	Z1	2.341	42.387	-1.085	86521	-16406	-10804	-40258	44795	-13358	-11669	-54780	57580
	…	…	…	…	…	…	…	…	…	…	…	…	…
	Z6	2.444	42.329	0.319	86521	-17707	-10784	-41228	46147	-18941	-7994	-44345	48879
Y2X2	…	…	…	…	…	…	…	…	…	…	…	…	…
Y2X3	…	…	…	…	…	…	…	…	…	…	…	…	…
Y2X4	…	…	…	…	…	…	…	…	…	…	…	…	…
Y3X2	…	…	…	…	…	…	…	…	…	…	…	…	…
Y3X3	…	…	…	…	…	…	…	…	…	…	…	…	…
Y3X4	…	…	…	…	…	…	…	…	…	…	…	…	…

FIELD TEST DEMONSTRATION

- **Test Results**
  - **Localization of SR3**

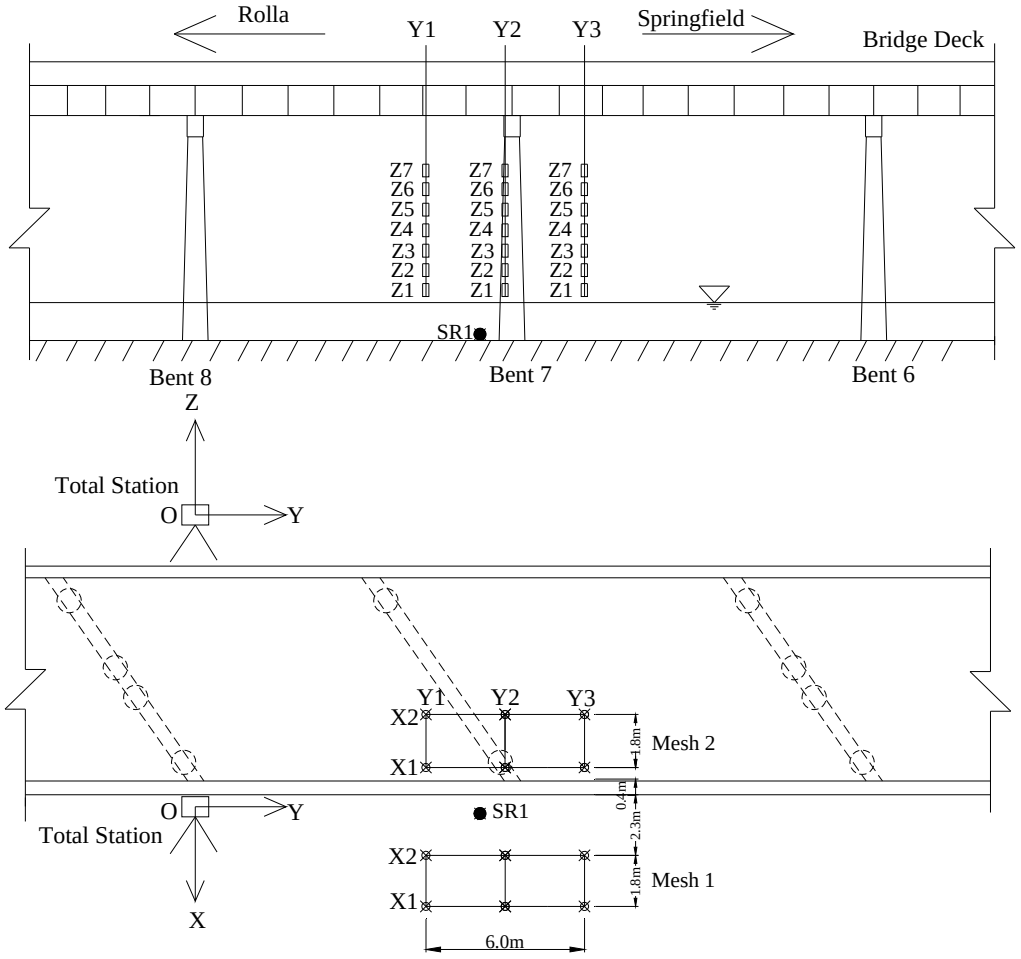
Point Name		Measurement Points Coordinate (m)			N42 Magnet Factor ($nT.m^3$)	AMF Intensity (nT)			SR3 & AMF Intensity (nT)
		X_i	Y_i	Z_i	K	B_{XA}	B_{YA}	B_{ZA}	B
Y1X2	Z1	0.656	42.259	-0.942	86521	-18675	-9823	-40007	45828
	…	…	…	…	…	…	…	…	…
	Z6	0.768	42.345	0.573	86521	-18661	-9888	-40226	45988
Y1X3	Z1	1.693	42.293	-1.141	86521	-18243	-9707	-39974	51393
	…	…	…	…	…	…	…	…	…
	Z6	1.736	42.275	0.366	86521	-18878	-9675	-40509	47256
Y1X4	Z1	2.341	42.387	-1.085	86521	-16406	-10804	-40258	57580
	…	…	…	…	…	…	…	…	…
	Z6	2.444	42.329	0.319	86521	-17707	-10784	-41228	48879
…	…	…	…	…	…	…	…	…	…
Predicted SR3 Location		**2.789**	**41.302**	**-2.823**	NA				
Measured SR3 Location		**2.714**	**41.104**	**-2.527**					
Location Prediction Error for SR3		**0.075**	**0.198**	**-0.296**					
SRSS Error in Coordinate		**0.364**							

