# Reliability-Based Dam Erodibility Assessment

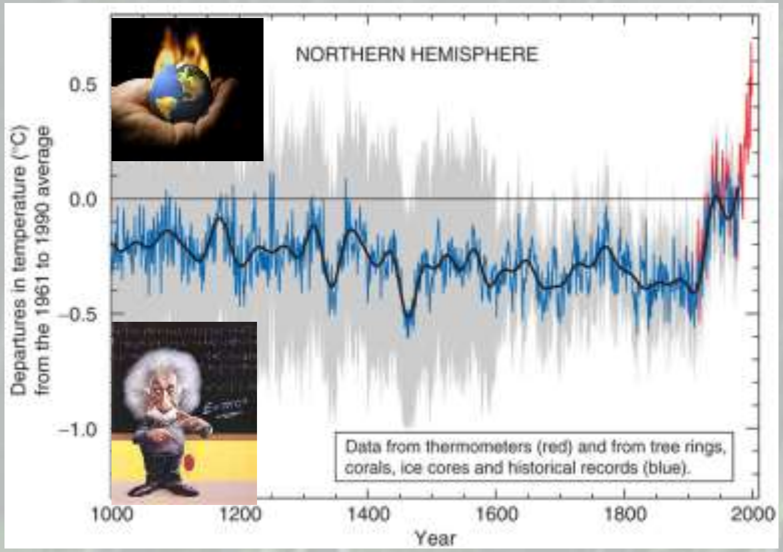
Chin Man W. MOK[1], Robert WRIGHT[2],
Rupeet MALHOTRA[2], James COOLEY[2], Rob WHITE[3]

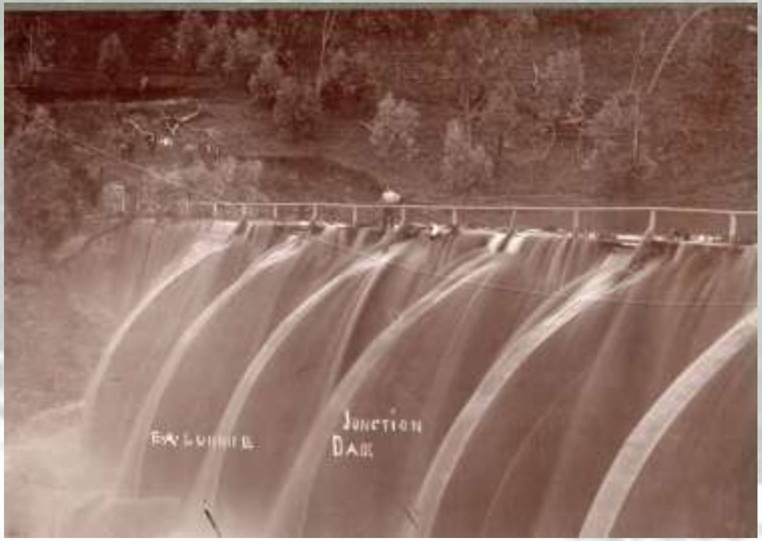
[1]**AMEC Environment and Infrastructure, Inc. and Technical University of Munich**

[2]**AMEC Environment and Infrastructure, Inc.**

[3]**Pacific Gas and Electric Company**

# Dam Overtopping and Erodibility



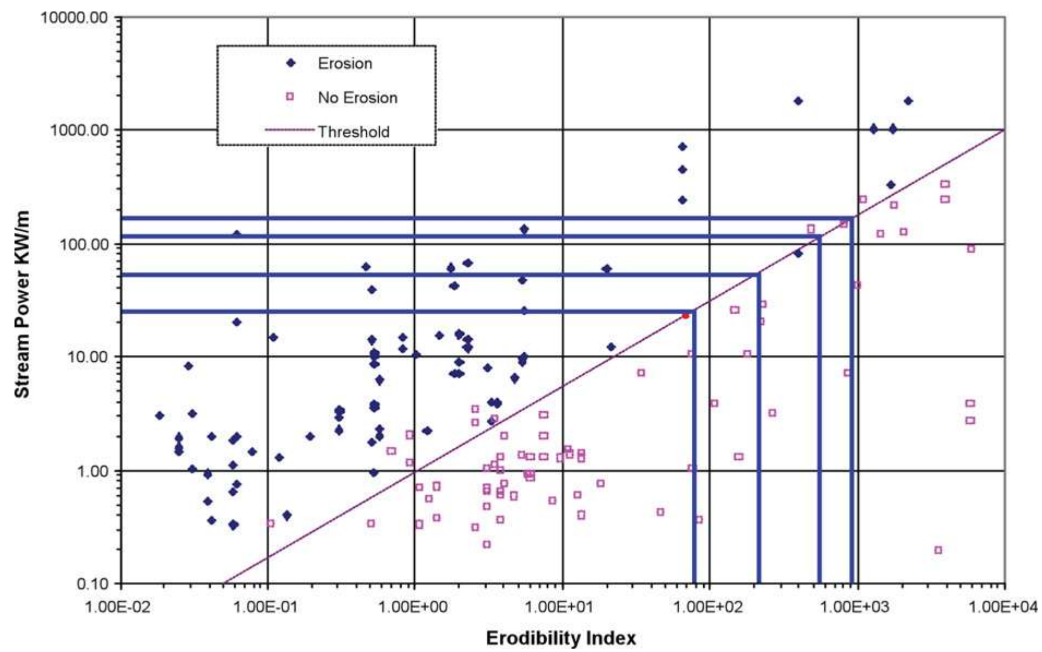




# Erodibility Index Method

- Annandale, 1995
- Empirical method based on comparison between:
  - Erosive stream power of impinging jet ($SP_{jet}$)
  - Resistive capacity of rock ($P_{scour\ Min}$): *function of erodibility index*

**Erosion threshold (rock) as defined by the Erodibility Index Method (Annandale 1995)**

$P_{scour\ Min} = K^{0.75}$

# Eroding Power of Impinging Jet

Potential maximum erosive stream power of jet :

$q$ = overtopping flow rate

*(function of overtopping depth, jet thickness or depth, initial velocity head, dam crest geometry)*

