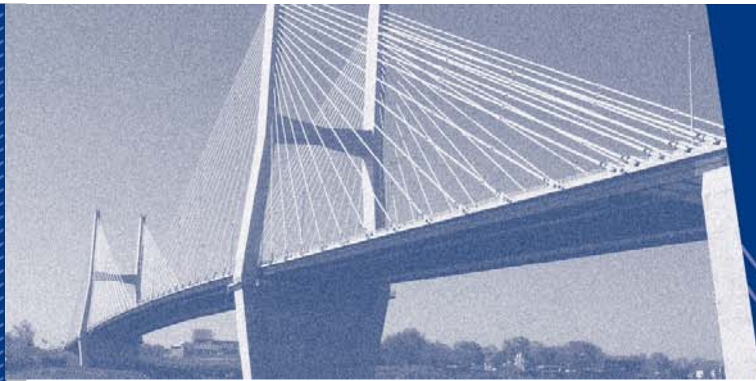
System and Process Assessment Research Laboratory



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

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Technical Advisory Council Meeting No.2

Missouri S&T

OUTLINE OF THIS PRESENTATION

- **Localization of Smart Rock**
  - **Localization Algorithm**
  - **Experimental Validation at Bridge Site**
- **Smart Rock Design and Prototyping**
  - **Motion under Various Flow Conditions**
  - **Design Guidelines**
  - **Final Design**
  - **Prototyping with Concrete Encasement**
- **Future Tasks**
  - **Deployment Plan**
  - **Field Measurement Plan**

LOCALIZATION OF SMART ROCK

- **Localization Algorithm**
  - **The total magnetic field (intensity) of a smart rock with embedded magnet and its surrounding ferromagnetic substances is measured with a magnetometer at various points around the smart rock.**
  - **The ambient magnetic field of the ferromagnetic substances is measured with the magnetometer and an orientation device at the same points.**
  - **The coordinates of the measurement points are surveyed using a survey equipment (Total Station).**
  - **The intensity and coordinate measurements at six or more points enable the localization of the smart rock.**

LOCALIZATION OF SMART ROCK

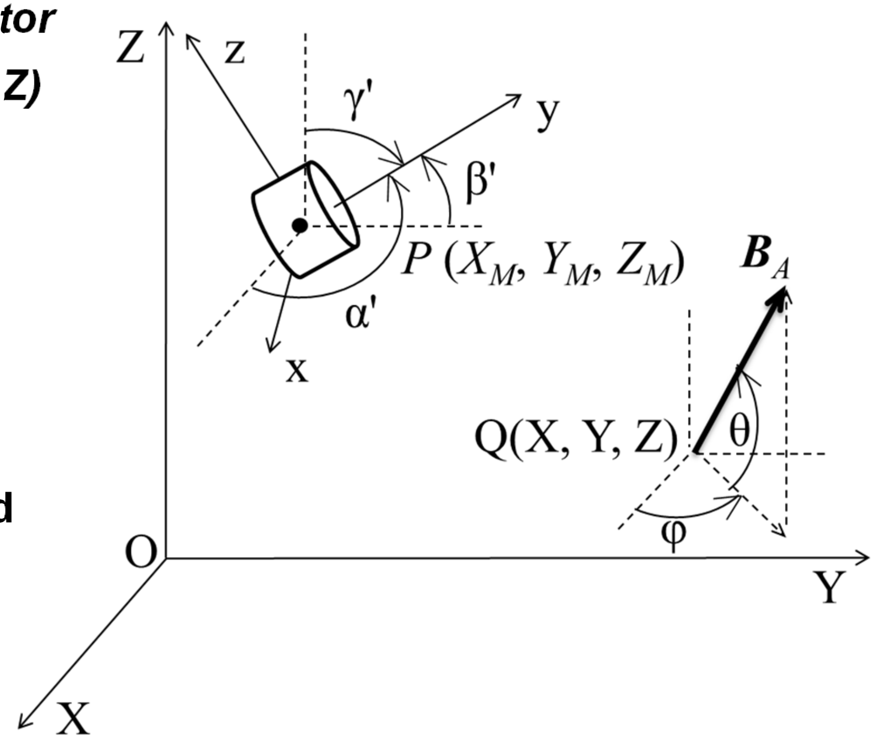
- **Localization Algorithm (Cont.)**
  - **Ambient Field in Global XYZ Coordinate System**
    - ✓ ***Surrounding ferromagnetic substances***
    - ✓ ***B_A= ambient magnetic field vector at a measurement point Q (X,Y,Z)***
    - ✓ ***Three components of B_A:***

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

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

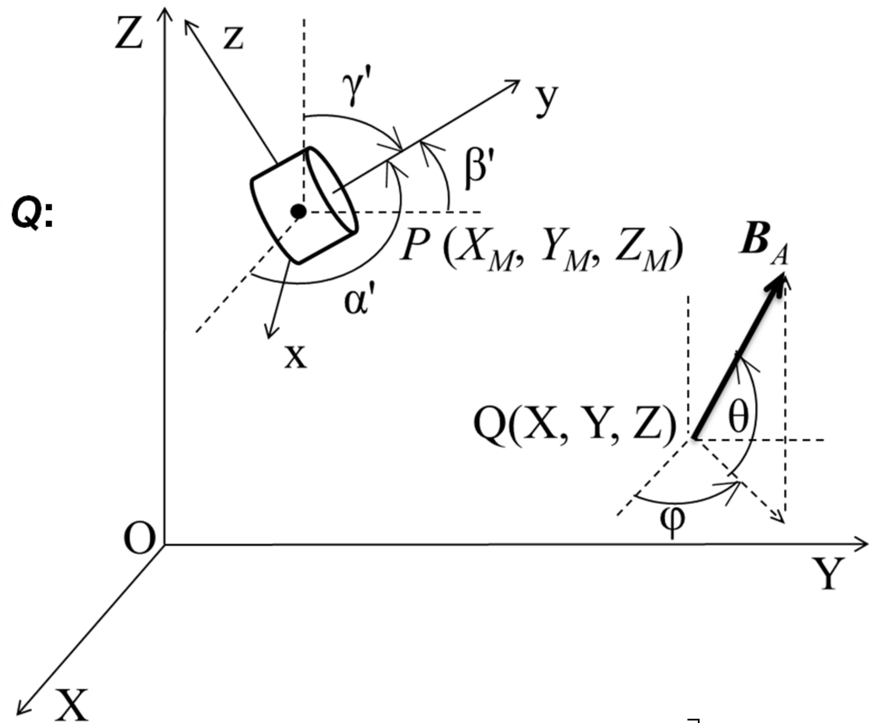
$$B_{ZA} = B_A \sin\theta$$

    - ✓ **$\theta(0, \pi)$ and $\varphi(0, 2\pi)$ are measured from a custom-made orientation device**



LOCALIZATION OF SMART ROCK

- **Localization Algorithm (Cont.)**
  - **Magnetic Field of a Permanent Magnet in XYZ System**
    - ✓ ***Cylindrical magnet $P(X_M, Y_M, Z_M)$***
    - ✓ ***Orientation defined in local xyz coordinate system***
    - ✓ ***Three components of B_M at Point Q:***



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

$$r = \sqrt{x^2 + y^2 + z^2}$$

$$x = a_{xX}(X - X_M) + a_{xY}(Y - Y_M) + a_{xZ}(Z - Z_M)$$

$$y = a_{yX}(X - X_M) + a_{yY}(Y - Y_M) + a_{yZ}(Z - Z_M)$$

$$z = a_{zX}(X - X_M) + a_{zY}(Y - Y_M) + a_{zZ}(Z - Z_M)$$

$$\mathbf{T} = \begin{bmatrix} a_{xX} & a_{xY} & a_{xZ} \\ a_{yX} & a_{yY} & a_{yZ} \\ a_{zX} & a_{zY} & a_{zZ} \end{bmatrix} = \begin{bmatrix} \cos\beta\cos\gamma & \cos\beta\sin\gamma & -\sin\beta \\ \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\cos\beta \\ \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\cos\beta \end{bmatrix}$$