FIELD TEST DEMONSTRATION

- **I-44 Roubidoux Ceek Bridge, MO (Bent 7 downstream)**

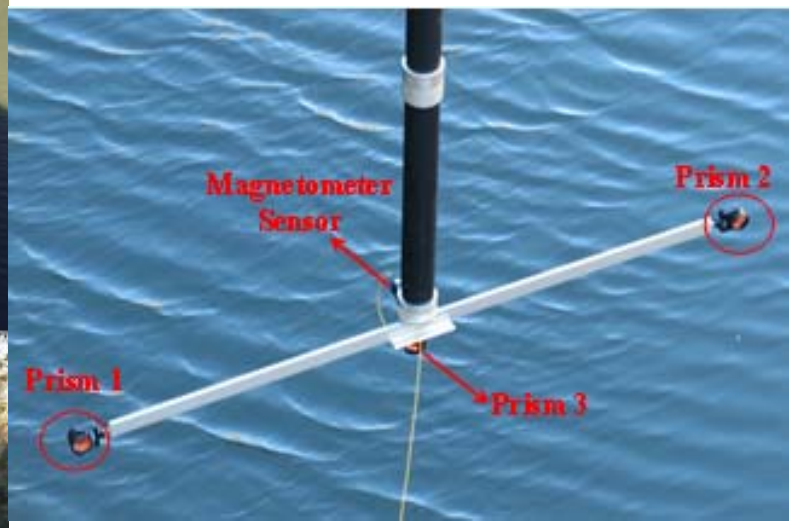
FIELD TEST DEMONSTRATION

- **Measurement Station Layout on Bridge Deck**



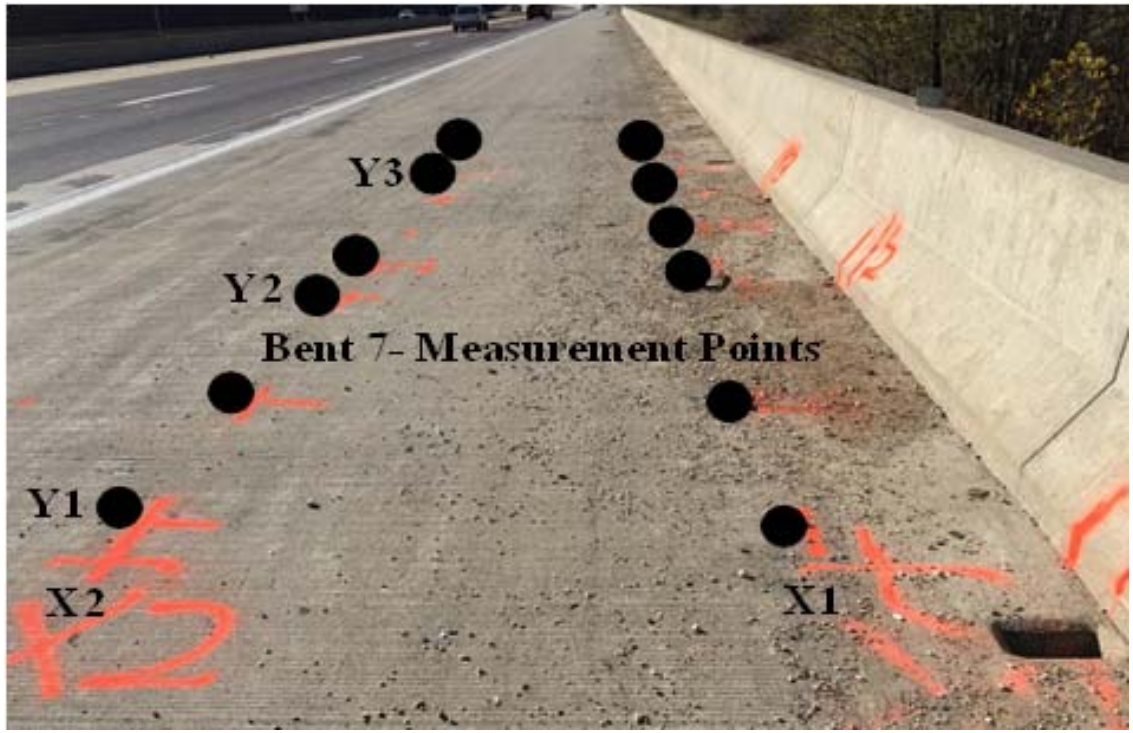
FIELD TEST DEMONSTRATION

- **Test Setup and Layout**