$H$ = total head of impinging jet

*(function of issuance elevation, impact depth of jet, velocity head)*

$D$ = jet outer diameter

*(function of crest geometry, jet arch length at impact)*

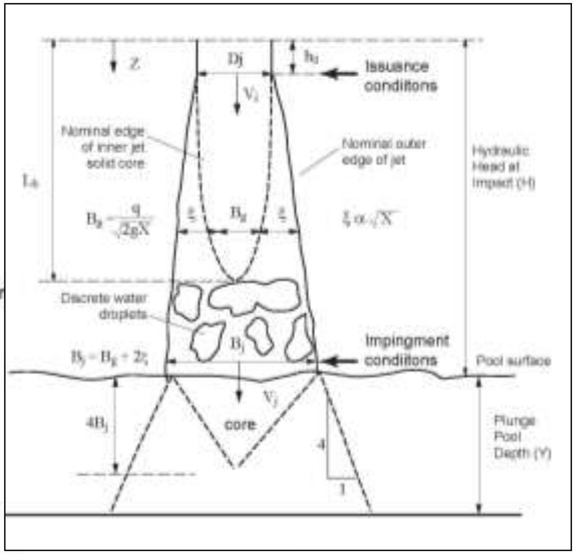
$g_w$ = specific weight of water

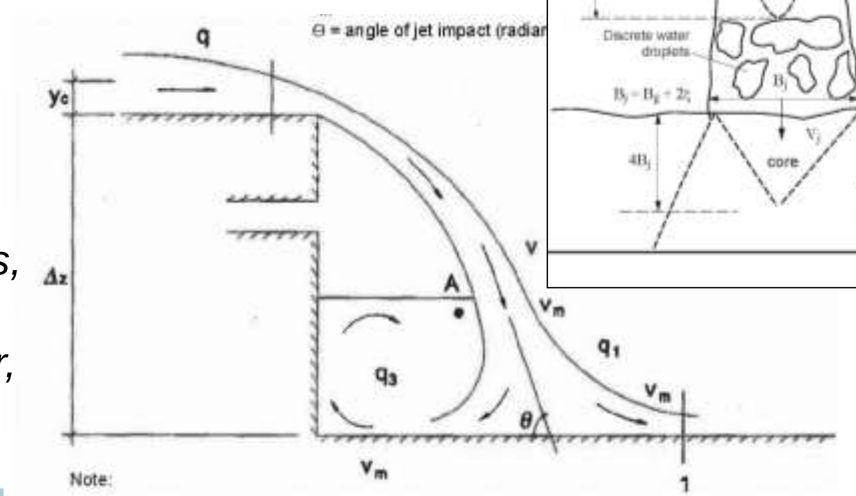
$$SP_{\max} = \frac{g_w \times q \times H}{D}$$

$$SP_{jet} = a \times SP_{\max}$$

$a$ =correction factor

*(function of jet characteristics, such as breakup length, impact length, core diameter, and outer diameter)*



# Resistive Capacity of Rock

Erodibility index (K) depends on:

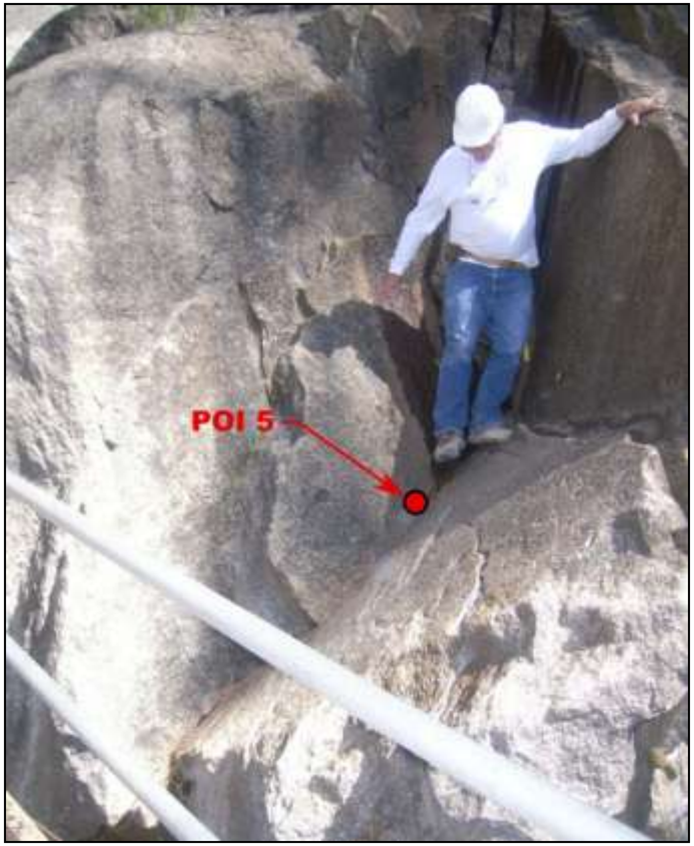
- $M_s$ = Intact rock strength parameter

  *(function of unconfined compressive strength)*
- $K_b$ = Block size parameter

  *(function of rock quality / rock joint set number)*
- $K_d$ = Interparticle shear strength parameter

  *(function of rock joint roughness / joint alternation)*
- $J_s$ = Relative orientation parameter

  *(function of relative shape of the block / dip angle / dip direction in relation to flow angle)*



# Uncertainties

- Hydrologic – rainfall, runoff, overtopping flow rates
- Hydraulic – jet characteristics, air entrapment
- Geologic – rock properties, joint characteristics
- Stability criteria

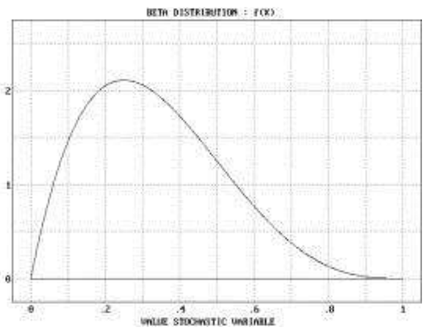
Reliability = 1- Probability of failure

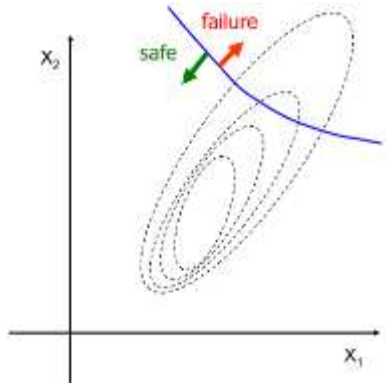
= function( streampower, erodibility index )

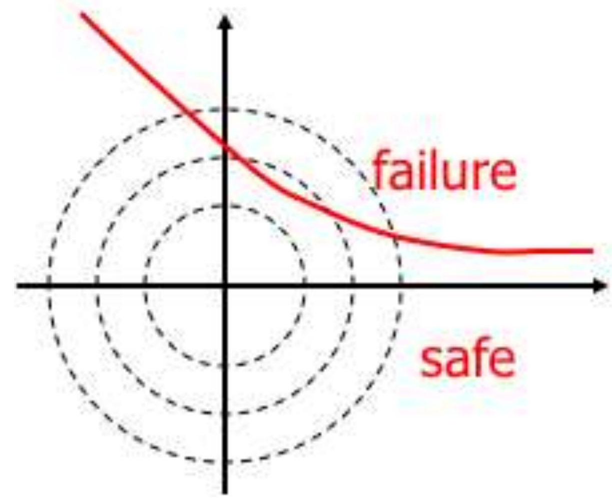
Using average properties ~ risk neutral

Safety margin/conservatism lies in design hydrologic event

# Reliability Evaluation

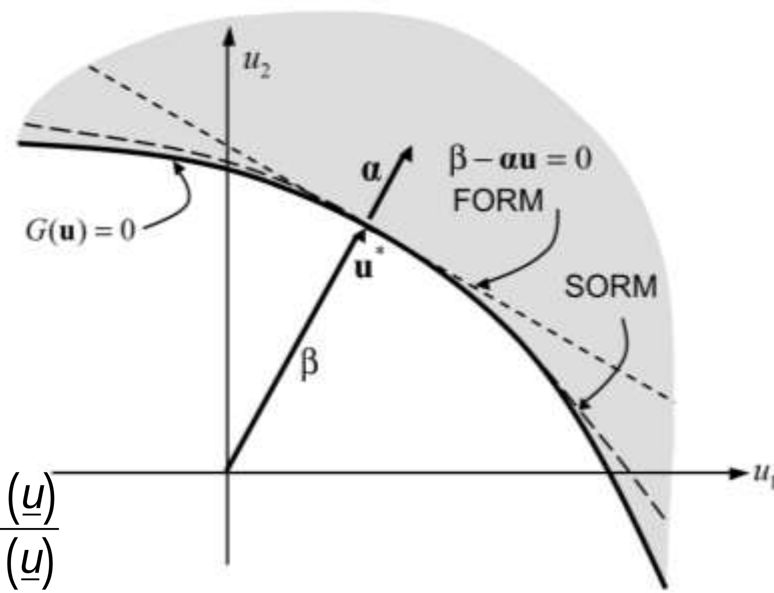



$$P_f = \mathrm{Prob}\left\{G\left(\underline{u}\right) < 0\right\} = \int_{G\left(\underline{u}\right)<0} \varphi\left(\underline{u}\right) d\underline{u} = \int I_G(\underline{u}) \cdot \varphi\left(\underline{u}\right) d\underline{u}$$