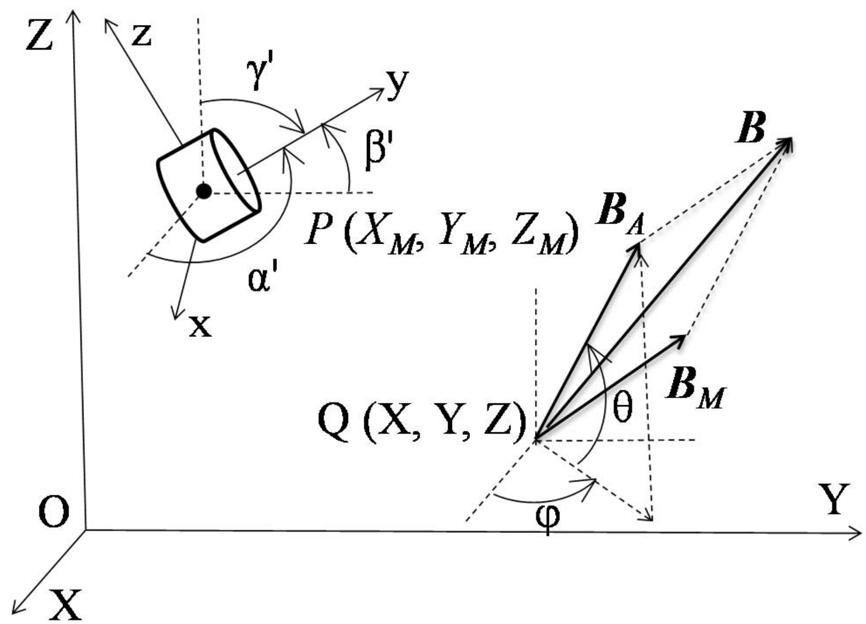
LOCALIZATION OF SMART ROCK

- **Localization Algorithm (Cont.)**
  - **Total Magnetic Field at Point Q in XYZ 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, Y, Z, X_M, Y_M, Z_M, α, β, γ*) ***at any measurement point Q (X,Y,Z)***
- ✓ **Given** *k, θ , φ, B_A, X, Y, Z,*

  B = B (*X_M, Y_M, Z_M, α, β, γ****)***
- ✓ **Minimum measurements at six points**



LOCALIZATION OF SMART ROCK

- **Localization Algorithm (Cont.)**
  - **Unknown Orientation**
    - ✓ ***SRSS error between predicted intensity*** $B_i^{(P)}$ ***and the measured intensity*** $B_i^{(M)}$ ***at n measurement points***

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

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

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

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

  - **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 OF SMART ROCK

- **Experimental Validation at Bridge Site**
  - **Gasconade River Bridge Site, MO**
  - **Two Smart Rocks**
    - ✓ ***Unknown orientation: Arbitrarily Oriented System (AOS)***
    - ✓ ***Known orientation: Automatically Pointing South System (APSS)***

(a) AOS

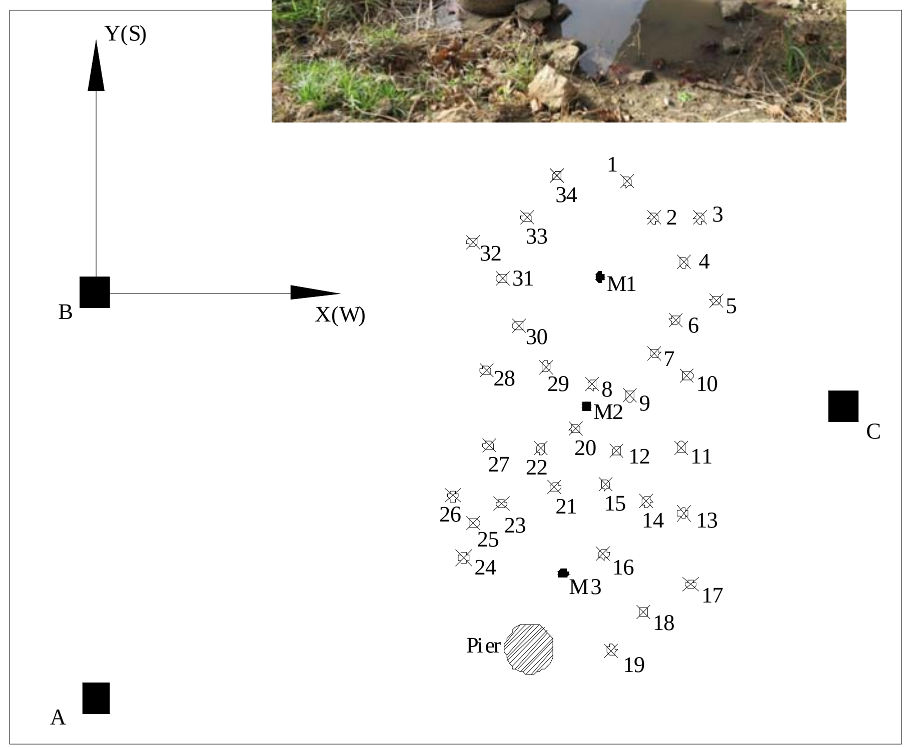
(b) APSS

LOCALIZATION OF SMART ROCK

- **Experimental Validation at Bridge Site (Cont.)**
  - ***Evaluation of*** *k, B_A, θ* ***and*** *φ*
    - ✓ ***K(AOS) = 41890.13($nT \cdot m^3$), measured with high precision level***
    - ✓ ***K(APSS) = 42542.27($nT \cdot m^3$), measured with low precision level***
    - ✓ ***Ambient magnetic field lines are no longer in parallel due to ferromagnetic substances (e.g. reinforcement in bridge pier and deck)***
    - ✓ ***Three parameters (B_A, θ and φ) define the ambient magnetic field for each measurement point in space***
      - The field intensity B_A was measured with a magnetometer.
      - An Ambient Magnetic Field Orientation Device (AMFOD) was developed and prototyped to measure the angles θ and φ.

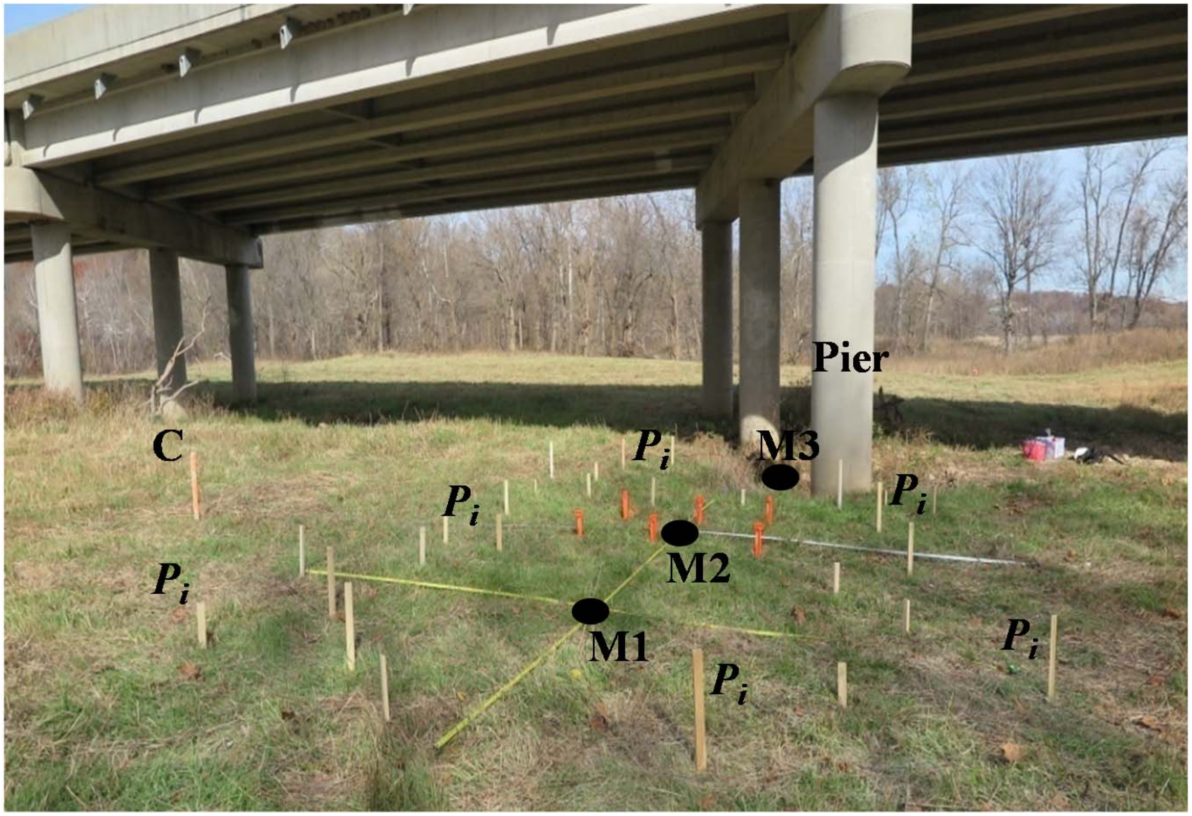
Localization of Smart Rock

- **Experimental Validation at Bridge Site (Cont.)**
  - ***Test Setup around a Scour Hole***
    - ✓ ***Three magnet 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 and 34 sensor positions or measurement points***
    - ✓ ***AMFOD was set at the 34 points to measure θ and φ***



Localization of Smart Rock

- **Experimental Validation of at Bridge Site (Cont.)**
  - ***Test Setup***



LOCALIZATION OF SMART ROCK

- **Experimental Validation of at Bridge Site (Cont.)**
  - ***Test Procedure***
    - ✓ ***Step 1: Set the Global XYZ Coordinate System***
    - ✓ ***Step 2: Select the Locations of Smart Rocks and the Sensor Head***
      - *Smart rocks located far away from, near, and close to the bridge pier*
      - *34 points distributed around M1, M2 and M3 bounded by circles with diameter of 1.5 m and 5 m around the pier*
    - ✓ ***Step 3: Select a Calibration Point C for AMFOD***
      - *Together with a fixed object as a reference to assist in determination of angle φ*
      - *Set away from the 34 measurement points to ensure the line of sight from laser light to Point C*