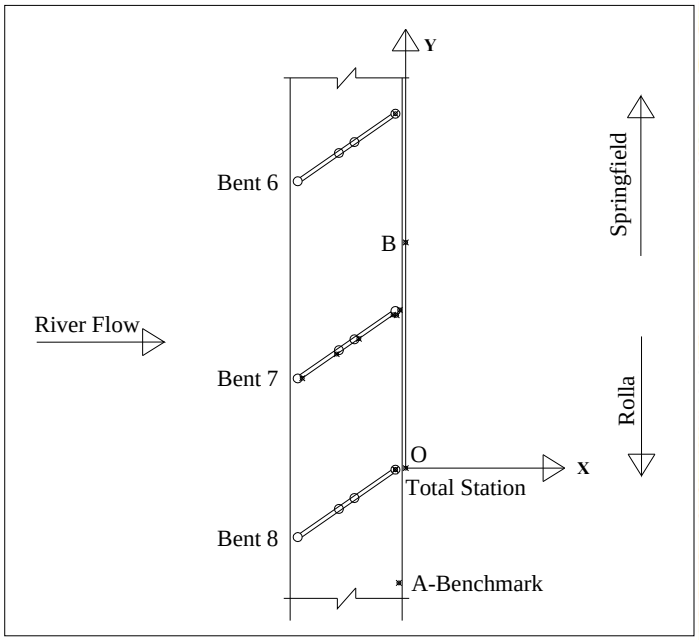
FIELD TEST DEMONSTRATION

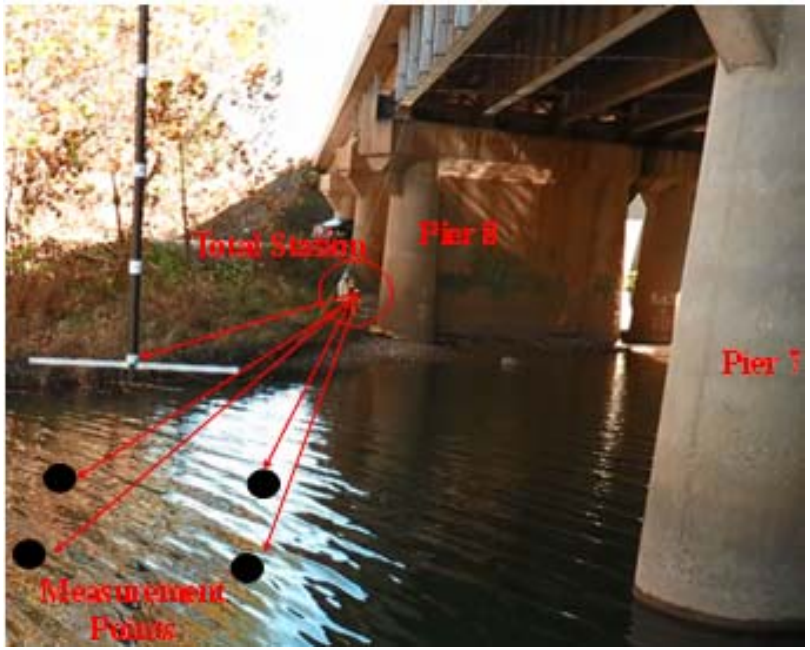
- **Test Set up and Layout**
  - **Measurement Points Layout on the Bridge Deck**



FIELD TEST DEMONSTRATION

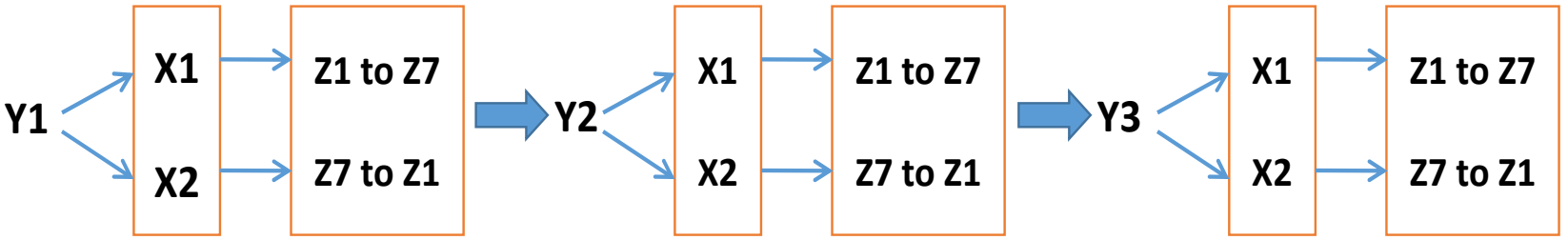
- **Test Procedure**
  - **Set a Cartesian coordinate system O-XY**