- Deterministic failure criteria
- Use Gaussian copula to transform random variables to uncorrelated standard normal variables
- Reliability methods
  - Monte Carlo simulations $\frac{1}{n}\sum_{i=1}^{n} I_G(\underline{u}_i)$
  - First-order / second-order reliability methods
  - Importance sampling simulations $\frac{1}{n}\sum_{i=1}^{n} I_G(\underline{u}_i) \cdot \frac{\varphi\left(\underline{u}\right)}{f\left(\underline{u}\right)}$



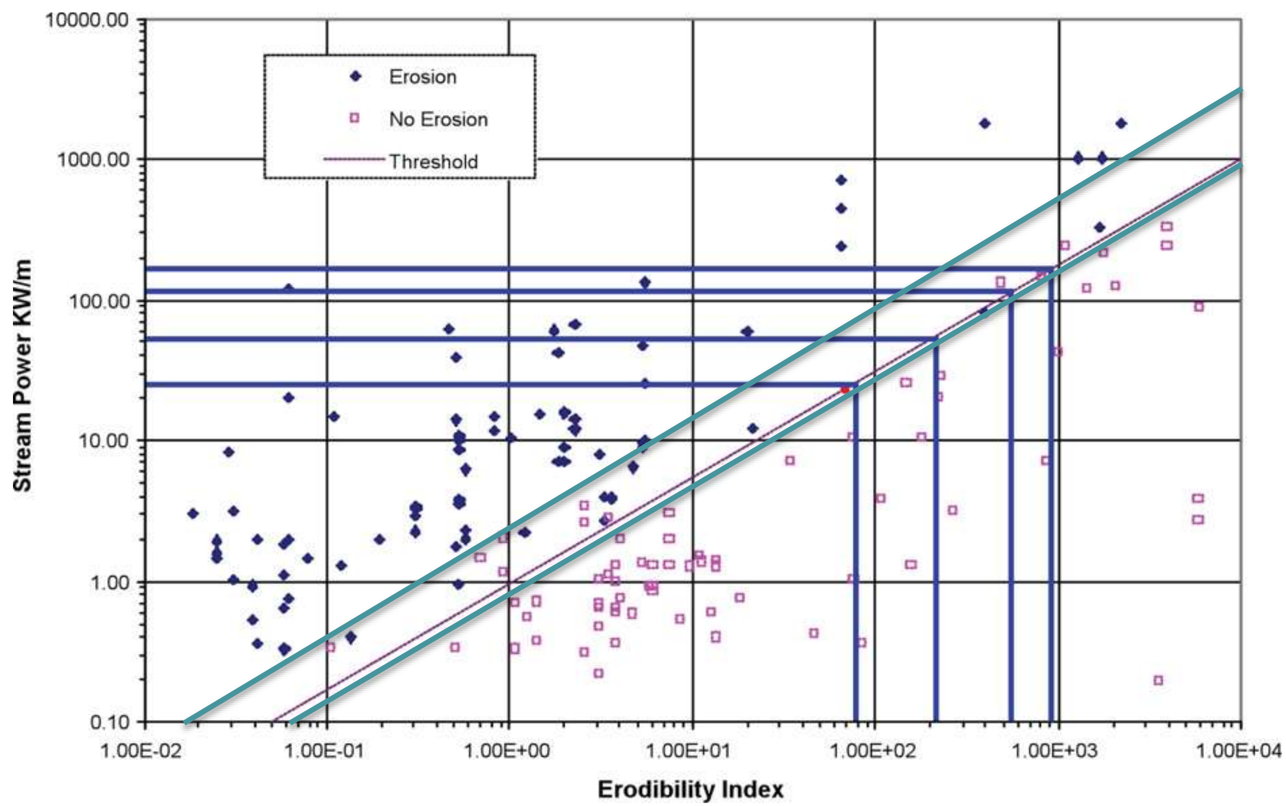
# Uncertain Failure Criterion

$p(\underline{u})$ = prob ( failure | u )

$$P_f = \int p(\underline{u}) \cdot \varphi(\underline{u}) d\underline{u}$$

Importance Sampling

$$\frac{1}{n}\sum_{i=1}^{n} p(\underline{u}_i) \cdot \frac{\varphi(\underline{u})}{f(\underline{u})}$$