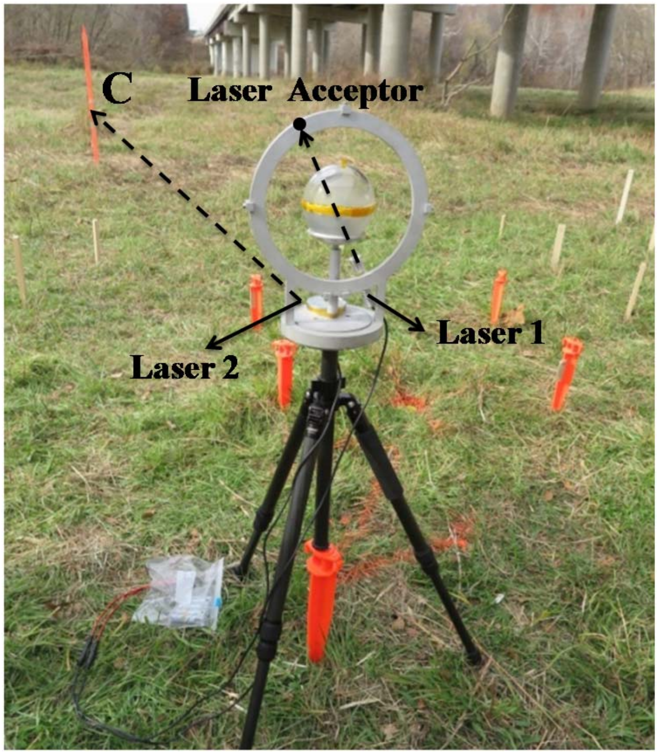
LOCALIZATION OF SMART ROCK

- **Experimental Validation of at Bridge Site (Cont.)**
  - ***Test Procedure (Cont.)***
    - ✓ ***Step 4: Determine the Coordinates of Smart Rocks, Sensor Head and Calibration Point***

Total Station and Prism for Positioning

LOCALIZATION OF SMART ROCK

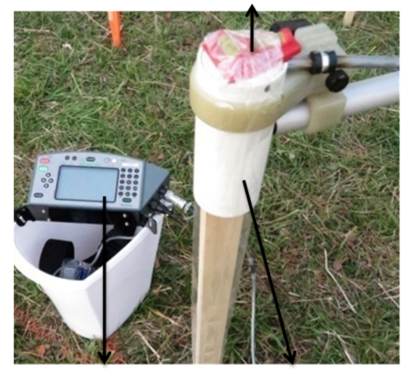
- **Experimental Validation of at Bridge Site (Cont.)**
  - ***Test Procedure (Cont.)***
    - ✓ ***Step 5: Measure θ and φ***
      - *AMFOD placed at measurement point*
      - *The center of high precision APSS kept along extension line of the orange plastic pole.*
      - *Shooting light of Horizontal Laser 2 hits on the wooden pole at Point C*
      - *Inside magnet automatically aligned to the ambient magnetic field*
      - *Shooting light of Laser 1 goes through the hole at the center line of APSS and hits on the center of laser acceptor*
      - *Read θ and φ*

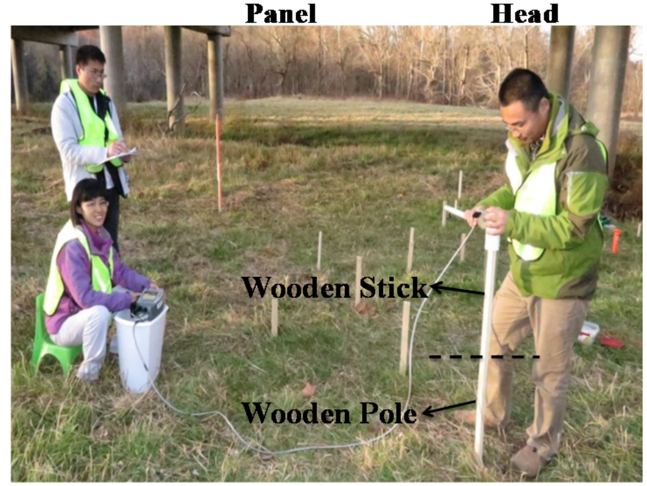


AMFOD Setup and Operational Mechanism

LOCALIZATION OF SMART ROCK

- **Experimental Validation of at Bridge Site (Cont.)**
  - ***Test Procedure (Cont.)***
    - ✓ ***Step 6: Measure the Ambient Magnetic Field Intensity***
      - *Level bubble attached on the sensor head ensures the sensor perpendicular to the ground*
      - *Keep the center of the sensor head consistent with that of the high precision APSS by a 57.7 cm wooden pole*
      - *Conduct measurement without vehicles*
      - *At least three measurements to ensure accuracy and* repeatability





Magnetometer Setup and Operation

LOCALIZATION OF SMART ROCK

- **Experimental Validation of at Bridge Site (Cont.)**
  - ***Test Procedure (Cont.)***
    - ✓ ***Step7 & 8: Measure the Total Magnetic Field Intensity of AOS and APSS at M1, M2 and M3***

(a) $M1_{APSS}$ or $M2_{APSS}$ **(b) APSS at M3** **(c) $M1_{AOS}$ or $M2_{AOS}$** **(d) AOS at M3**

LOCALIZATION OF SMART ROCK

- **Experimental Validation at Bridge Site (Cont.)**
  - ***Test Results***

Table 1 Sensor Coordinates and Ambient Magnetic Field Intensities

Measurement Point	Sensor Coordinates			Ambient Magnetic Field					
				Direction		Intensity			
	X/m	Y/m	Z/m	θ / rad	φ / rad	B_A /nT	B_{AX} /nT	B_{AY} /nT	B_{AZ} /nT
C	15.284	-2.264	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P1	10.882	2.202	-0.547	1.213	1.503	50798	1213	17748	47581
P2	11.425	1.481	-0.454	1.222	1.525	51417	810	17567	48316
P3	12.365	1.479	-0.576	1.222	1.477	51363	1637	17491	48266
P4	12.040	0.587	-0.483	1.197	1.485	51366	1603	18674	47825
P5	12.701	-0.160	-0.512	1.196	1.512	51296	1102	18768	47727
…	…	…	…	…	…	…	…	…	…
P33	8.813	1.487	-0.724	1.143	1.511	51330	1262	21249	46709
P34	9.455	2.322	-0.436	1.162	1.410	51417	3264	20158	47188

LOCALIZATION OF SMART ROCK

- **Experimental Validation at Bridge Site (Cont.)**
  - ***Test Results ($M1_{APSS}$)***

Location of Sensor Head	X(m)	Y(m)	Z(m)	$B_i^{(M)}$ (nT)
P1	10.882	2.202	-0.517	58120
P2	11.425	1.481	-0.424	56946
…	…	…	…	…
P9	10.940	-2.065	-0.687	52055
P10	12.119	-1.657	-0.665	50942
P20	9.822	-2.717	-0.665	53002
P28	7.989	-1.553	-0.659	51464
P29	9.216	-1.476	-0.661	51031
P30	8.651	-0.664	-0.757	48911
…	…	…	…	…
P34	9.455	2.322	-0.406	56421
Predicted APSS Location $M1_{APSS}$	**10.249**	**0.454**	**-1.352**	N/A
Measured APSS Location $M1_{APSS}$	**10.326**	**0.305**	**-1.407**	
Location Prediction Error for M_{APSS}	**-0.077**	**0.149**	**0.055**	
SRSS Error in Coordinate	0.176 m			

LOCALIZATION OF SMART ROCK

- **Experimental Validation at Bridge Site (Cont.)**
  - ***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 OF SMART ROCK

- **Experimental Validation at Bridge Site (Cont.)**
  - ***Test Results (M1$_{AOS}$)***

Location of Sensor Head	X(m)	Y(m)	Z(m)	$B_i^{(M)}$ (nT)
P1	10.882	2.202	-0.517	53558
P2	11.425	1.481	-0.424	52767
…	…	…	…	…
P9	10.940	-2.065	-0.687	49665
P10	12.119	-1.657	-0.665	49567
P20	9.822	-2.717	-0.665	51538
P28	7.989	-1.553	-0.659	50607
P29	9.216	-1.476	-0.661	48149
P30	8.651	-0.664	-0.757	47696
…	…	…	…	…
P34	9.455	2.322	-0.406	54539
Predicted AOS Location M1$_{AOS}$	**10.265**	**0.235**	**-1.456**	N/A
Measured AOS Location M1$_{AOS}$	**10.326**	**0.305**	**-1.422**	
Location Prediction Error for M1$_{AOS}$	**-0.061**	**-0.070**	**-0.034**	
SRSS Error in Coordinate	0.099 m			

