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A Computational Approach to the Study of the Stability of Pier Riprap at the Middle Fork Feather River

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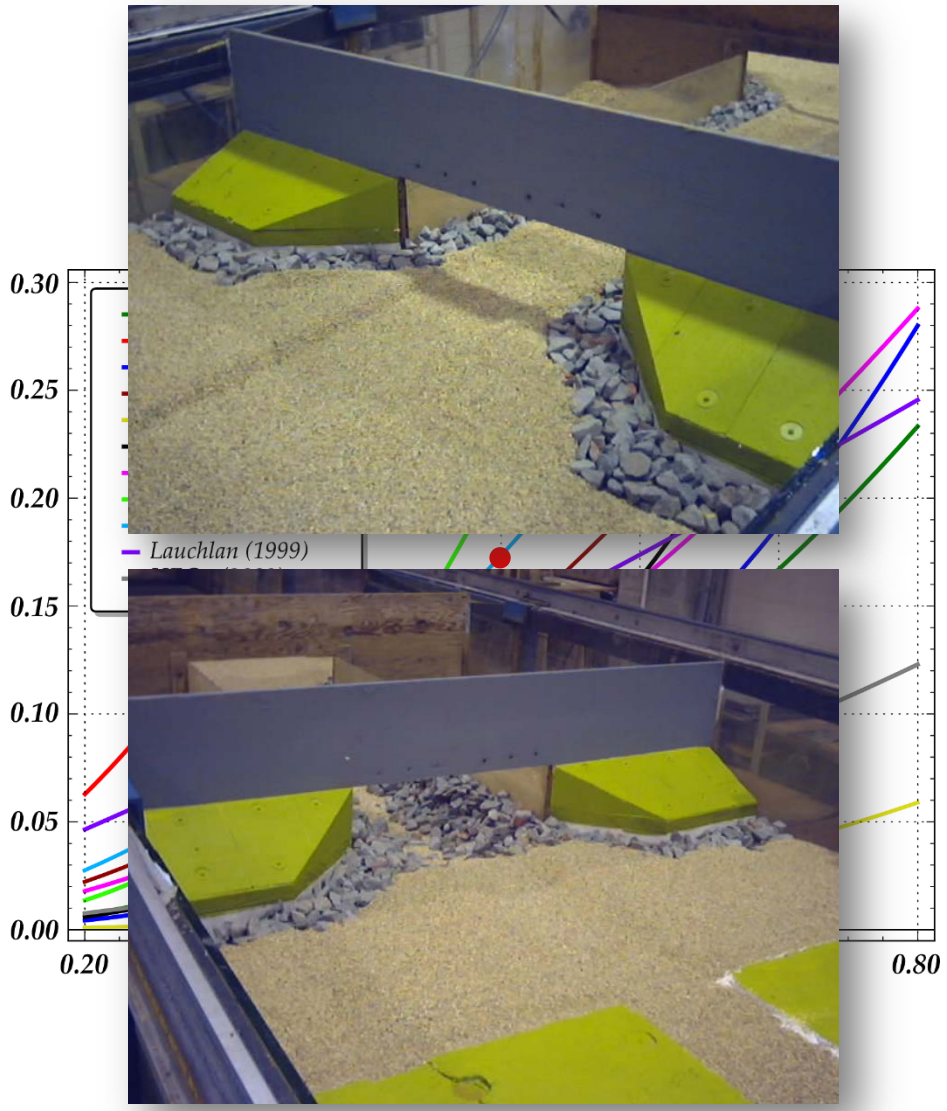
Motivation

- Sizing of the riprap is based mostly on limited field observations and scaled laboratory tests under ideal, controlled conditions.
- The size of riprap required for many field applications is too large for testing in the laboratory.
- There is significant uncertainty in the formulas for sizing riprap.
- Recent advances in computational fluid dynamics (CFD) and computational structural mechanics (CSM) make it possible to do fluid structure interaction (FSI) simulations to compute water force distribution and consequent motion of individual rocks.