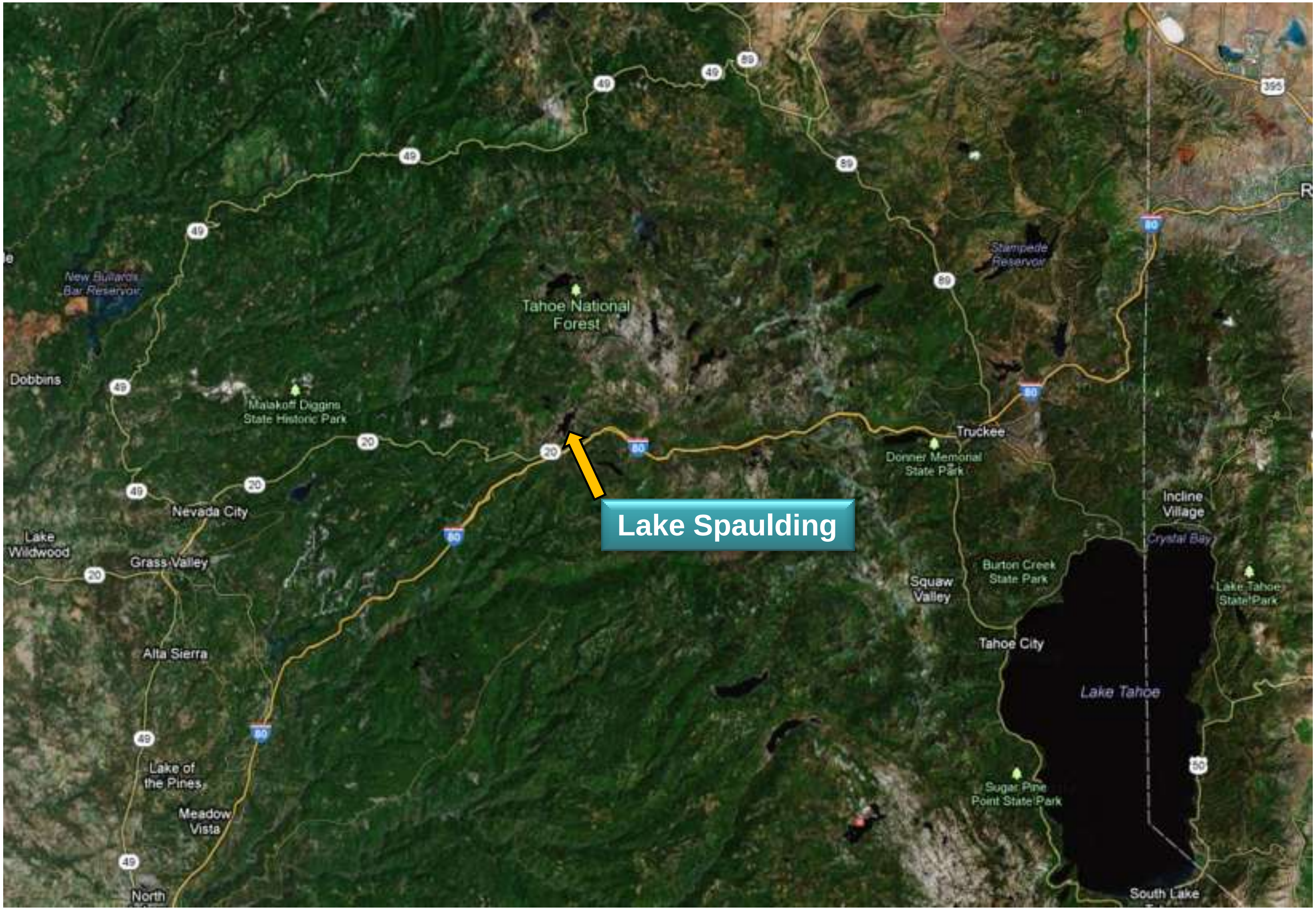


# Rock Data Collection

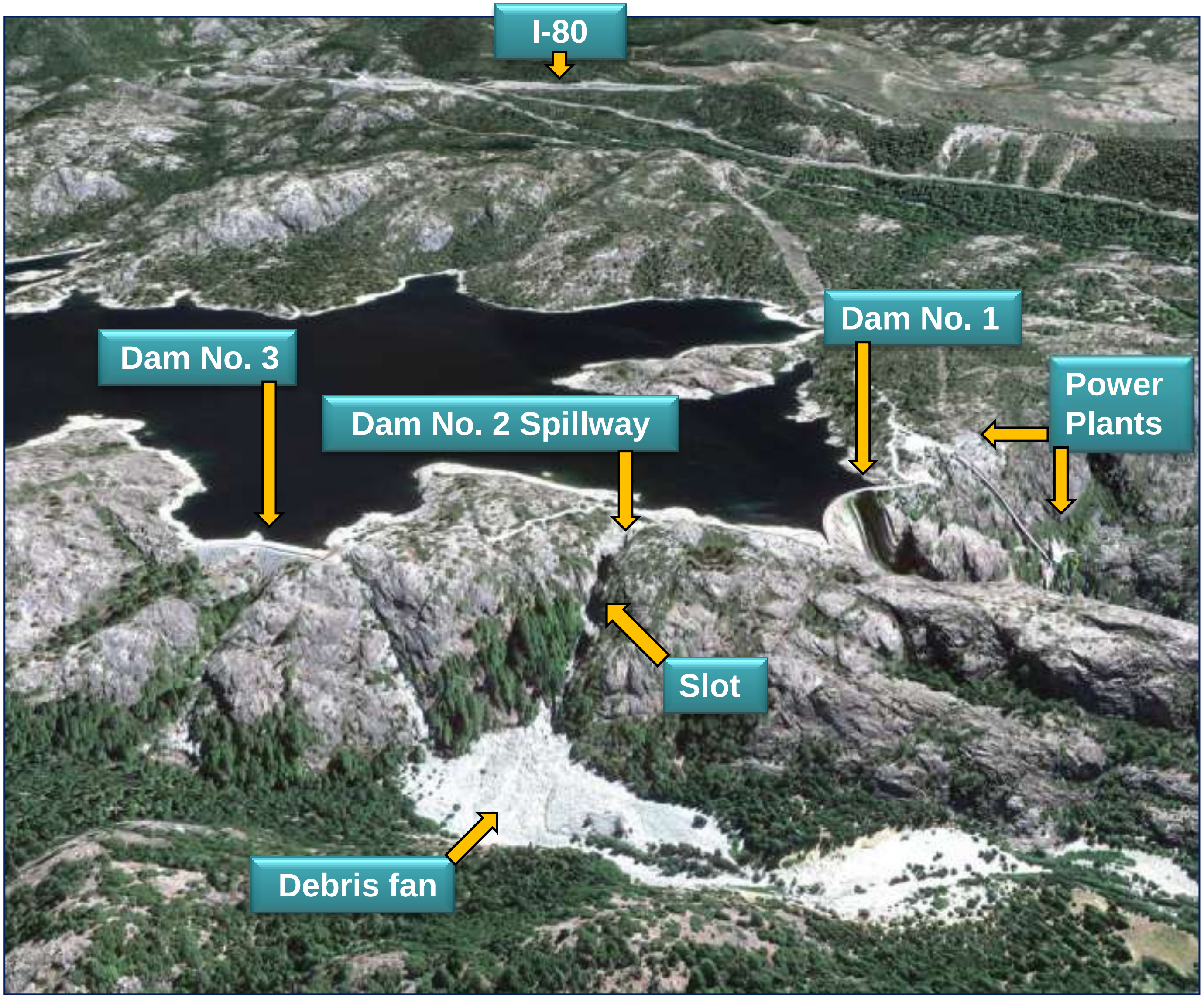
# Manual vs LiDAR methods of measuring joint properties


Photo taken July 27, 2012

# Site location



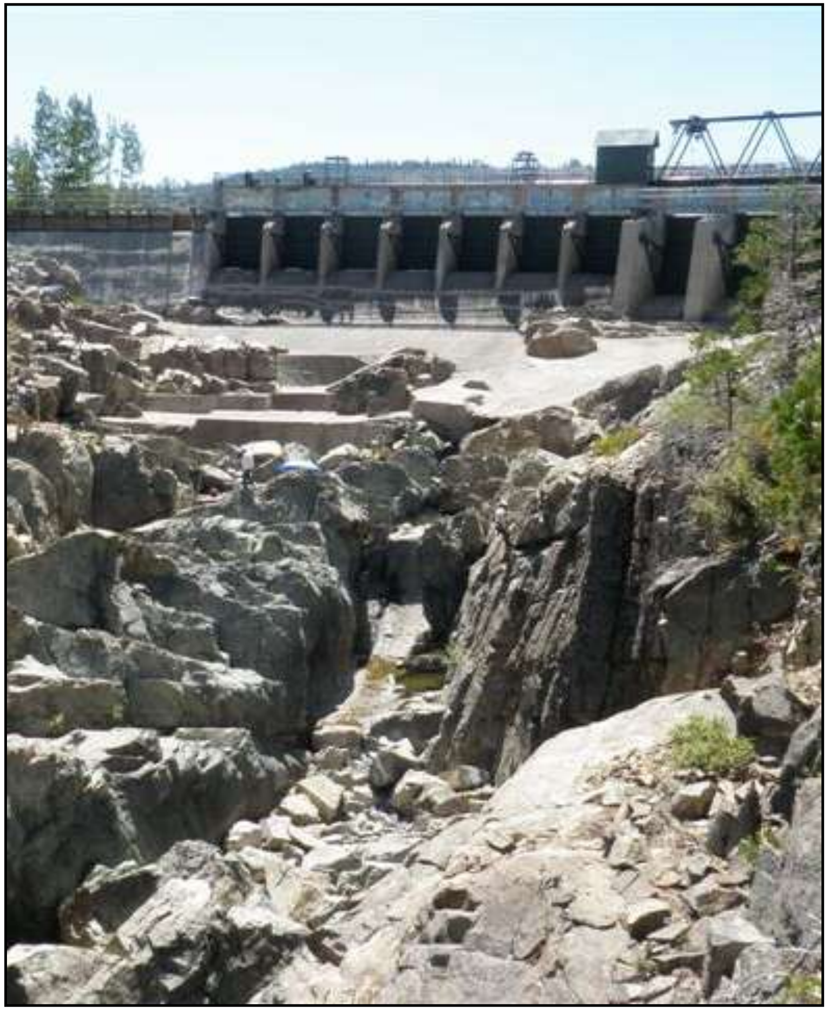
# Oblique view (looking southeast) of Lake Spaulding and Dams