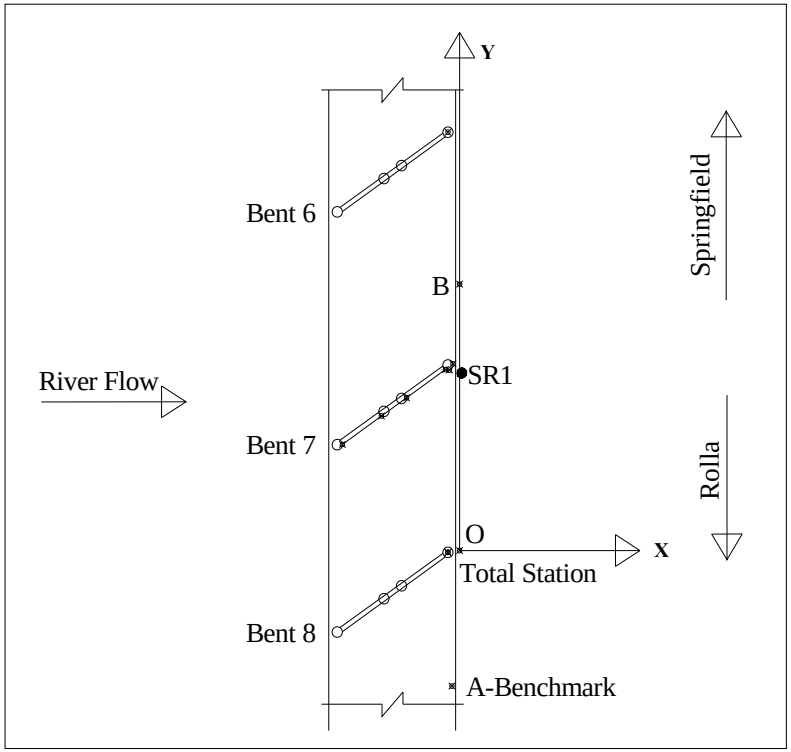
FIELD TEST DEMONSTRATION

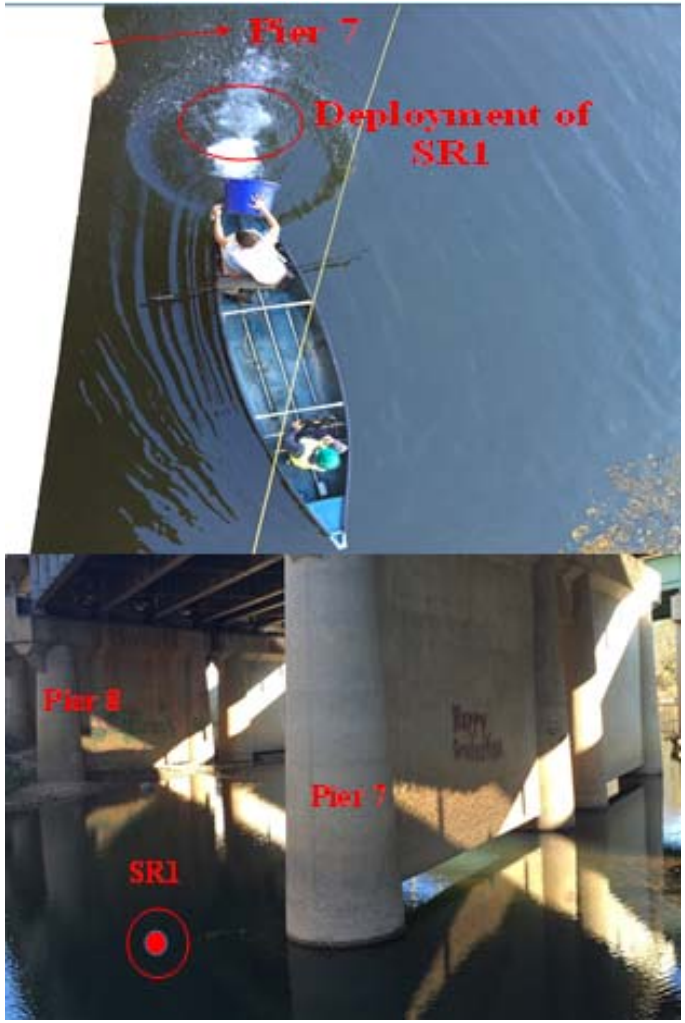
- **Test Procedure**
  - **Ambient Magnetic Field Measurement**
    - ✓ ***Magnetic field from Earth and ambient ferromagnetic constructions***
    - ✓ ***Conduct before deployment of the smart rock***
    - ✓ ***Bent 7 Measurement: Y1, Y2, Y3 along Y axis, X1, X2 along X axis, and Z1,Z2, ..., Z7 along Z axis, total 42 points.***
    - ✓ ***Measurement points sequence:***



