Trinity River near Hoopa, CA

Gravel Bed Armoring

Colorado State University
CIVE 717

Craig Baxter
Ryan Brown

What is Gravel Bed Armoring?

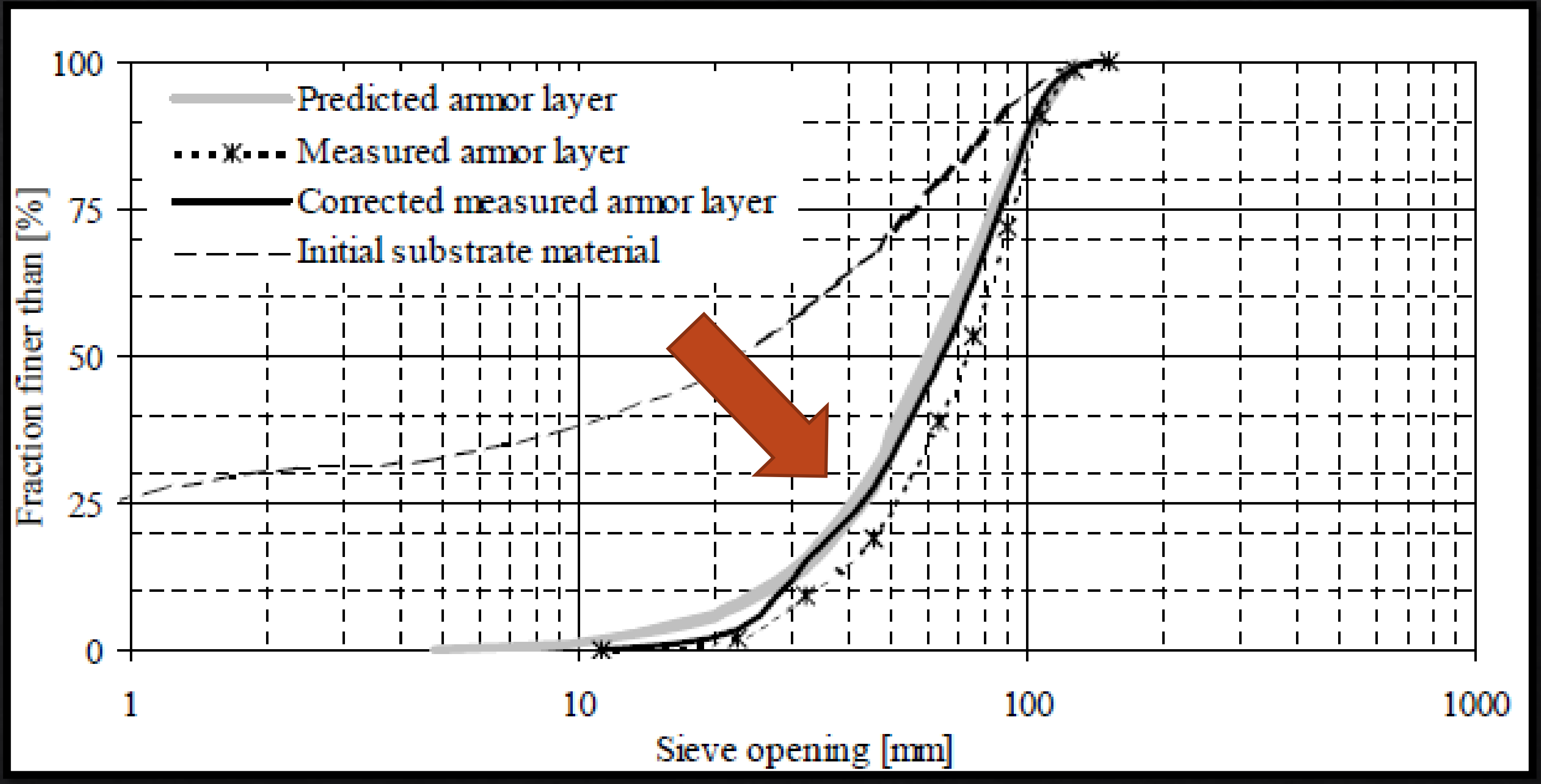
- A general coarsening of bed relative to substrate
- Forms due to selective entrainment of finer particles at bed surface
- Armor layer is only mobile during highest floods

Armor layer in flume experiment. Coarse layer on surface clearly visible with fine grained substrate below.

http://www.seas.virginia.edu/research/curran/images/flumeandrocks.jpg

What is Gravel Bed Armoring?