- *Kornel Kerenyi, J. Sterling Jones, and Stuart Stein, Bottomless Culvert Scour Study: Phase II Laboratory Report, FHWA-HRT-07-026, 2007*

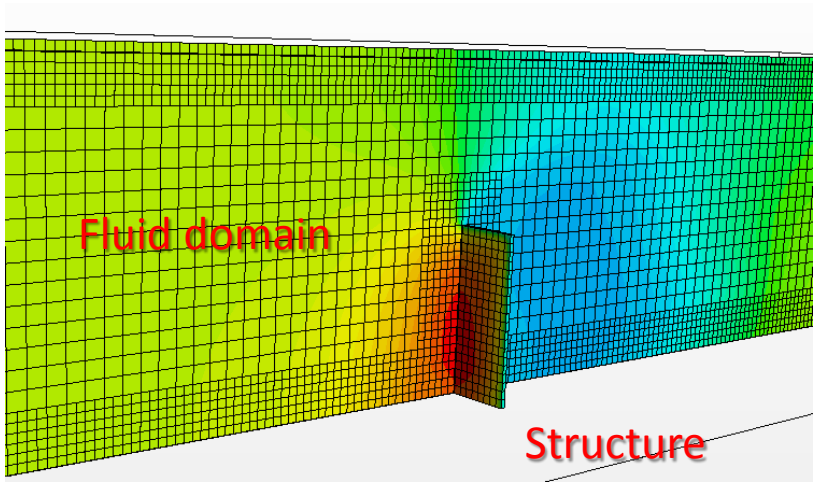
What is Fluid Structure Interaction (FSI)?

- Fluid structure interaction (FSI) problems involve solving for the fluid flow force load on a solid surface and the response of the solid to the load. Subsequently updating the fluid flow due to deformations in the structure.

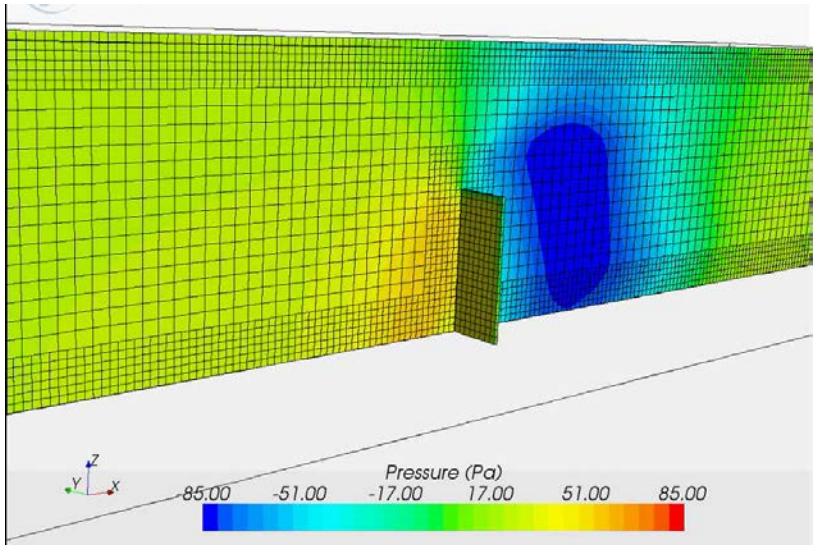
- In recent years a number of CFD and CSM software vendors have been developing the capabilities needed to solve FSI problems, but these are not sufficiently robust.

- Although advancements are noticeable, there is no single software yet that can handle such problems (monolithic approach) routinely.

Pure CFD



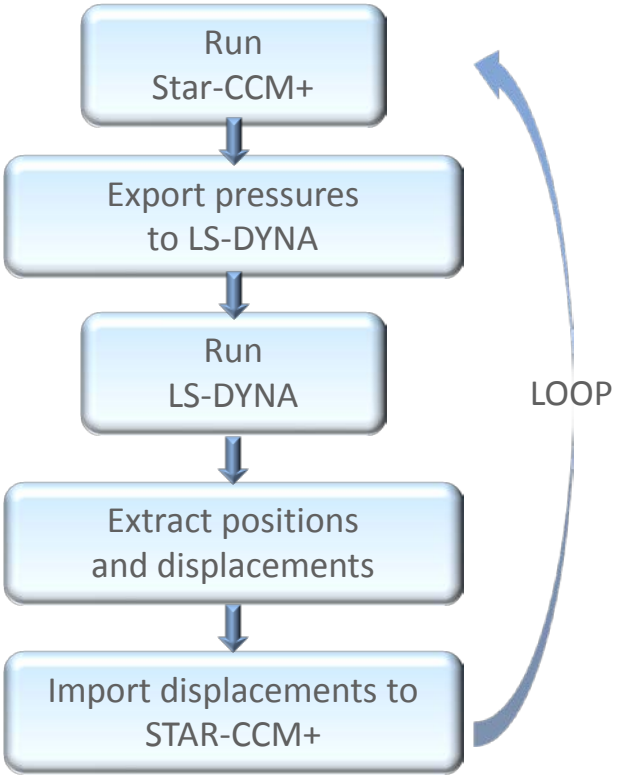
Fluid Structure Interaction



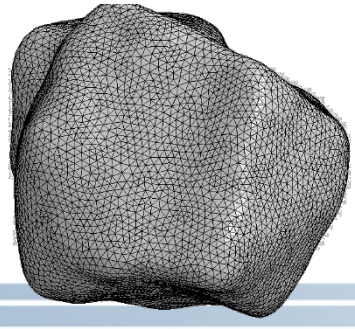
Coupling between CFD and CSM software for rock motion – a concept

- TRACC has licenses for STAR-CCM+ (CFD) and LS-DYNA (CSM) software.