FIELD TEST DEMONSTRATION

- **Test Procedure**
  - **Deployment of Smart Rocks**
    - ✓ ***Smart Rock 1(SR1) around Bent 7***





FIELD TEST DEMONSTRATION

- **Test Procedure**
  - **Measure the Total Magnetic Field Intensity**
    - ✓ ***Magnetic field from both smart rock and AMF.***
    - ✓ ***Bent 7 Measurement: Y1, Y2, Y3 along Y axis, X1, X2, along X axis, and Z1,Z2, ..., Z7 along Z axis, total 42 points.***
    - ✓ ***Measurement points sequence same as that of AMF.***

FIELD TEST DEMONSTRATION

- **Test Results**
  - **Coordinates and Intensities at Measurement Points around Bent 7**

		Measurement Points Coordinate (m)			N42 Magnet Factor ($nT.m^3$)	AMF Intensity (nT)				SR3 & AMF Intensity (nT)			
		X_i	Y_i	Z_i	K	B_{XA}	B_{YA}	B_{ZA}	B_A	B_X	B_Y	B_Z	B
Y1X1	Z1	3.854	21.793	-1.002	86521	22781	1016	-48909	53964	21379	-827	-48734	53224
	…	…	…	…	…	…	…	…	…	…	…	…	…
	Z7	3.834	21.554	0.795	86521	22631	2399	-48778	53826	22073	253	-48957	53703
Y1X2	Z1	2.068	21.869	-0.993	86521	22776	1666	-48933	53999	18988	6554	-49341	53274
	…	…	…	…	…	…	…	…	…	…	…	…	…
	Z7	2.083	21.606	0.781	86521	22496	3237	-49477	54447	21054	7653	-50118	54896
Y2X1	…	…	…	…	…	…	…	…	…	…	…	…	…
Y2X2	…	…	…	…	…	…	…	…	…	…	…	…	…
Y3X1	…	…	…	…	…	…	…	…	…	…	…	…	…
Y3X2	…	…	…	…	…	…	…	…	…	…	…	…	…

FIELD TEST DEMONSTRATION

- **Test Results**
  - **Localization of SR1**

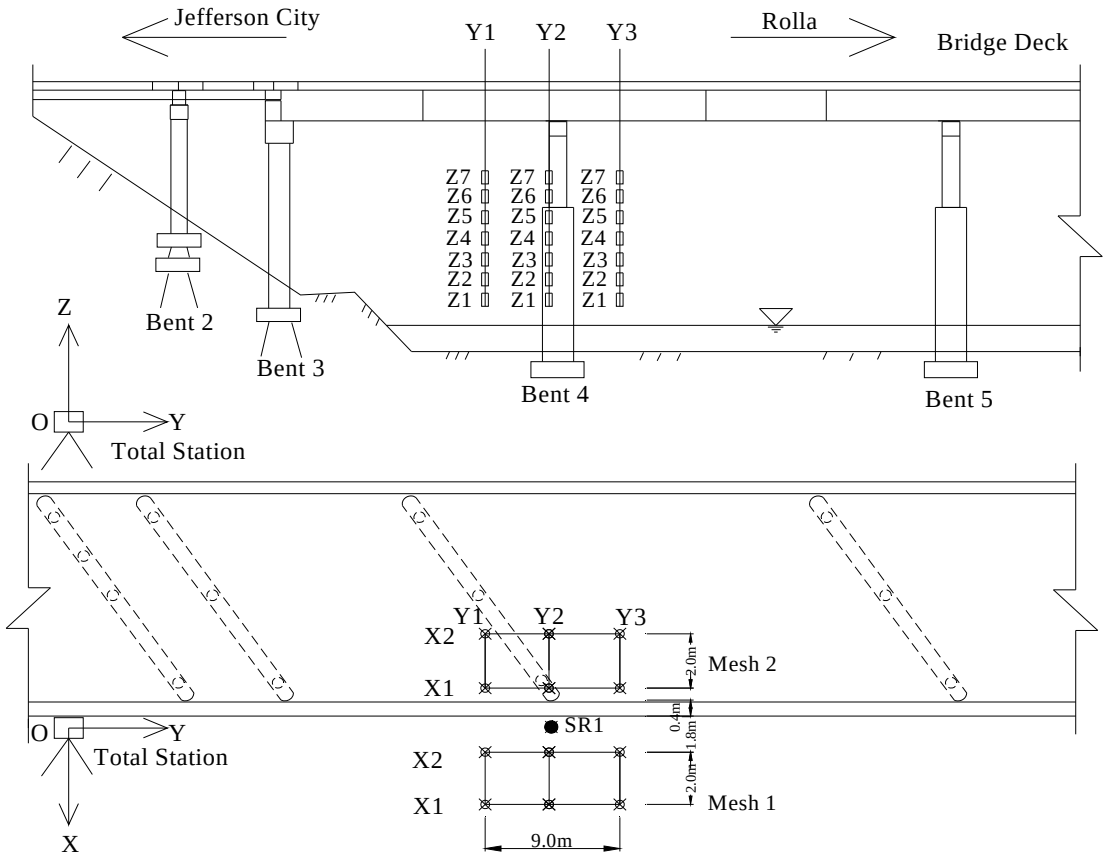
	X_M/m	Y_M/m	Z_M/m
Predicted SR1 Location	0.063	23.491	-3.032
Measured SR1 Location	0.089	23.235	-3.042
Location Prediction Error for SR1	0.026	0.256	-0.010
SRSS Error in Coordinate	0.258m		