- Changes particle size distribution from typical S-curve to concave curve



Three Conditions for Armoring

(Julien, 2002)

1. Stream bed must be degrading
   - Stream capacity is greater than supply
2. Coarse bed material
   - Minimum grainsize (d_{sc}) defined at $\tau_{\star c} = 0.05$
3. Sufficient supply of coarse material
   - High percentage of grains larger than d_{sc} leads to quick armoring
   - Low percentage of grains larger than d_{sc} leads to slower armoring

Measurement

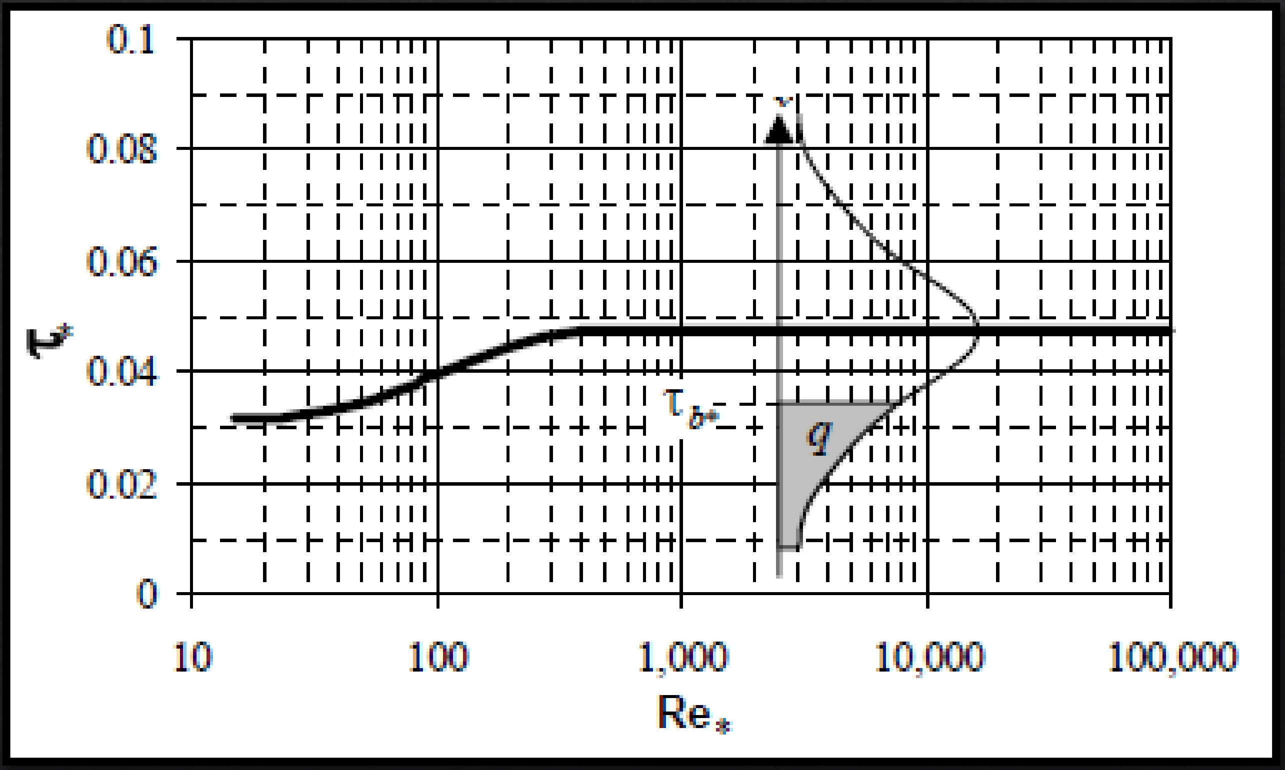
- Volumetric sampling of armor/sub-armor layers (Bunte and Abt, 2001)
  - Grain size statistics determined by count using gravelometer or by weight with sieving
- Degree of Armoring defined by armor ratio