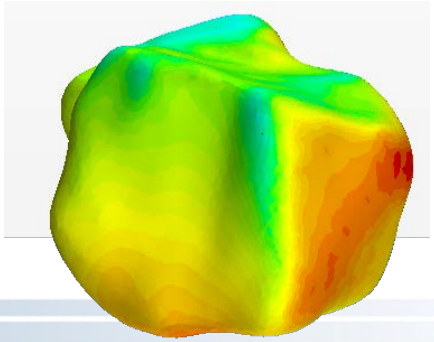
- The two separate codes can handle two different aspects of the rock motion:
  - STAR-CCM+ (CFD) computes the pressure distribution on the surface
  - LS-DYNA (CSM) computes the contact forces and displacements of the rocks from contact + fluid forces



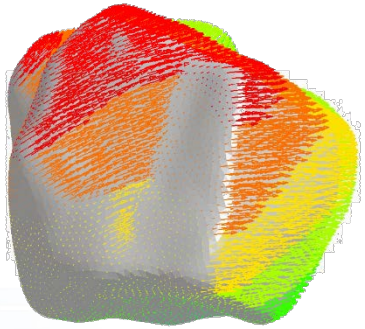
Surface mesh



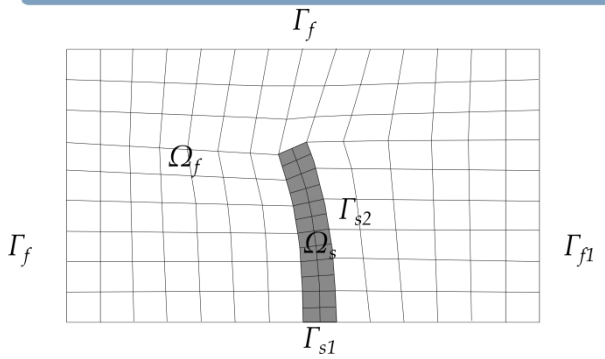
Pressures



Displacements

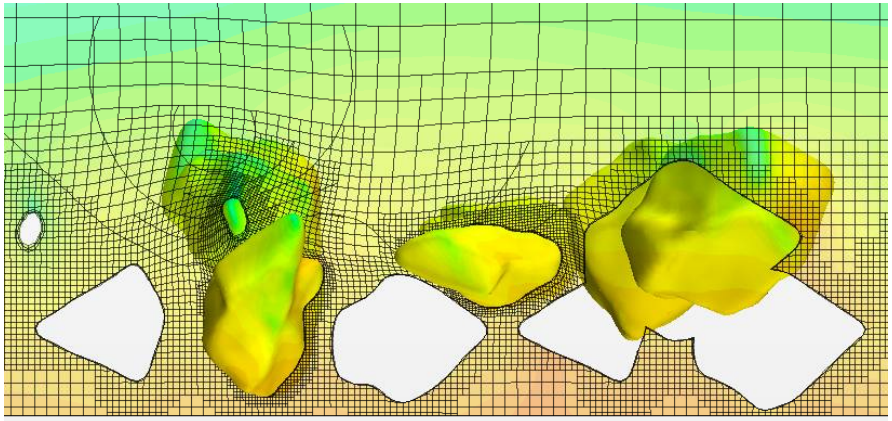


One more issue: mesh motion

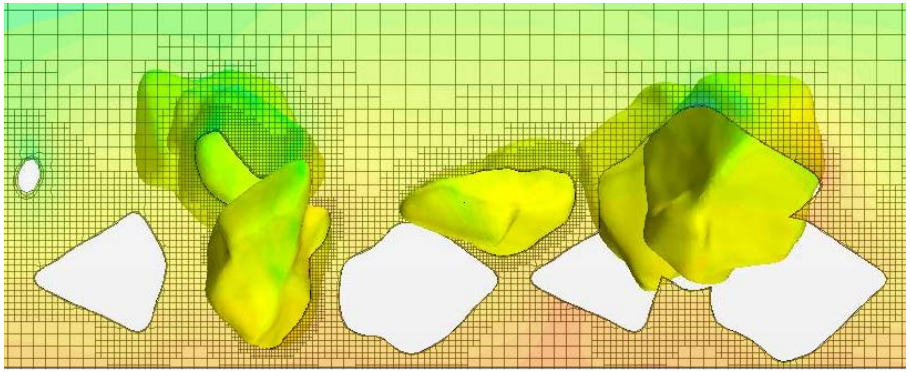


- Three motions in the FSI problem are considered:
  - Fluid motion
  - Structure motion
  - Fluid grid motion
- The mesh morpher yields a high quality mesh in the whole computational domain based on the initial mesh and the displacement of the boundaries.