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LOCALIZATION OF SMART ROCK

- **Experimental Validation at Bridge Site (Cont.)**
  - ***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			

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions**
  - ***Criteria of Incipient Motion of Rocks***
    - ✓ ***Critical velocity (HEC 18, 3rd version)***

$$V_c = \frac{K_s^{1/2}\left(S_s - 1\right)^{1/2} d^{1/2} y^{1/6}}{n}$$

    - ✓ ***Critical shear stress(HEC18, 3rd version)***

$$\tau_c = K_s(\rho_s - \rho_w)\,\mathrm{gd}$$

$$\tau_{local} = \left(\frac{nV_{local}}{K_u}\right)^2 \frac{\gamma_w}{y^{1/3}}$$

    - ✓ ***Riprap size design(HEC 23)***

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

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions (Cont.)**
  - ***Incipient Motion at Various Bridge Sites***
    - ✓ ***Highway 1 over Waddell Creek (Br. No. 36-0065)***

Highway No.1 Waddell Creek Bridge

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***Highway 1 over Waddell Creek (Br. No. 36-0065)(Cont.)***
      - *Located about 17miles north of the city of Santa Cruz*
      - *Build in 1947, 4-span structure with total 180.8ft long and 31.7ft wide*
      - Continuous reinforced concrete (RC) T-girders supported on RC piers and seat-type abutments
      - *Up stream of the bridge, small mountain dominates the terrain; down stream, the channel alignment changes with flow intensity towards the Pacific Ocean*
      - *In Feb,2000, high flows from a storm caused severe erosion to the upstream channel banks and extending to the embankment at Abutment 1. Some piles at Pier 2 was exposed.*
      - *Then, classified as scour critical*

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***Highway 1 over Waddell Creek (Br. No. 36-0065)(Cont.)***
      - *The 100-year flood discharge (Q100) is 170 m^3/s estimated from the regional flood-frequency equation based on the historical gage data from USGS.*
      - *High water elevation level(HWEL) is 2.865 m during 100-year flood.*
      - *The flow depth (y) and velocity (V) in the directly upstream of various piers is:*

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

      - *Select Bent 2 for calculation because of its unstable during 100-year flood provided by Caltrans*

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***Highway 1 over Waddell Creek (Br. No. 36-0065)(Cont.)***
      - *Based on critical velocity (Bent 2)*

$$2.286 = \frac{0.052^{1/2}\left(\frac{\rho_s}{1000}-1\right)^{1/2} 0.25^{1/2}3.566^{1/6}}{0.0325}, \quad \rho_s = 1278 kg / m^3$$

Where,

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 m/s^2;

d = 0.25 m for smart rocks based on the required space for magnet embedment;

V_c = V = 2.286 m/s at Bent 2;

y = 3.566 m at Bent 2;

$n = 0.041d^{1/6}$=0.0325.

Smart Rock Design and Prototyping

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***Highway 1 over Waddell Creek (Br. No. 36-0065)(Cont.)***
      - *Based on riprap size (Abutment 5)*

$$0.25 = \frac{0.692(1.7 \times 1.585)^2}{2 \times 9.81\left(\frac{\rho_s}{1000} - 1\right)}, \qquad \rho_s = 2024 kg/m^3$$

Where,

$D_{50} = 0.25$ *m;*

K=1.7 for a rectangle pier;

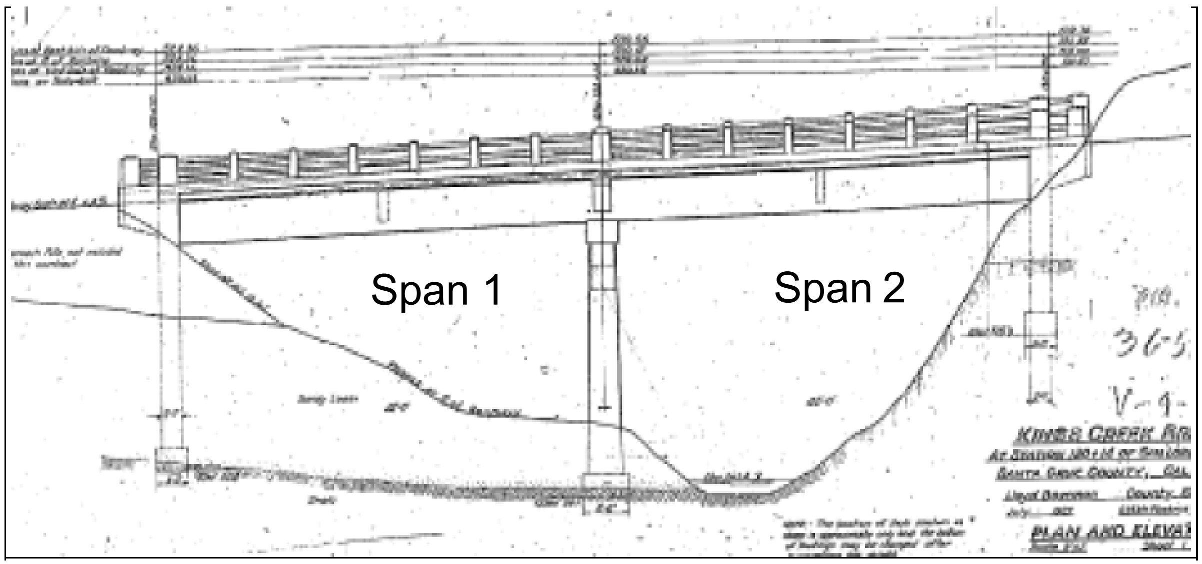
V = 1.585 m/s at Bent 4;

$S_s = \rho_s/1000$ *in kg/m*^{3}*; and*

$g = 9.81$ *m/s*^{2}*.*

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***Highway 9 over Kings Creek (Bridge No.36-0054)***



Schematic view of Kings Creek Bridge No.36-0054

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***Highway 9 over Kings Creek (Bridge No.36-0054)(Cont.)***
      - *2-span structures in Santa Cruz County over the Kings Creek*
      - *Located at the apex of a bend, main channel flow under span 2*
      - *Classified as scour critical in 2004 and footing pads at Bent 2 were exposed*
      - *A 2D hydraulic model of the flow was established by Caltrans to determine hydraulic parameter*
      - *The 100-year flood discharge (Q100) is 76.693 m^3/s.*
      - *The flow depth (y) and velocity (V) was estimated as 0.3 m/s and 0.18m, respectively, at Bent 2.*

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***Highway 1 over Waddell Creek (Br. No. 36-0065)(Cont.)***
      - *Based on critical velocity (Bent 2)*

$$0.2 = \frac{0.052^{1/2}\left(\frac{\rho_s}{1000}-1\right)^{1/2} 0.25^{1/2} 0.18^{1/6}}{0.0325}, \quad \rho_s = 1006\, kg / m^3$$

Where,

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;

$g = 9.81\ m/s^2$;

d = 0.25 m for smart rocks based on the required space for magnet embedment;

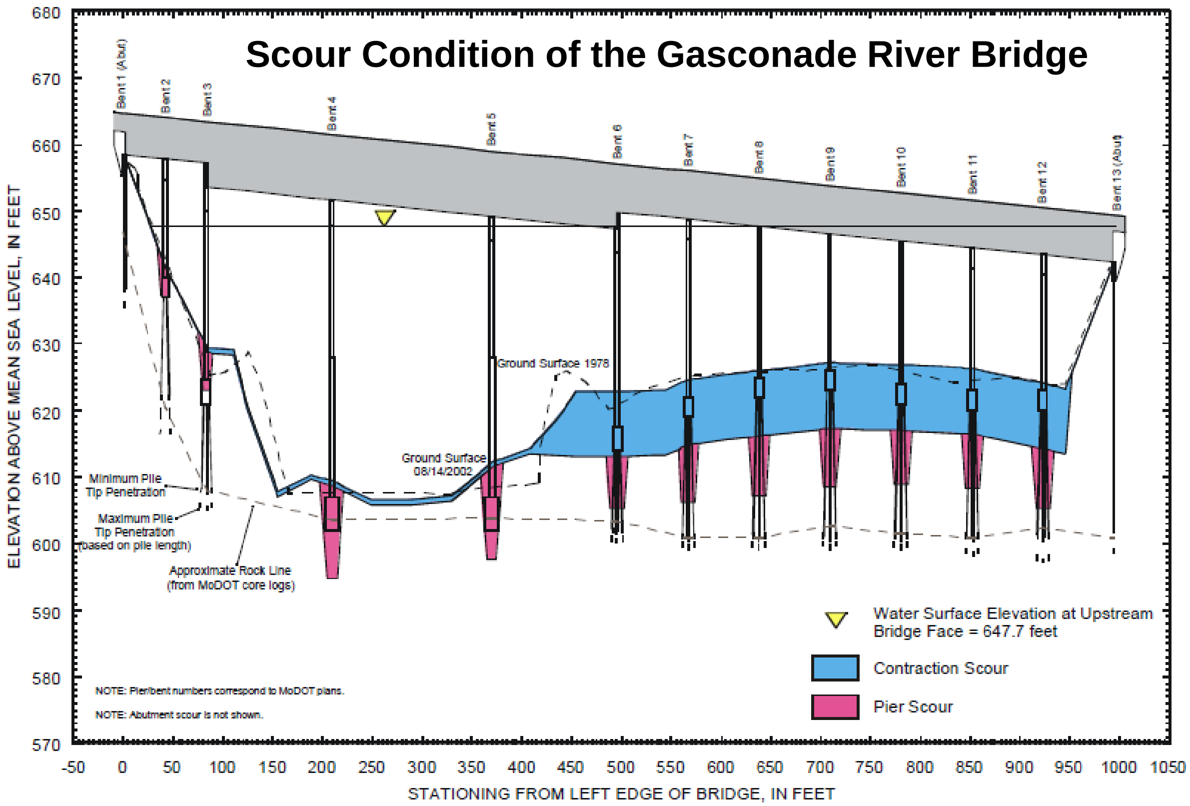
V_c = V = 0.2 m/s at Bent 2;

y = 0.18 m at Bent 2;

$n = 0.041d^{1/6}$=0.0325.