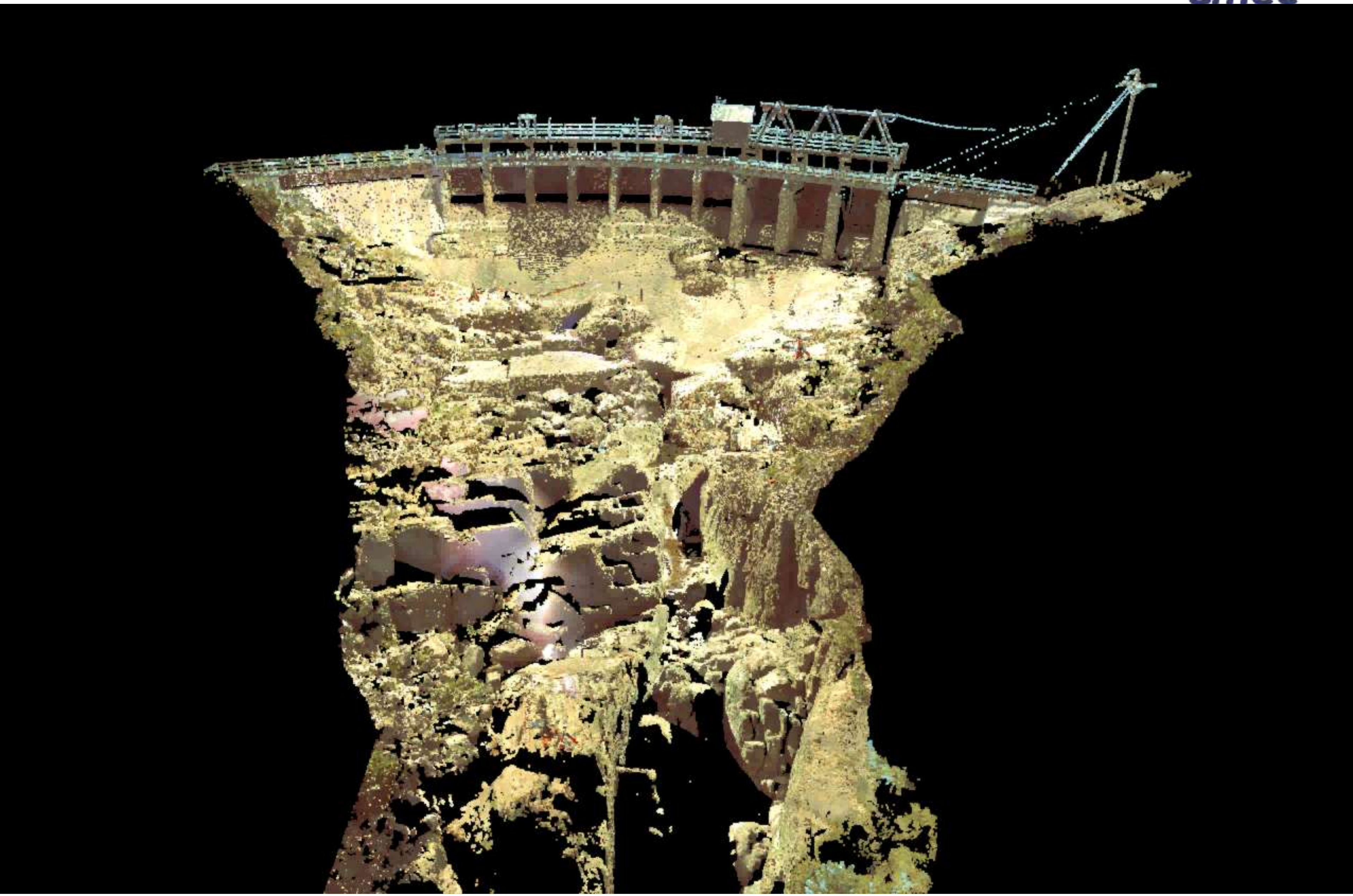


# Vertical view of Dam No. 2 spillway, slot, and debris fan

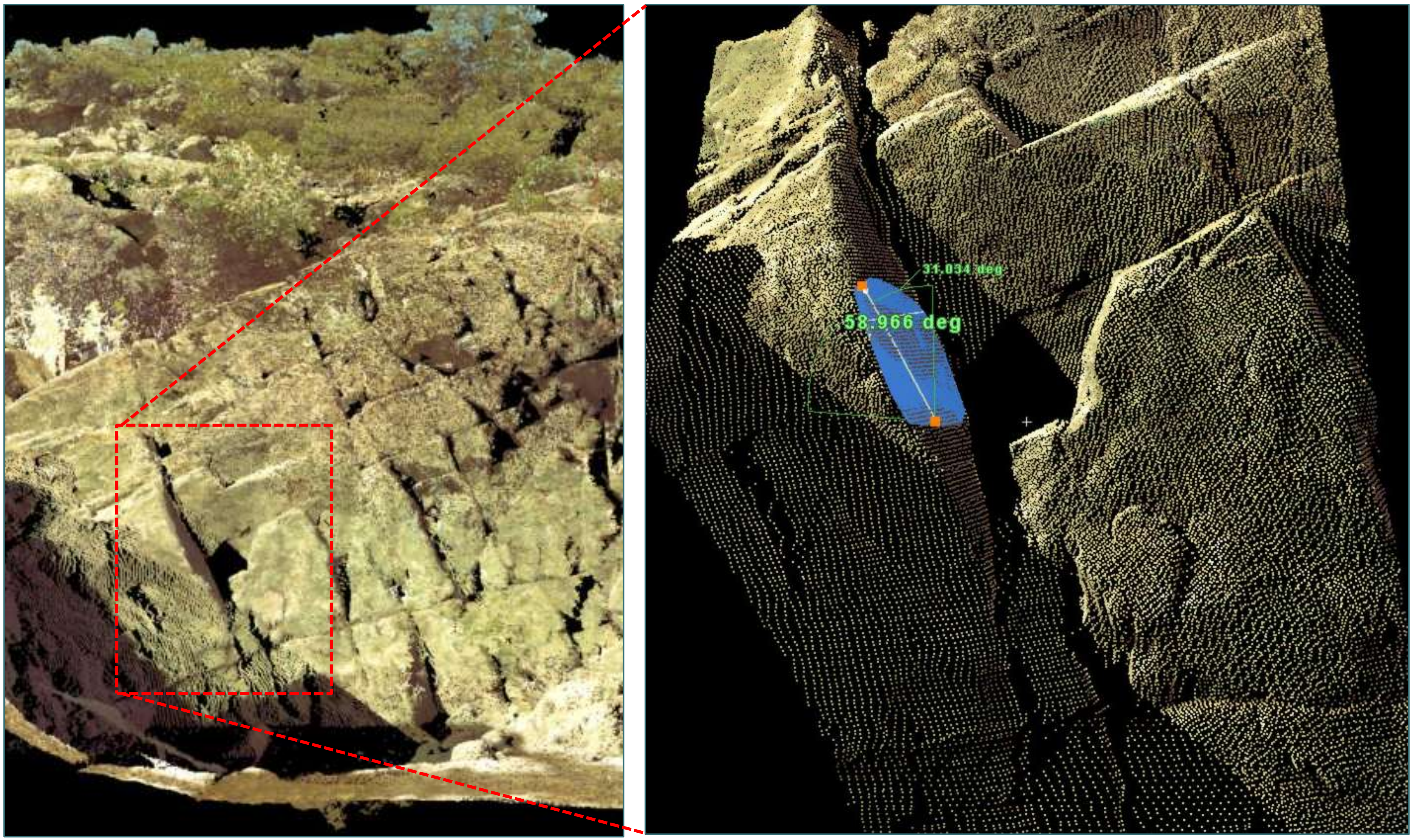
# Spaulding Dam No. 2 spillway specifications