$$Armor\ Ratio = {D_{50,\,surface}}/{D_{50,\,subsurface}}$$

Photos by Kristin Bunte

Prediction of Armor Layer

- Gessler (1965) developed method of prediction
- Modified Shield's diagram to show 50% probability of Removal/Non-Removal



(Oehy 1999)

Prediction of Armor Layer

- Probability of particle removal depends on ratio of bed shear stress to critical stress $\left({}^{\tau_b}/_{\tau_c}\right)$
- Probability of removal of a particle from the surface layer is given by:

$$q = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{{}^{\tau_b}/_{\tau_c}-1} exp\left(-\frac{x^2}{2\sigma^2}\right) dx$$

Where:

σ = geometric standard deviation

x = dummy variable of integration

Prediction of Armor Layer

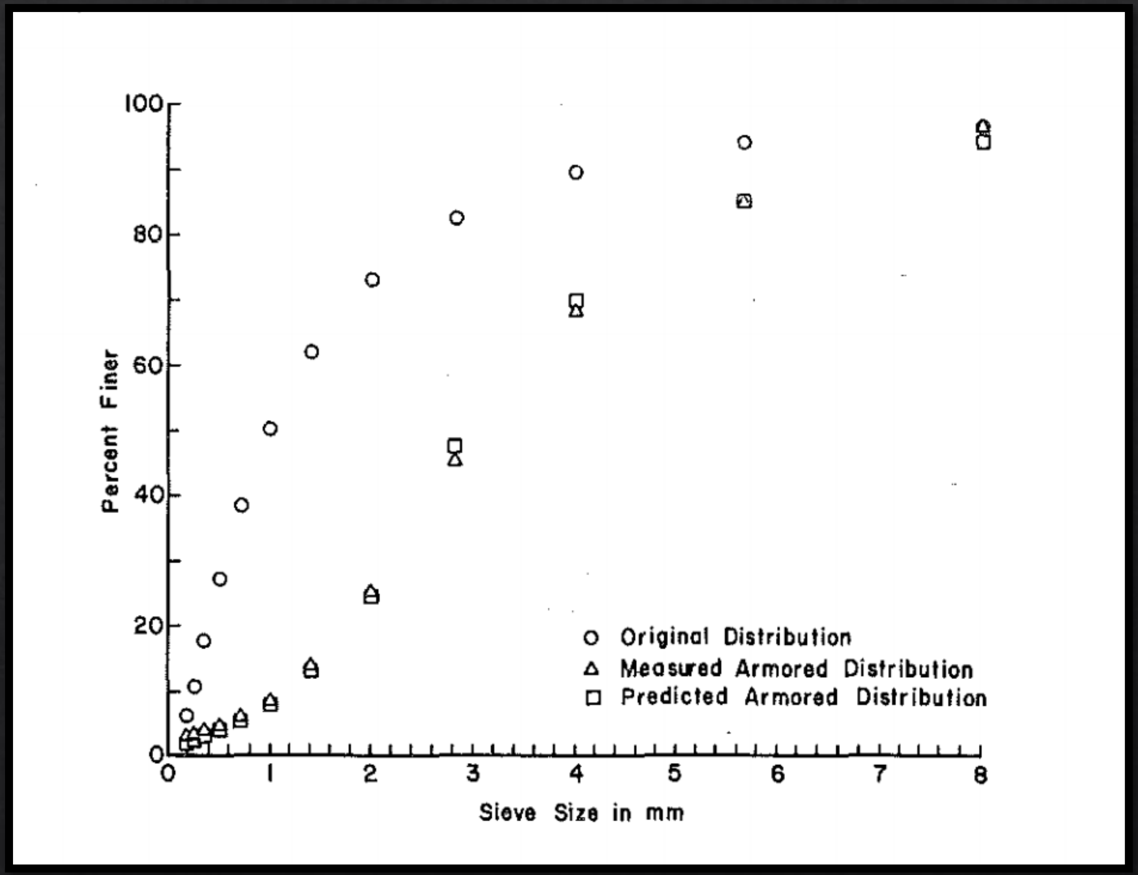
- The particle size distribution of an armor layer assuming constant bed shear stress is given by:

$$P_A(d) = \frac{\int_{d_{min}}^{d} q p_0(d) dd}{\int_{d_{min}}^{d_{max}} q p_0(d) dd}$$

Where

$p_0(d)$ = probability density of intiial grain size distribution

Prediction of Armor Layer



Prediction of armor layer compared to measurements (Shen and Lu 1983)

Effects Of Armoring

- Stabilizes channel elevation
- Stabilizes channel morphology
- Issues
  - Reduction in availability of appropriate spawning gravels downstream of dams
  - Limits transport of sediment

Sockeye salmon spawning in Chilkoot River, Alaska

Photo by Paul Vecsei

Effect of Dams on Armoring Process

- Dams impedes natural flow of sediment downstream
- Fine sediment supply downstream is cut off
- Coarse particles remain and create armor layer
- Reduced peak flows reduce large grain mobility
  - Maintains armor layer

Downstream of Lewiston Dam on the Trinity River in Northern California.

Removal of Armor Layer

Habitat Improvement

- Gravel Augmentation
  - Burry armored layer below gravel of suitable size (i.e. spawning gravels)
  - Only a temporary fix
- Experimental Ideas
  - Venditti et al. (2010) proposed introducing finer gravel bed load pulses to mobilize existing armor layer
  - Smoothing of bed increases near bed velocity which entrains larger particles to removes armor layer
  - Only demonstrated by flume experiments to date

Removal of Armor Layer

- Gravel Mining
  - In channel gravel mining removes coarsened bed
  - Channel stability compromised → incision
  - Headcut propagates upstream putting infrastructure at risk

In channel gravel mining in Ecuador. This practice is very common in many developing countries.