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***US63 Gasconade River Bridge***



SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***US63 Gasconade River Bridge(Cont.)***
      - *Located approximately 5.5 miles southeast of Vienna in Maries County, MO.*
      - *Built in 1970's, 12-span concrete-girder Structures.*
      - *Bent 4 is potentially scour critical.*
      - *The 100-year flood discharge(Q100 = 146000 cfs = 4234 m^3/s) estimated from historical data recorded from USGS gage station at Jerome, MO(gage No. 06933500).*
      - *The cross sectional area (A) was estimated to be 36544 ft^2 (3395 m^2).*

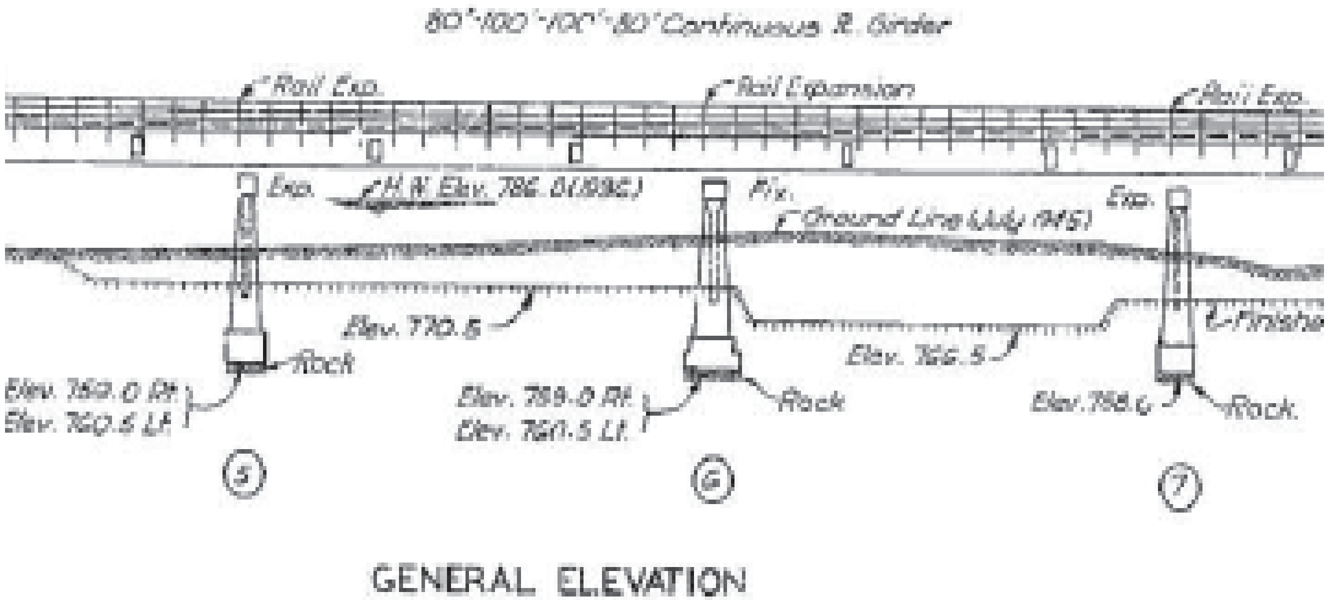
SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***US63 Gasconade River Bridge(Cont.)***
      - *The average channel velocity,* $V_{average}$ = Q_{100} */A* = 1.218 *m/s*.
      - *The velocity upstream of bent 4, V=1.7* $V_{average}$ considering pier in the main current of flow around a bend.
      - *Flow depth at Bent 4 is approximately 40ft (12.192m).*
      - *Therefore, with same size of 0.25m, the density is:*

$$1.218\times1.7=\frac{0.052^{1/2}\left(\frac{\rho_s}{1000}-1\right)^{1/2}0.25^{1/2}12.192^{1/6}}{0.0325},\quad \rho_s=1151kg/m^3$$

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***I-44 Roubidoux Creek Bridge (Bridge No.L0039)***



Schematic view of I-44 Roubidoux Creek Bridge at Bents 5-7

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***I-44 Roubidoux Creek Bridge (Bridge No.L0039)(Cont.)***
      - *Located about 12 miles south of Crocker in Pulaski County, MO.*
      - *10-spans with main flow going between Bents 5 and 7*
      - *Bent 6 is potentially scour critical.*
      - *The maximum discharge and flow depth (Q_{max} = 18200 cfs = 515.4 m^3/s and y=18.70 ft= 5.70 m) recorded at the USGS gage station(USGS 0698300, Roubidoux Creek above Fort Leonard Wood, MO).*
      - *The cross sectional area (A) was estimated to be 11703 ft^2 (1087 m^2).*

SMART ROCK DESIGN AND PROTOTYPING

- **Motion under Various Flow Conditions(Cont.)**
  - ***Incipient Motion at Various Bridge Sites(Cont.)***
    - ✓ ***I-44 Roubidoux Creek Bridge (Bridge No.L0039)(Cont.)***
      - *The average channel velocity, $V_{average}$* = Q_{max} */A* = 0.474 *m/s*.
      - *The velocity upstream of bent 4, V=1.7 $V_{average}$* considering pier in the main current of flow around a bend.
      - *Therefore, with same size of 0.25m, the density is:*

$$0.474\times1.7=\frac{0.052^{1/2}\left(\frac{\rho_s}{1000}-1\right)^{1/2}0.25^{1/2}5.70^{1/6}}{0.0325},\quad \rho_s=1030\,kg/m^3$$

SMART ROCK DESIGN AND PROTOTYPING

- **Design Guidelines of Smart Rocks**
  - ***Introduction***
    - ✓ ***Passive smart rocks embedded with permanent magnets, and remotely located with one or several magnetometers***
    - ✓ ***Active smart rocks embedded with electronic device, and located from a remote measurement through wireless communication***
    - ✓ ***Properly designed smart rocks***
    - ✓ ***Onset movement of riprap slope protection***
    - ✓ ***Maximum scour depth***

SMART ROCK DESIGN AND PROTOTYPING

- **Design Guidelines of Smart Rocks**
  - ***Design Considerations***
    - ✓ ***Meet two requirements***
      - *Facilitate remote measurement for rock localization*
      - *Ensure automatic movement to the bottom of a scour hole to be monitored*
    - ✓ ***The size of smart rock is constrained by minimum size of permanent magnet***
    - ✓ ***Always stay at the river bed***
    - ✓ ***Overcome water current and roll down the slope of a scour hole***
    - ✓ ***Remain at the bottom of the hole***
    - ✓ ***Density of smart rocks range from that of water and rocks***
    - ✓ ***Size and density highly depend on critical velocity and depth of water flow***
    - ✓ ***Use*** $d = \frac{(nV_c)^2}{K_s y^{1/3}(S_s - 1)}$ ***and*** $D_{50} = \frac{0.692(KV)^2}{2g(S_s - 1)}$

SMART ROCK DESIGN AND PROTOTYPING

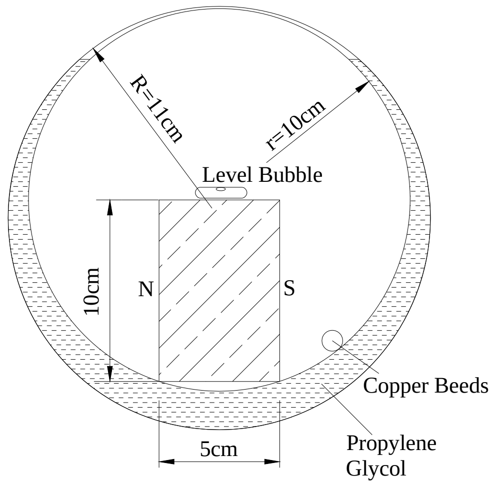
- **Design Guidelines of Smart Rocks**
  - ***Design Procedure***
    - ✓ ***Step 1: Determine hydraulics parameters near a bridge site***
      - *Flow velocity and water depth directly upstream of piers for 100-year flood*
      - *Collected from hydraulic studies by USGS or FEMA*
      - *Estimated from the data recorded by USGS gage station*
    - ✓ ***Step 2: Constrain the size and density of a smart tock***
      - *Inversely proportional relation between size and density*
      - *Given density, find out the size*
      - *Given size, find out density (preferred because of the embedded object)*
    - ✓ ***Step 3:Finalize the design of smart rocks***
      - *Multiply by a design factor(1.2-1.3) to account for any potential errors*
      - *Consider the easy of deployment and fabrication*