FIELD TEST DEMONSTRATION

- **US63 Gasconade River Bridge, MO (Bent 4 upstream)**

FIELD TEST DEMONSTRATION

- **Measurement Station Layout on Bridge Deck**

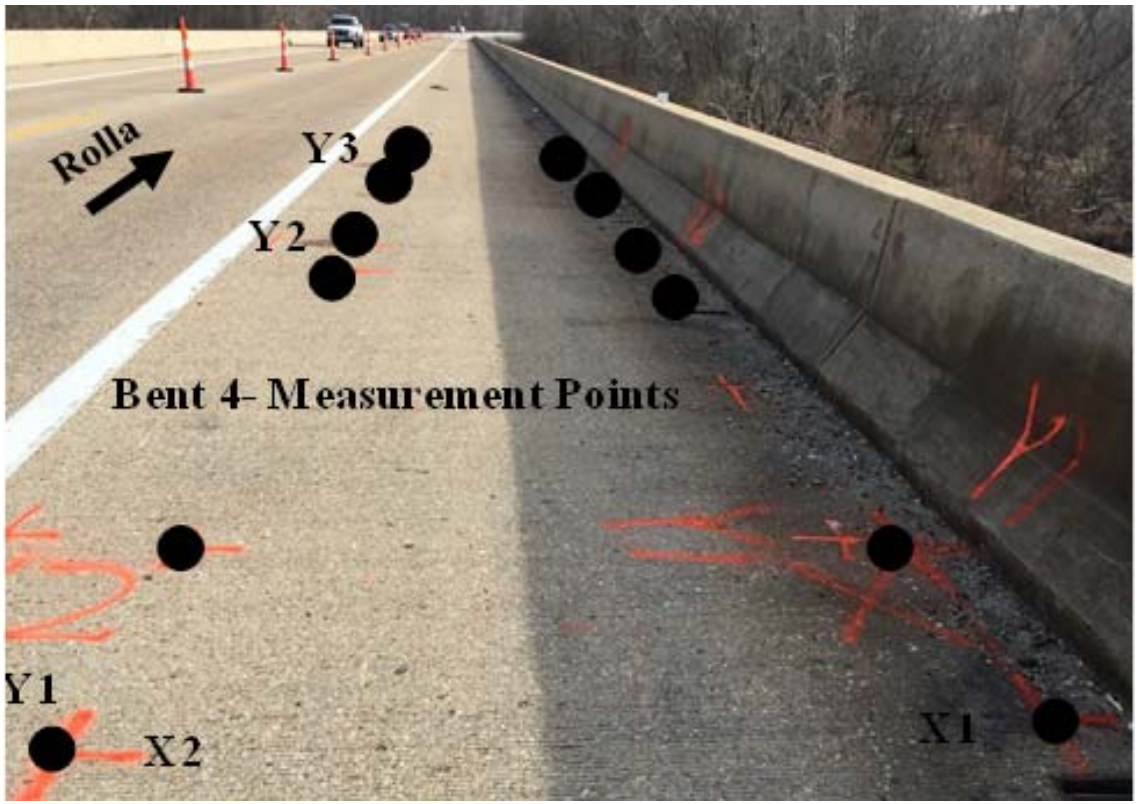


FIELD TEST DEMONSTRATION

- **Test Setup and Layout**

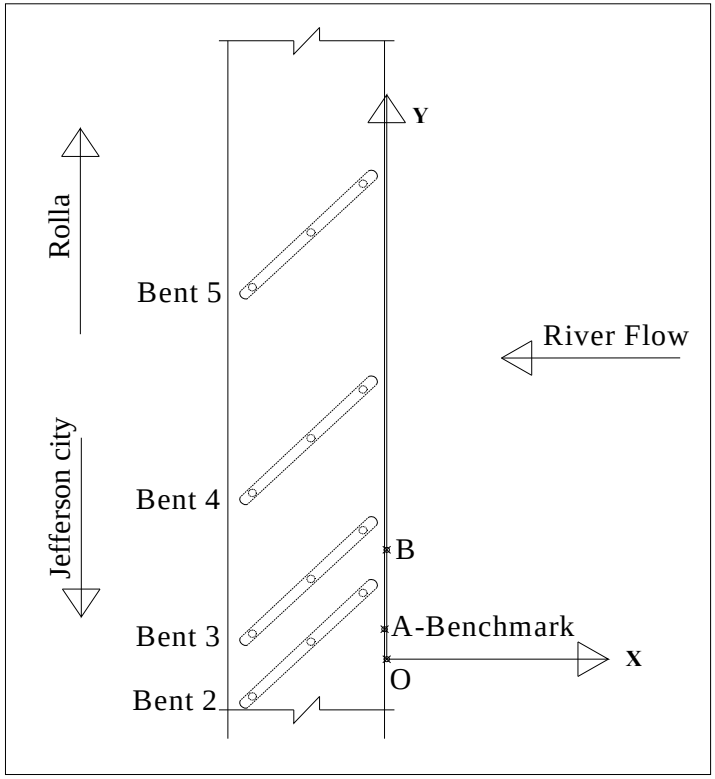
FIELD TEST DEMONSTRATION

- **Test Set up and Layout**
  - **Measurement Points Layout on the Bridge Deck**