- Constructed in 1916
- Curved (300-foot radius) concrete arch dam
- Crest height = 42 feet
- Crest length = 309 feet
- Crest width = 4 feet
- Nominal crest elevation = 5,016.1 feet (top of parapet)
- Three 14 ft x 20 ft radial gates ogee spillway crest at 4,994.6 feet
- Seven 14 ft x 15 ft radial gates ogee spillway crest at 4,999.6 feet
- Stoplog spillway ogee crest at 5,009.6 feet
- 72 hour October (PMF) = 70,490 cfs inflow and 68,450 cfs outflow
- October PMF = 41.95 inches ((HMR 36) – 45.76 inches (HMR 58/59)
- Maximum October PMF flood water surface elevation = 5,018.5 feet
- Maximum October PMF freeboard = -2.4 feet (overtops 12.9 hours)
- December 1964 flood = 33,000 cfs (estimated at zero freeboard)
- January 1997 Flood of Record (FOR) = 34,200 cfs

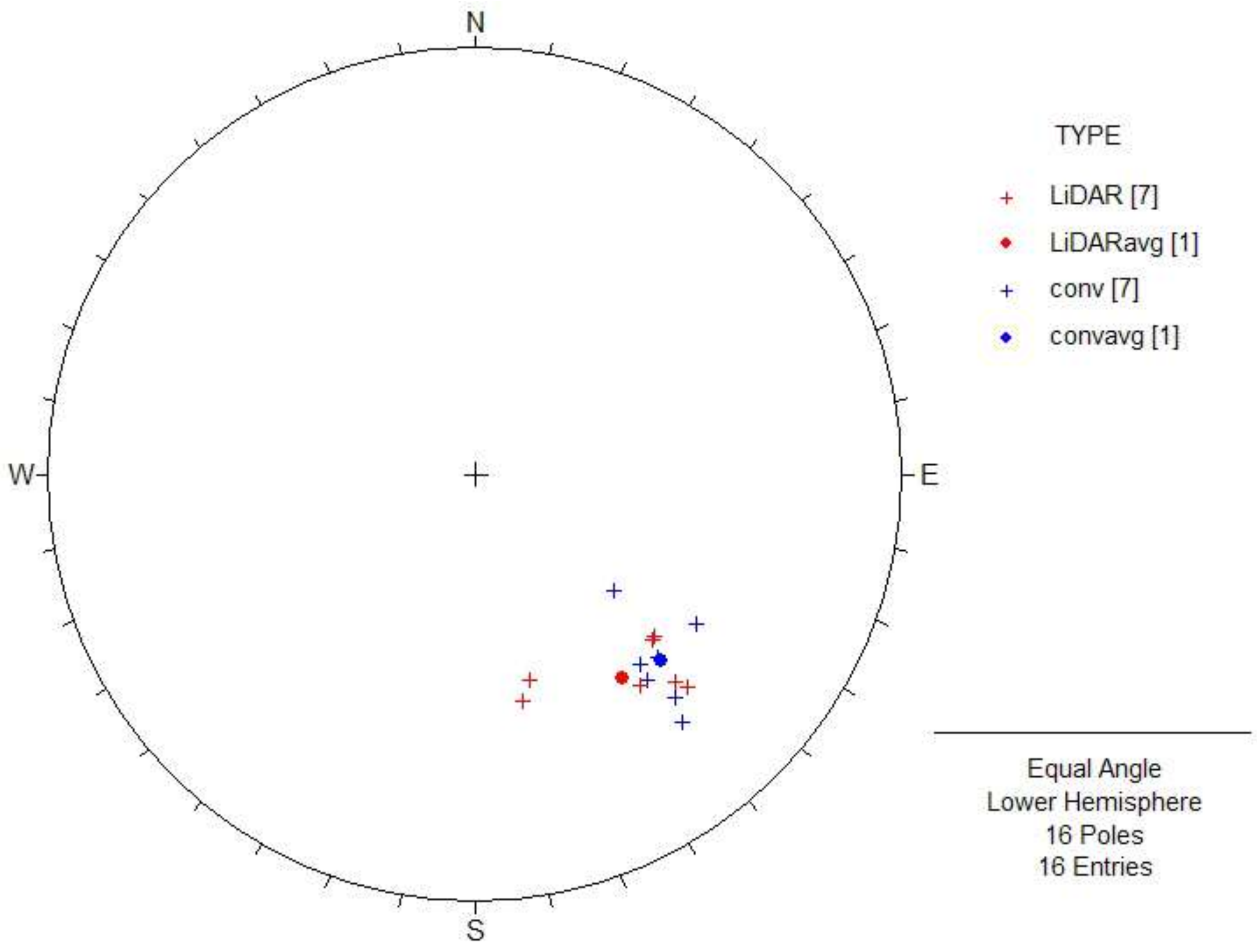




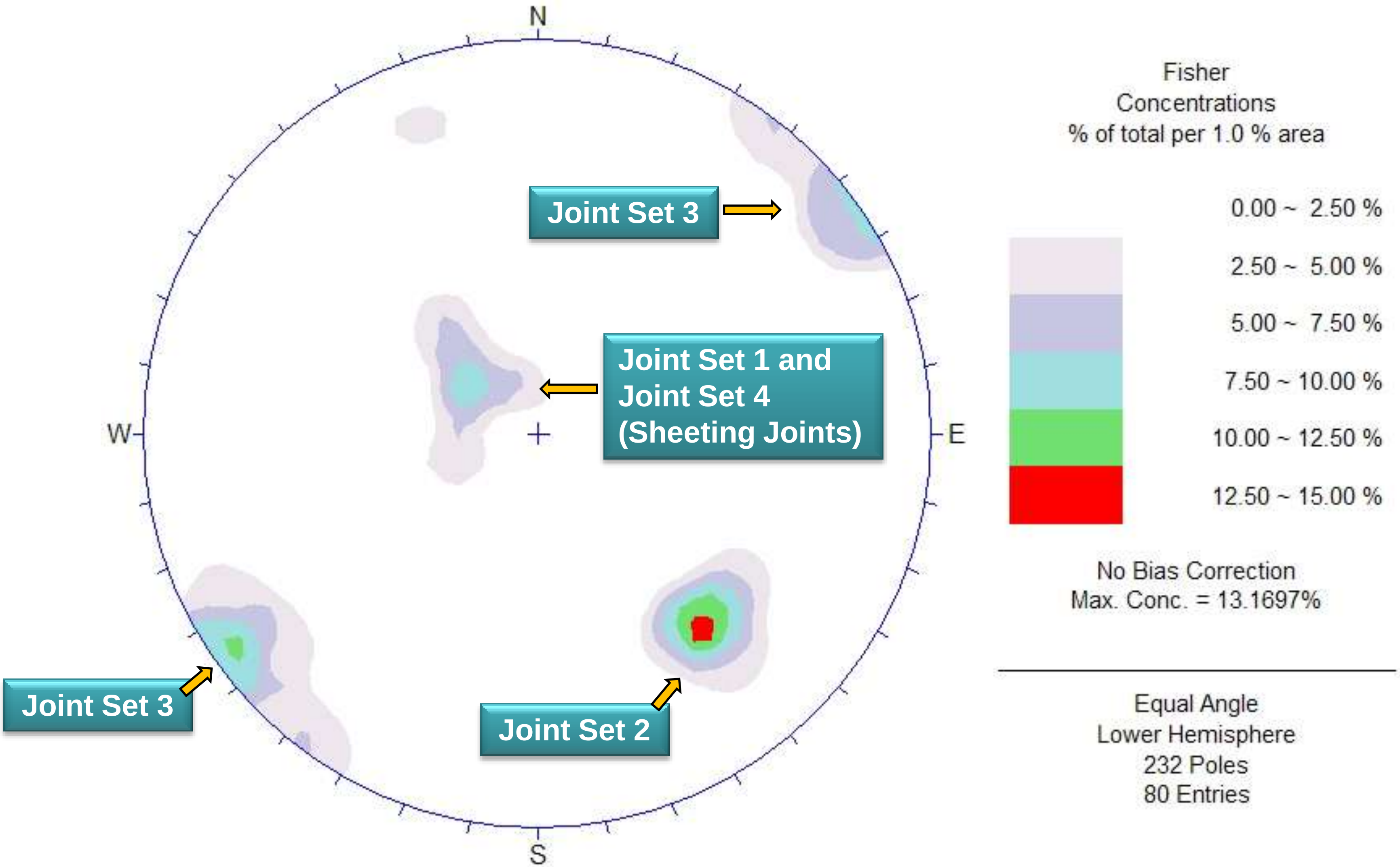
# LiDAR data point cloud showing dip measurement (Joint Set 2)