http://ecuadorianrivers.org/wp-content/uploads/2011/11/Gravel-Mining.jpg

Santa Ana River Case Study

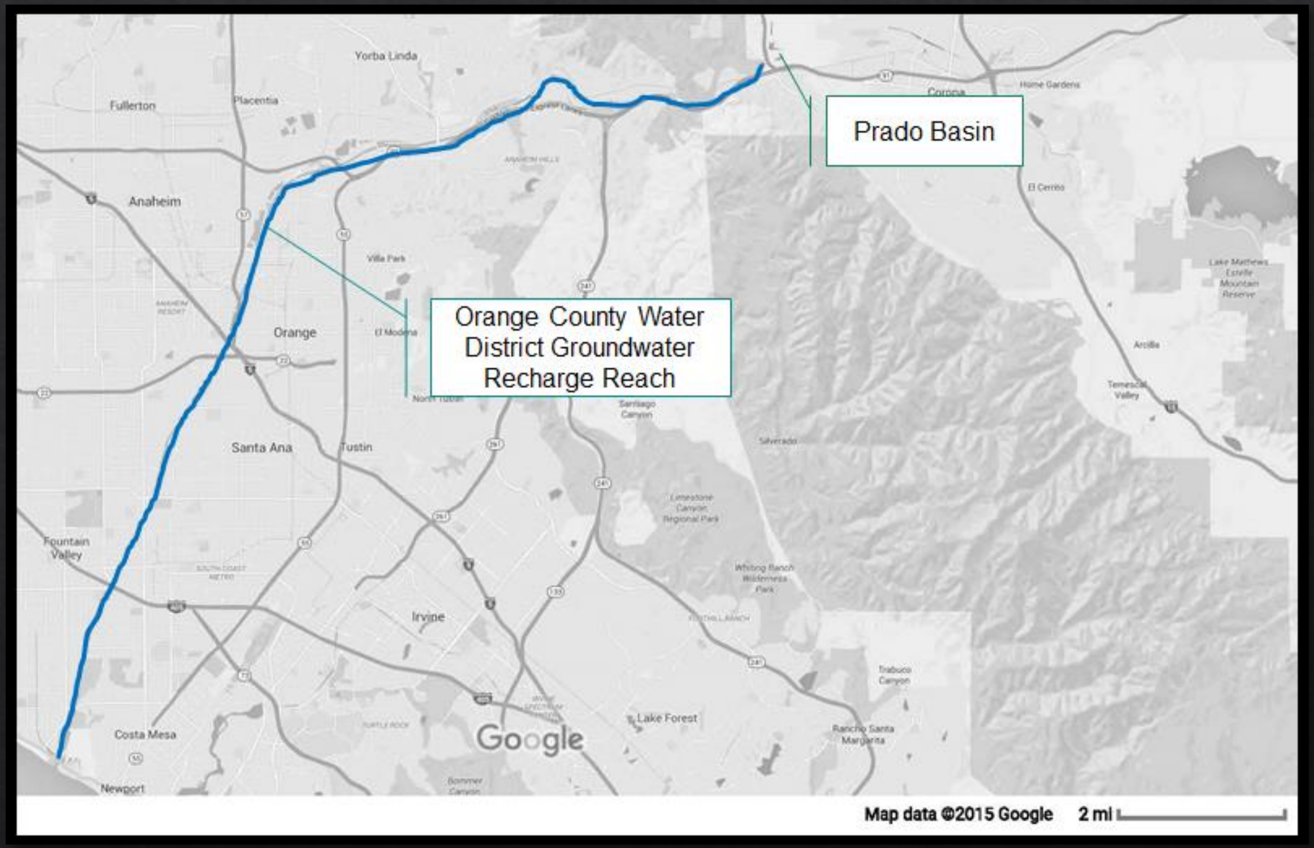
- Prado Dam built in 1941
- Primary purpose is flood control
- Traps sediment in the Santa Ana River
- Orange County Water District (OCWD) operates groundwater recharge reach downstream

Prado Dam (Photo from LA Times)

Problem

Groundwater recharge rates have been declining.

Santa Ana River Case Study



Santa Ana River Case Study

- Bed sampling in 2008 revealed a coarsening of bed material within OCWD recharge reach
- Particle size distributions show the beginning of moving toward a concave curve typical of armoring