SMART ROCK DESIGN AND PROTOTYPING

- **Final Design of Smart Rocks**
  - ***Size and Density***
    - ✓ ***Diameter of 0.25m based on standard mold size***
    - ✓ ***Multiply by 1.2 or 1.3 times to avoid washing away***
    - ✓ ***Highway 1 Waddell Creek Bridge: $1.2 \times 1278 = 1530$ kg/m^3***
    - ✓ ***Highway 9 Kings Creek Bridge: $1.3 \times 1006 = 1308$ kg/m^3***
    - ✓ ***US63 Gasconade River Bridge: $1.3 \times 1151 = 1496$ kg/m^3***
    - ✓ ***I-44 Roubidoux Creek Bridge: $1.3 \times 1030 = 1339$ kg/m^3***
    - ✓ ***The target density of smart rocks: 1530 kg/m^3***

SMART ROCK DESIGN AND PROTOTYPING

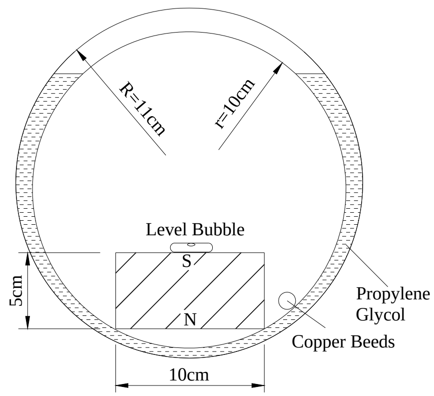
- **Final Design of Smart Rocks (Cont.)**
  - ***Internal Configuration (APSS)***
    - ✓ ***Monitored along the river bank***
    - ✓ ***Measurement station in South or North pole of the magnet***
    - ✓ ***Rapid convergence and high accuracy of APSS location***
    - ✓ ***However, easy affected by ferromagnetic substance***



APSS Model of Smart Rocks

SMART ROCK DESIGN AND PROTOTYPING

- **Final Design of Smart Rocks (Cont.)**
  - ***Internal Configuration (APUS)***
    - ✓ ***Automatically Pointing Upward System (APUS)***
    - ✓ ***Magnetometer set on the bridge deck, measurement station in south pole of the magnet***
    - ✓ ***Two poles of magnet aligned with vertical sensor of the magnetometer***
    - ✓ ***Gravity-orientated direction, reduces the degree of freedom, less effect by ferromagnetic substance***



(a) Schematic View **(b) Prototype Smart Rock (c)** ***Balanced Magnet***

APUS Model of Smart Rocks

SMART ROCK DESIGN AND PROTOTYPING

- **Final Design of Smart Rocks (Cont.)**
  - ***Design Details***

A cylindrical magnet placed in side an organic glass ball(inside ball), an outside organic glass ball, liquid filled in between two balls, and a concrete shell encasement*. Inside ball floating inside the outside ball.*

✓ ***Diameter Selection***

- *Magnet: 10 cm in diameter and 5cm in height*
- *Inside ball: 20 cm based on availability of casting molds, smart rock size and floating requirement*
- *Outside ball: 21 cm based on sufficient spacing for lubrication*

✓ ***Liquid Selection***

- *No friction force on the inside ball*
- *Nontoxicity requirement*
- *Density greater than 850 kg/m^3*
- *Therefore, propylene glycol with 1040kg/m^3*

SMART ROCK DESIGN AND PROTOTYPING

- **Final Design of Smart Rocks (Cont.)**
  - ***Effect of Deposit Resetting***

Overall Arrangement of Resetting Tests

SMART ROCK DESIGN AND PROTOTYPING

- **Final Design of Smart Rocks (Cont.)**
  - ***Effect of Deposit Resetting (Cont.)***

(a) 0.0 m

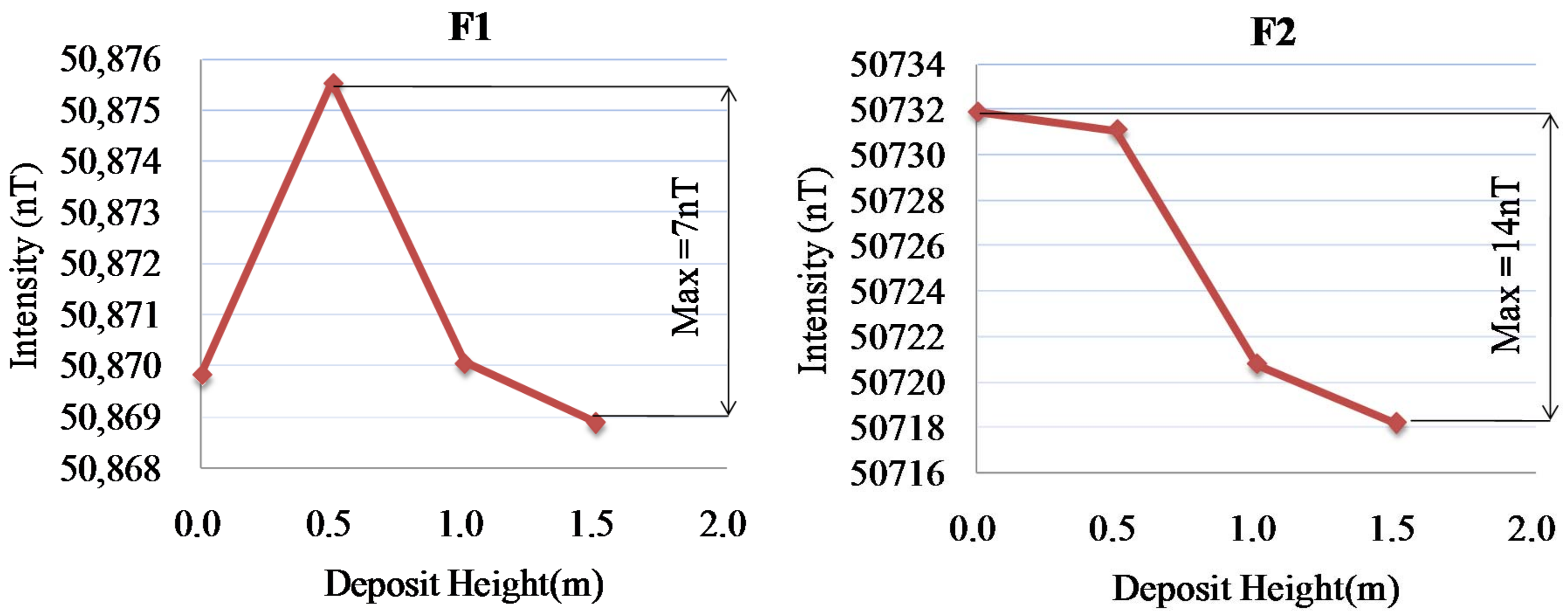
(b) 0.5 m

(c) 1.0 m

(d) 1.5 m

SMART ROCK DESIGN AND PROTOTYPING

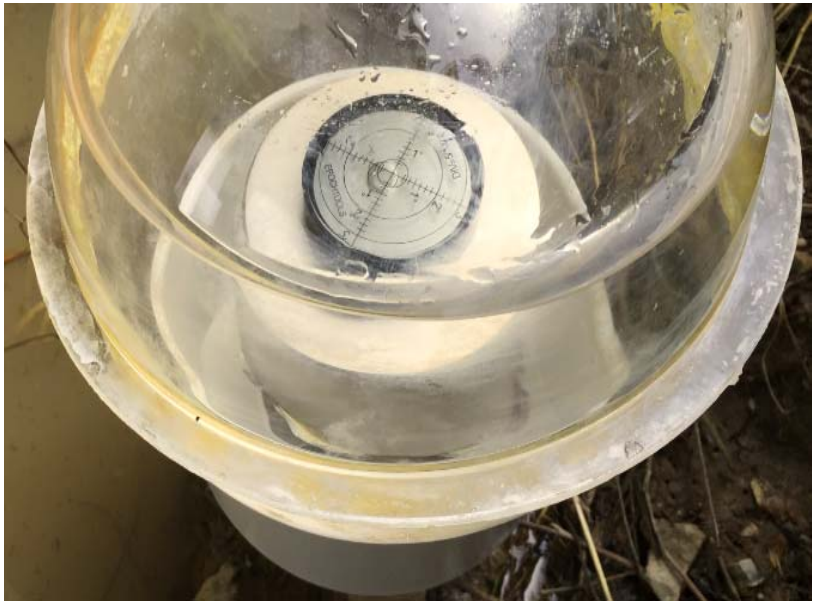
- **Final Design of Smart Rocks (Cont.)**
  - ***Effect of Deposit Resetting (Cont.)***