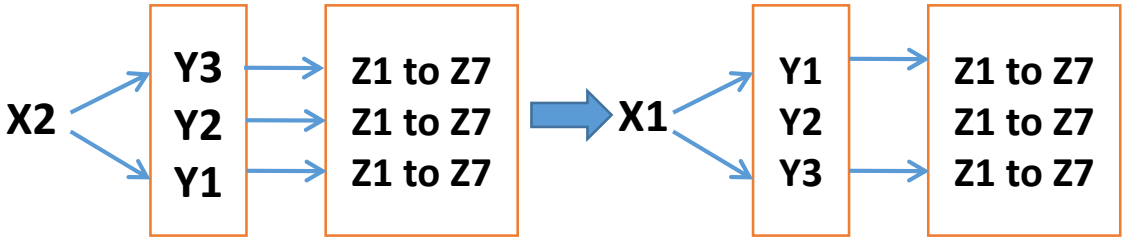
FIELD TEST DEMONSTRATION

- **Test Procedure**
  - **Set a Cartesian coordinate system O-XY**



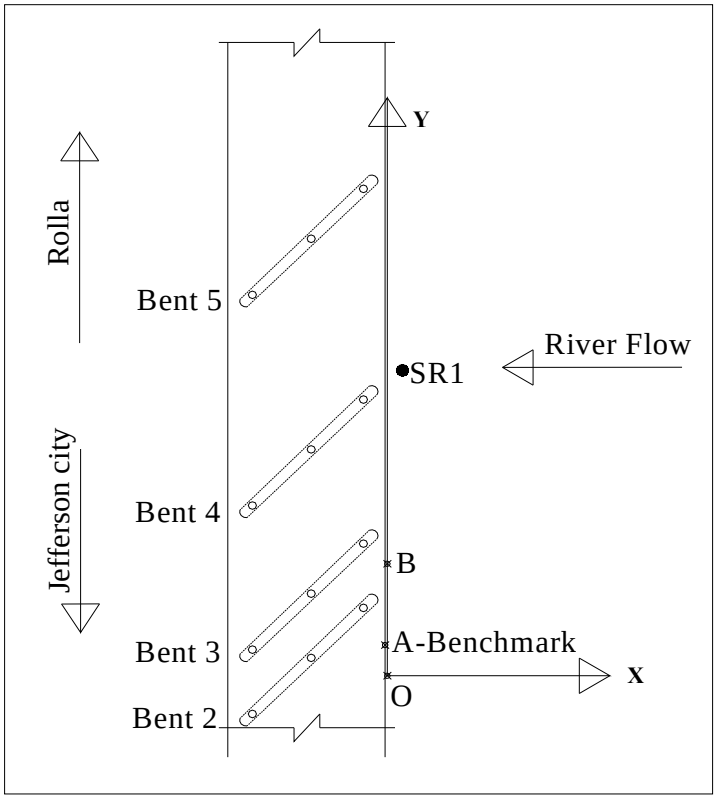
FIELD TEST DEMONSTRATION

- **Test Procedure**
  - **Ambient Magnetic Field Measurement**
    - ✓ ***Magnetic field from Earth and ambient ferromagnetic constructions***
    - ✓ ***Conduct before deployment of the smart rock***
    - ✓ ***Bent 4 Measurement: Y1, Y2, Y3 along Y axis, X1, X2 along X axis, and Z1,Z2, ..., Z7 along Z axis, total 42 points.***
    - ✓ ***Measurement points sequence:***



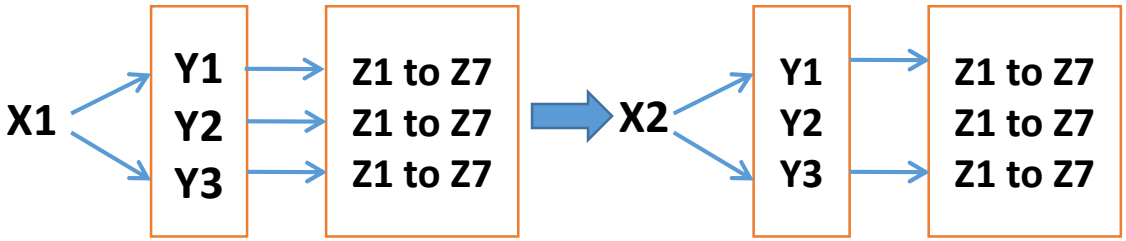
FIELD TEST DEMONSTRATION

- **Test Procedure**
  - **Deployment of Smart Rocks**
    - ✓ ***Smart Rock 1(SR1) around Bent 4***



FIELD TEST DEMONSTRATION

- **Test Procedure**
  - **Measure the Total Magnetic Field Intensity**
    - ✓ ***Magnetic field from both smart rock and AMF.***
    - ✓ ***Bent 7 Measurement: Y1, Y2, Y3 along Y axis, X1, X2, along X axis, and Z1,Z2, ..., Z7 along Z axis, total 42 points.***
    - ✓ ***Measurement points sequence same as that of AMF.***



FIELD TEST DEMONSTRATION

- **Test Results**
  - **Coordinates and Intensities at Measurement Points around Bent 7**

		Measurement Points Coordinate (m)			N45 Magnet Factor ($nT.m^3$)	AMF Intensity (nT)				SR3 & AMF Intensity (nT)			
		X_i	Y_i	Z_i	K	B_{XA}	B_{YA}	B_{ZA}	B_A	B_X	B_Y	B_Z	B