# Comparison of manual and LiDAR measured Joint Set 2 joints



# Poles of primary joint sets in Spaulding Dam No. 2 spillway



# Rock Block Stability Evaluation

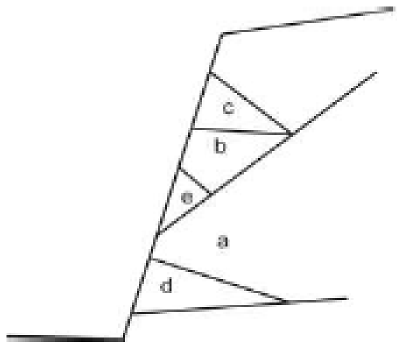
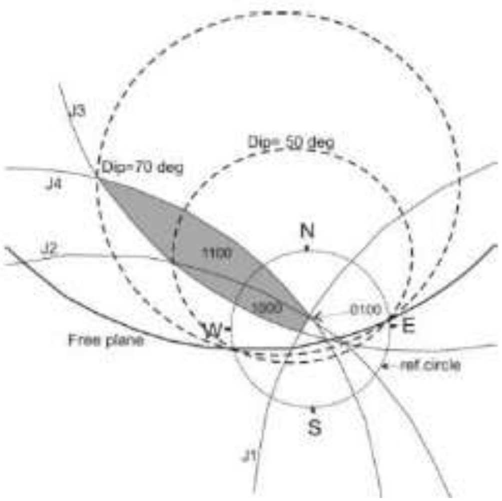
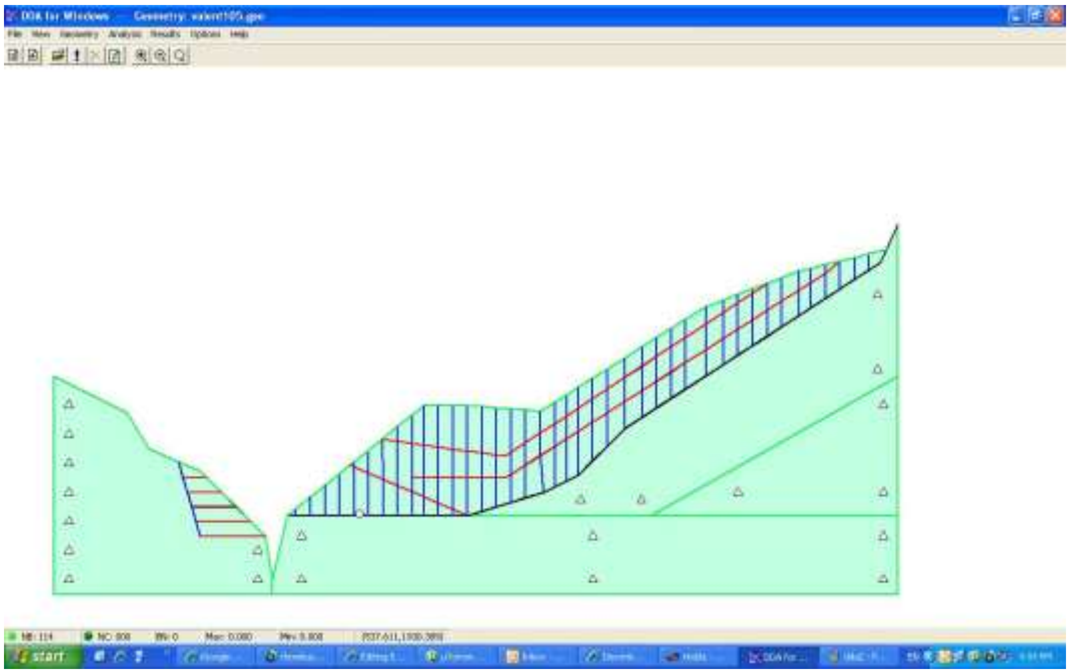