The intensity variations at different heights for measurement F1 and F2

SMART ROCK DESIGN AND PROTOTYPING

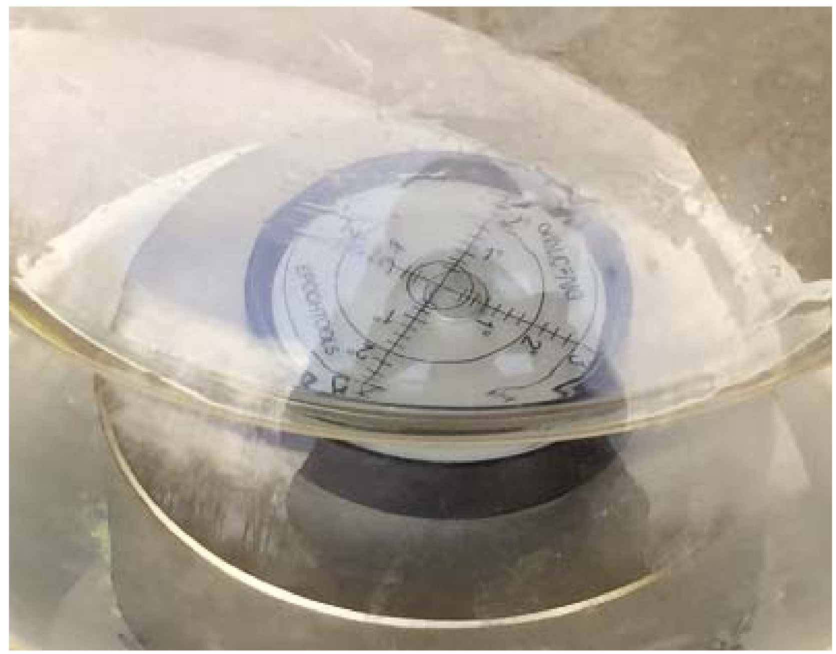
- **Final Design of Smart Rocks**
  - ***Effect of Steel Reinforcement***
    - ✓ ***Bubble in the center 10m away from the bridge pier***
    - ✓ ***Bubble slightly deviated, indicating an inclination angle of less than 0.5°***

The Prototype APUS Placed next to a Bridge Pier

SMART ROCK DESIGN AND PROTOTYPING

- **Final Design of Smart Rocks**
  - ***Effect of Steel Reinforcement (Cont.)***
    - ✓ ***Little effect on the localization of the APUS***



The Prototype APUS Placed on a Bridge Foundation

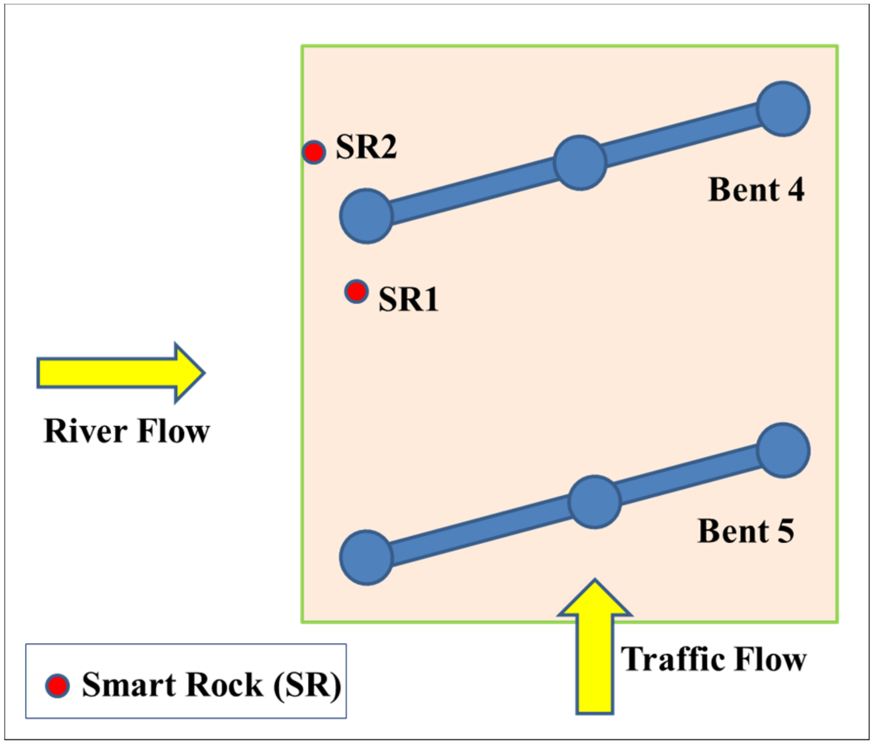
SMART ROCK DESIGN AND PROTOTYPING

- **Prototyping with Concrete Encasement**
  - ***Spherical concrete encasement***
  - ***25-cm-diameter mold***
  - ***Close to the target value of 1530 kg/m^3***
  - ***Total density is 1520 kg/m^3, appropriated for Highway 1 Waddell Creek Bridge, Highway 9 Kings Creek Bridge, US-63 Gasconade River Bridge and I-44 Roubidoux Creek Bridge***

A Prototype Smart Rock

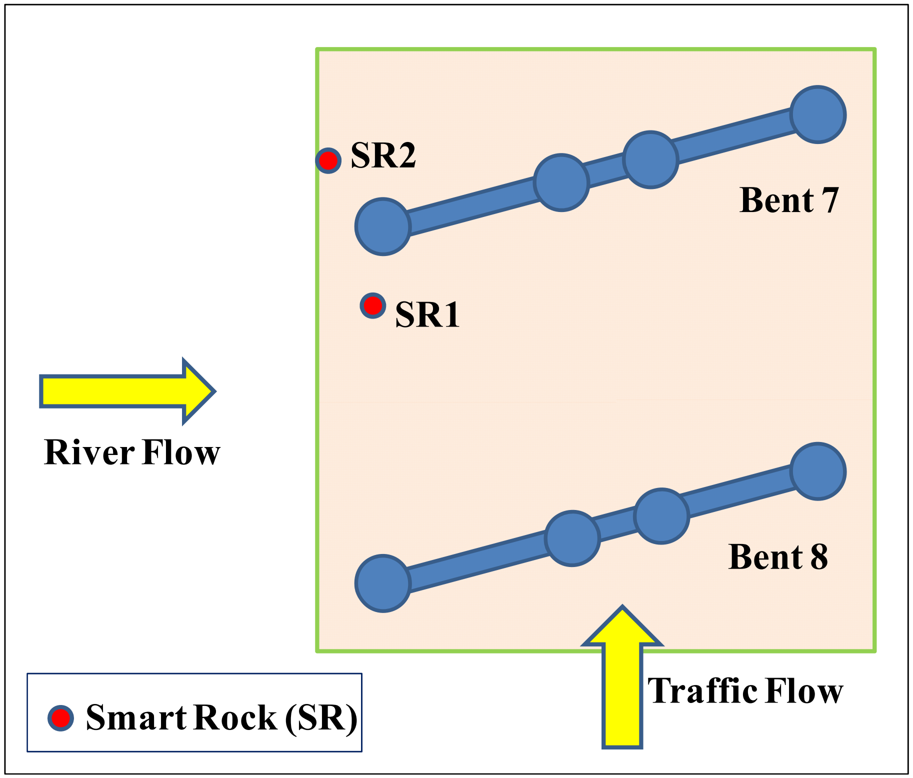
FUTURE TASKS

- **Deploymentof Smart Rocks**
  - **US 63 Gasconade River Bridge**
    - ✓ ***The exact location of smart rocks (SR1, SR2) around Pier 4 will be determined when deployed.***



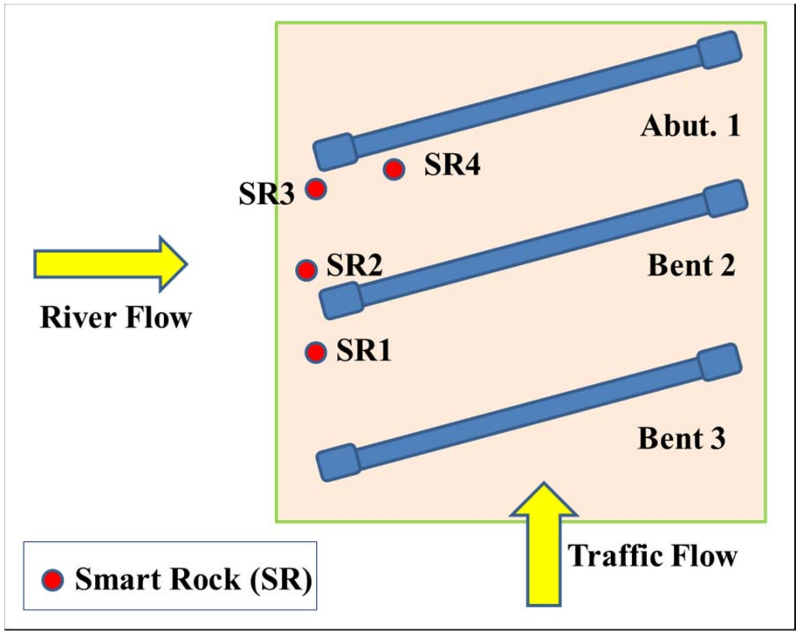
FUTURE TASKS

- **Deployment of Smart Rocks (Cont.)**
  - **I-44 Roubidoux Creek Bridge**
    - ✓ ***The exact location of smart rocks (SR1, SR2) around Pier 7 will be determined when deployed.***