Y1X1	Z1	2.931	63.700	-11.014	101770	-16429	-6508	-47393	50580	-15752	-5836	-47896	50756
	…	…	…	…	…	…	…	…	…	…	…	…	…
	Z7	3.016	63.526	-9.198	101770	-16125	-5723	-47231	50235	-15817	-5403	-47516	50370
Y1X2	Z1	2.949	68.191	-10.988	101770	-17208	-7072	-46566	50145	-16512	-7637	-46998	50397
	…	…	…	…	…	…	…	…	…	…	…	…	…
	Z7	2.895	67.757	-9.221	101770	-17613	-6984	-46113	49854	-17124	-5446	-46719	50056
Y2X1	…	…	…	…	…	…	…	…	…	…	…	…	…
Y2X2	…	…	…	…	…	…	…	…	…	…	…	…	…
Y3X1	…	…	…	…	…	…	…	…	…	…	…	…	…
Y3X2	…	…	…	…	…	…	…	…	…	…	…	…	…

FIELD TEST DEMONSTRATION

- **Test Results**
  - **Localization of SR1**
  - **The ground truth of the coordinate is SR1 was not measured due to the fast water current.**
  - **The predicted location is reasonable according to the relative position to the measurement points.**

	X_M/m	Y_M/m	Z_M/m
Predicted SR1 Location	0.460	68.168	-17.002

CONCLUDING REMARKS

- **The APUS smart rocks have been deployed at three sites of the Waddell Creek Bridge, CA, the Roubidoux Creek Bridge, MO, and the Gasconade River Bridge, MO.**
- **The AOS, APSS, and APUS smart rock localization algorithms without and with knowing the magnet polarization in *a priori* have been validated at the three sites, all giving satisfactory results (<< 0.5 m).**
- **The test crane can be set on a trailer and moved as needed in application.**

ACKNOWLEDGEMENTS

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