**Figure 4**: Blocks in a surface cut. (a) infinite; (b) tapered; (c) stable; (d) potential key block; (e) key block.

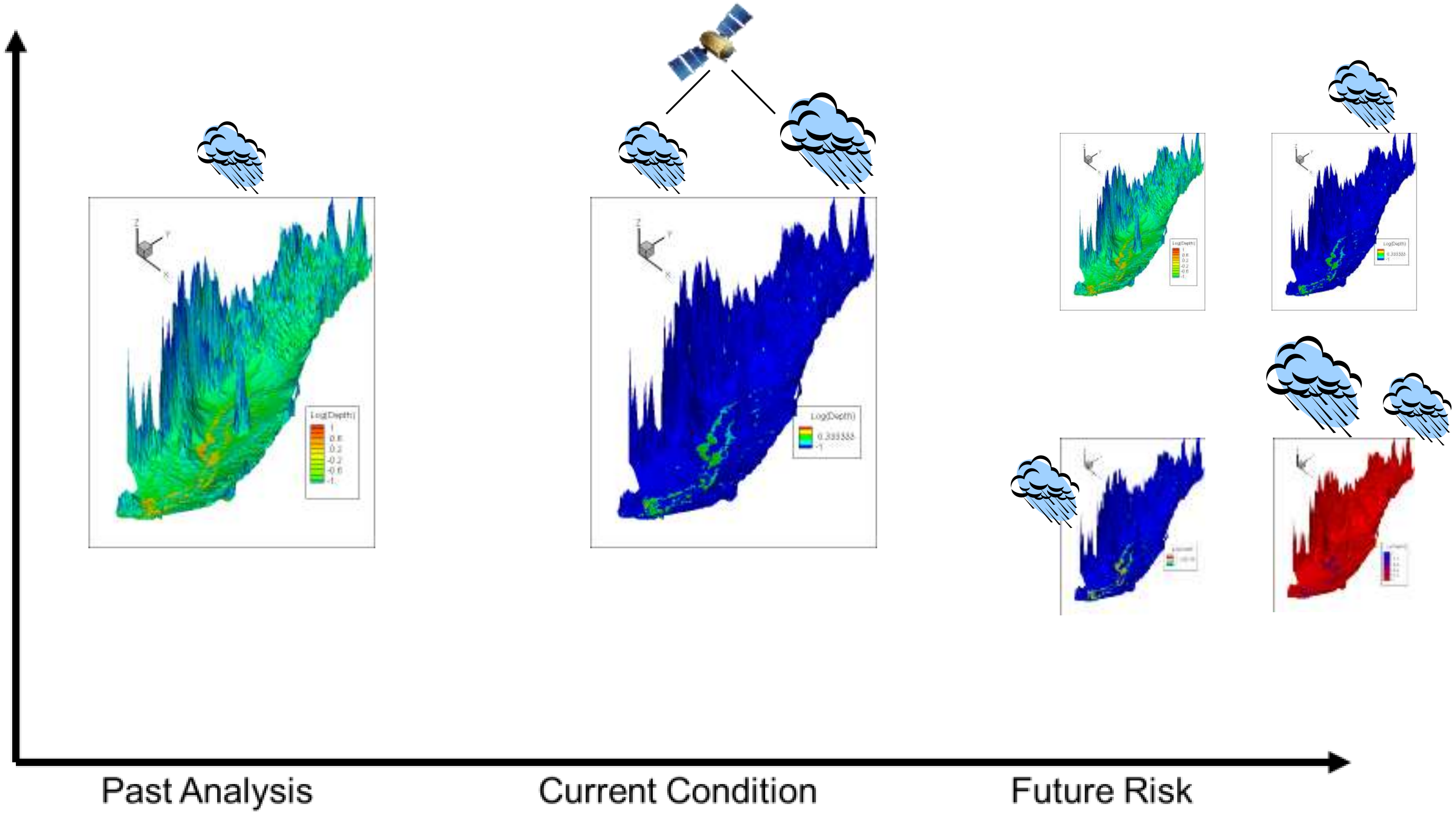



Block Theory

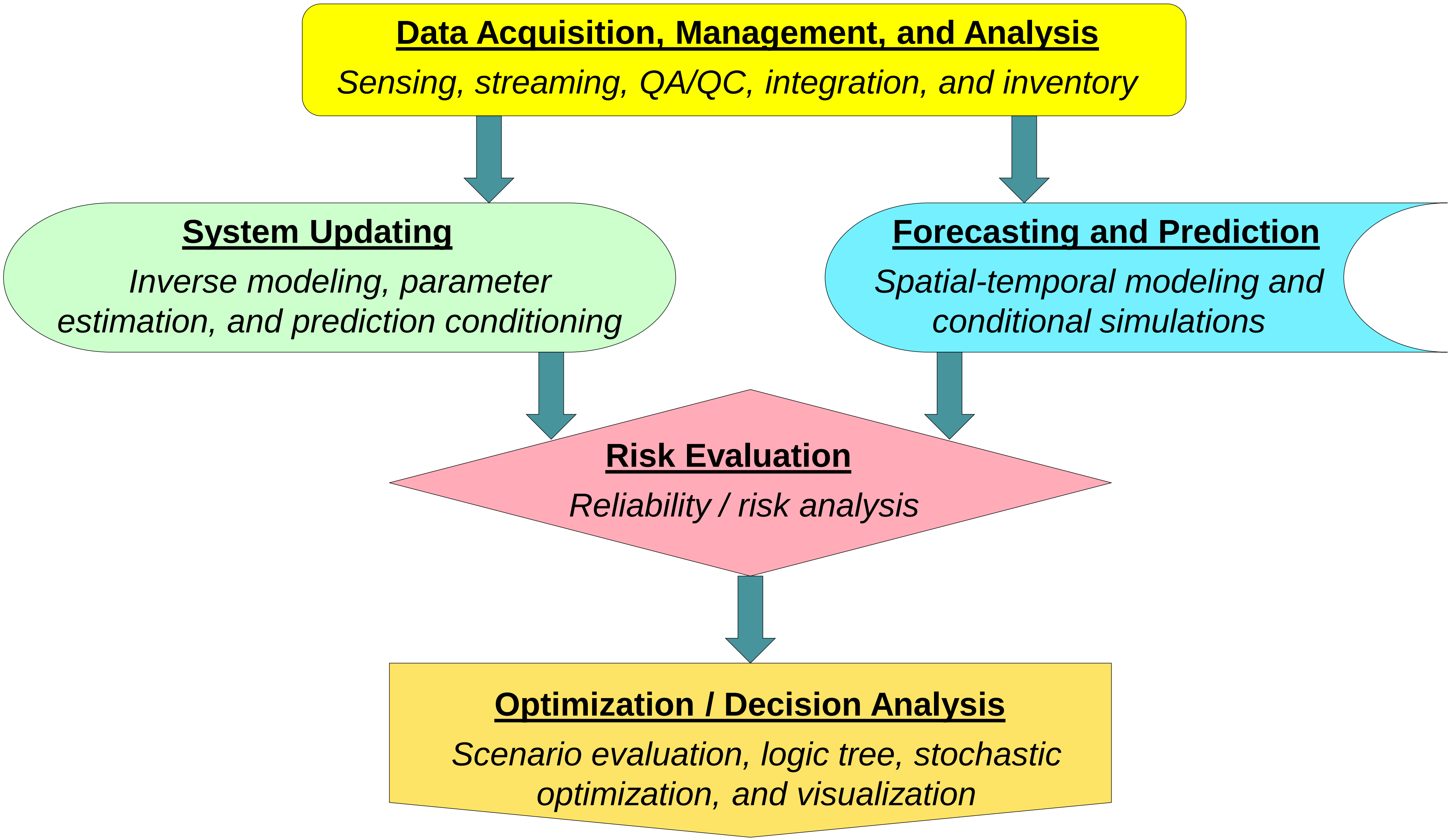


Discontinuous Deformation Analysis

# Past, Current & Future



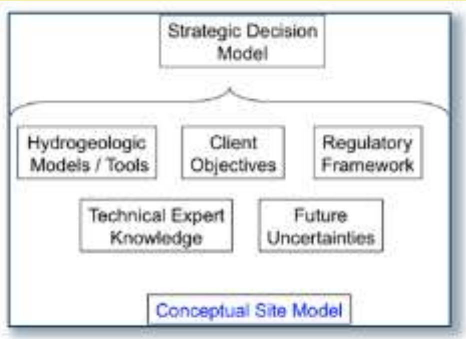
# A Holistic and Adaptive Risk-Based Decision Support Framework For Water Resources Management



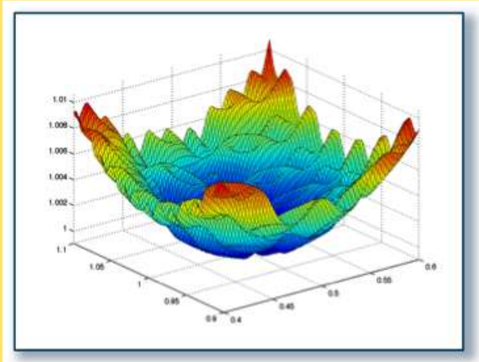
# Optimization / Decision Analysis –

**<u>Optimization / Decision Analysis</u>**

*Scenario evaluation, logic tree, stochastic optimization, and visualization*




Decision Analysis



Optimization

Real-Time Operations

# Reliability-Based Dam Erodibility Assessment

Chin Man W. MOK[1], Robert WRIGHT[2],
Rupeet MALHOTRA[2], James COOLEY[2], Rob WHITE[3]

[1]**AMEC Environment and Infrastructure, Inc. and Technical University of Munich**

[2]**AMEC Environment and Infrastructure, Inc.**

[3]**Pacific Gas and Electric Company**