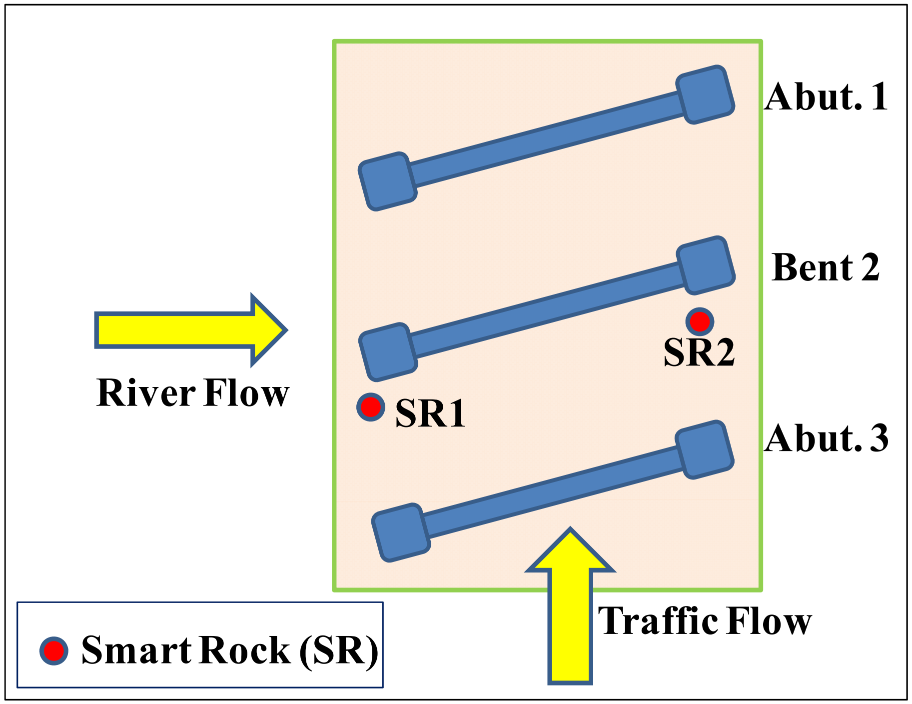
FUTURE TASKS

- **Deployment of Smart Rocks (Cont.)**
  - **Highway 1 Waddell Creek Bridge**
    - ✓ ***The exact location of smart rocks (SR1, SR2) around Pier 2 will be determined when deployed.***
    - ✓ ***SR3 and SR4 around abutment 1 are deployed to monitor the effectiveness of the riprap measure.***



FUTURE TASKS

- **Deployment of Smart Rocks (Cont.)**
  - **Highway 9 Kings Creek Bridge**
    - ✓ ***Main flow goes through between Bent 2 and Abut.3.***
    - ✓ ***SR1 and SR2 are in the upstream and downstream sides of the pier at Bent 2.***

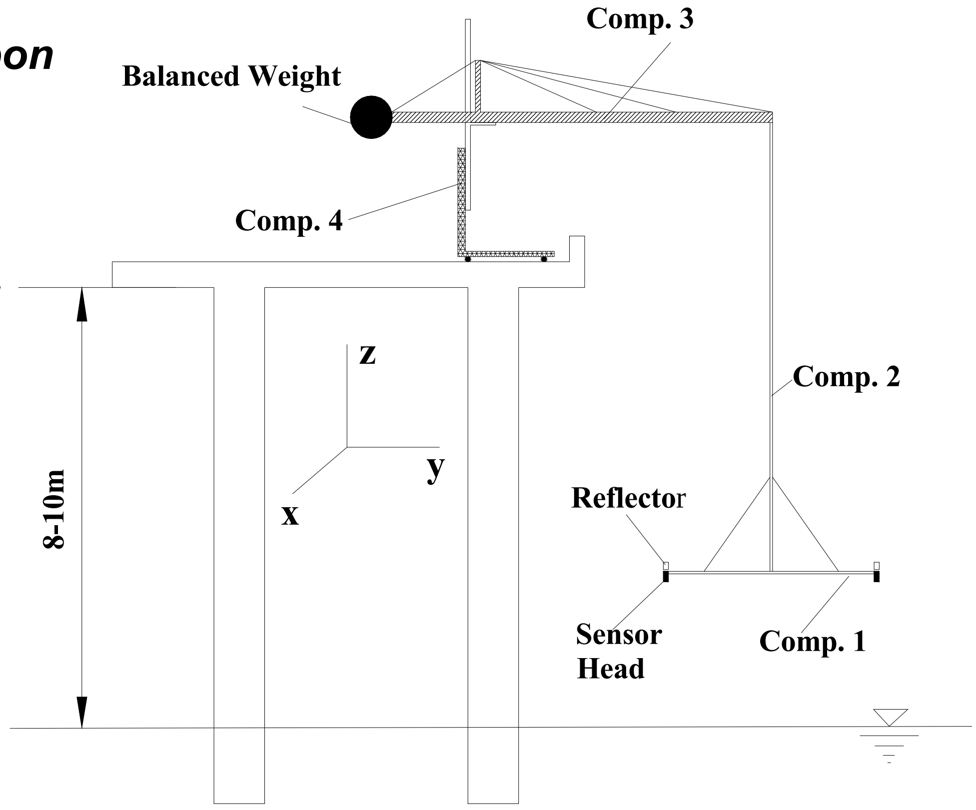


FUTURE TASKS

- **Measurement Plan**
  - **Concept and Practice on Bridge Deck**
    - ✓ ***Wood Frame with sensor***
    - ✓ ***X- Longitudinal direction of the bridge***
    - ✓ ***Y- Transverse direction of the bridge***
    - ✓ ***Z- Upward***
    - ✓ ***Movement in X-, Y-, and Z- directions***
    - ✓ ***Measurement points distribute above the smart rocks***
    - ✓ ***However, wood frame swung under wind load makes the difficulty to get the correct measurements.***

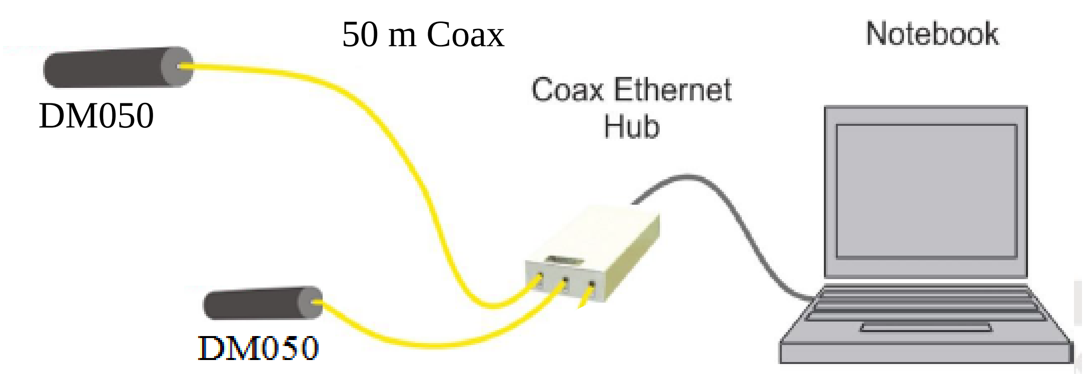
FUTURE TASKS

- **Measurement Plan (Cont.)**
  - **Prototype Light Frame for Rapid Assembling on Site**
    - ✓ ***Comp.1 – Lower horizontal beam for fixing sensor (carbon fiber)***
    - ✓ ***Comp. 2 – Vertical beam (carbon fiber)***
    - ✓ ***Comp. 3 – Higher Horizontal beam (Aluminum alloy)***
    - ✓ ***Comp. 4 – Manual forklift***
    - ✓ ***X-, Y-, and Z- direction movement by forklift***



FUTURE TASKS

- **Measurement Plan (Cont.)**
  - **A 3 Axis Magnetometer**
    - ✓ ***STL Digital Magnetometer (Type DM050) – Measure X-, Y- and Z-component of any magnetic field***
    - ✓ ***50 meter 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***



Any Comments?