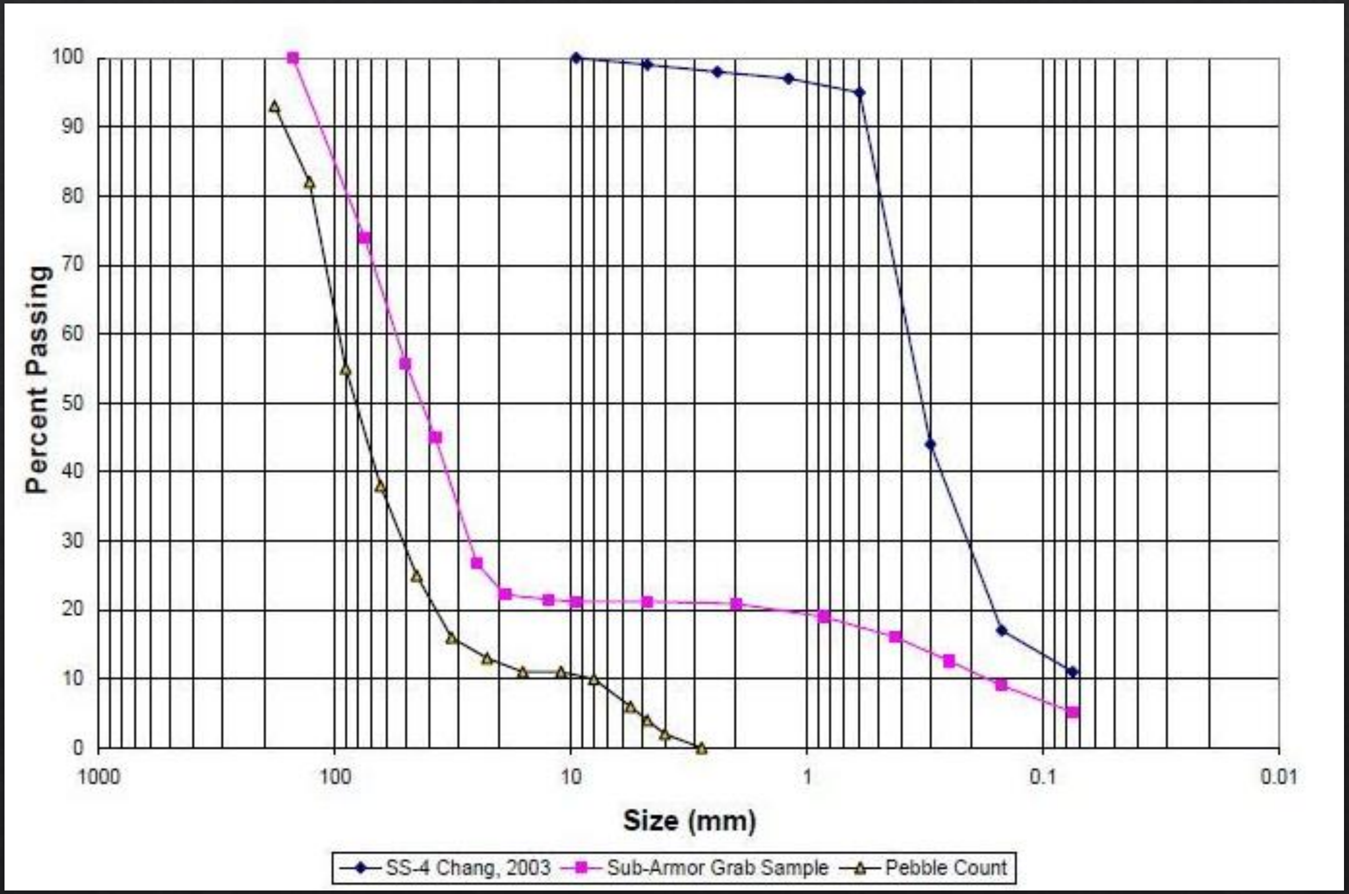
Question

Could armoring of bed within recharge reach be causing reduced infiltration rates?

Santa Ana River Case Study

Sample Location with Coarsening Bed
(Engineering and Hydrosystems 2009)

Santa Ana River Case Study



Particle size distributions showing coarsening over time
(Engineering and Hydrosystems 2009)

Santa Ana River Case Study

- Intuition suggests coarser particles inherently having more porosity which would increase infiltration
- The theory in the OCWD recharge reach is that a sand bed creates a very efficient, self cleaning, infiltration system
- The lack of sand moving into the recharge reach due to Prado Dam is allowing more silts and clays to move deeper into the bed layer which decreases infiltration

Santa Ana River downstream of Prado Dam

Santa Ana River Case Study

- The Prado Feasibility project would introduce sediment removed from Prado Basin downstream
- Primary goal is to sustain or increase infiltration rates in the OCWD recharge reach
- New sand sized particles could help break up the coarsening bed
  - Well established in literature (Jackson and Beschta 1984)

Infiltration area on Santa Ana River

Conclusions

- Armoring has important effects on hydraulics and sediment transport in gravel bed rivers
- Armoring stabilizes channels and prevents further degradation
- Armoring can be accurately predicted
- Armoring can have detrimental effects on aquatic habitat
- If sediment supply is cut off by a dam, armoring can be exacerbated beyond natural conditions
- There are various methods that can remove or minimize armor layers

References

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