- Once the contact between the rocks occurs or the motion (mesh distortion) is too large, a full domain remesh is required.

Mesh morphing during motion

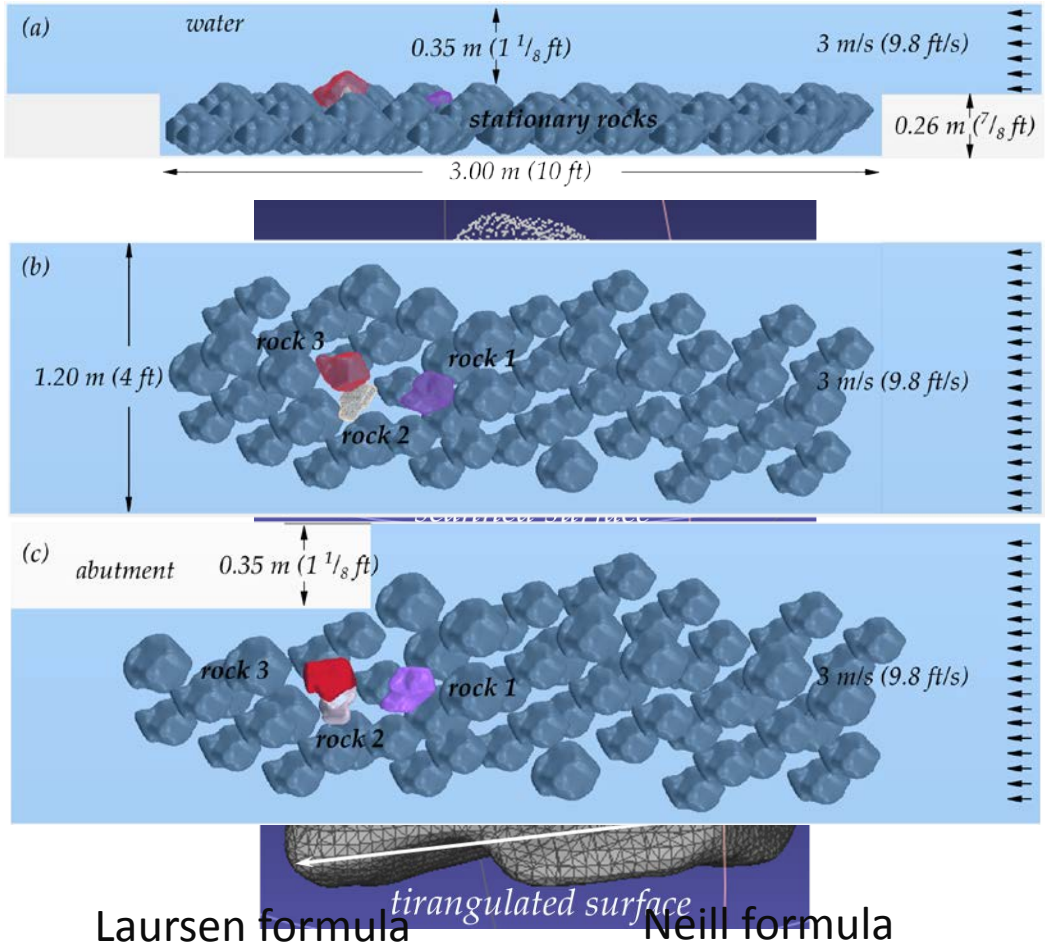


Remeshed domain



Geometry of the CFD models

- A single rock was laser scanned to obtain a cloud of points on the surface.
- After triangulation, the surface was modified to create several additional representative rock shapes.
- Multiple geometrical layouts with different complexity levels have been studied to test the procedure.
- Two of them have been used as a demonstration of the method.



Laursen formula

$$V_{CL} = K_U y_2^{1/6} D_{50}^{1/3}$$

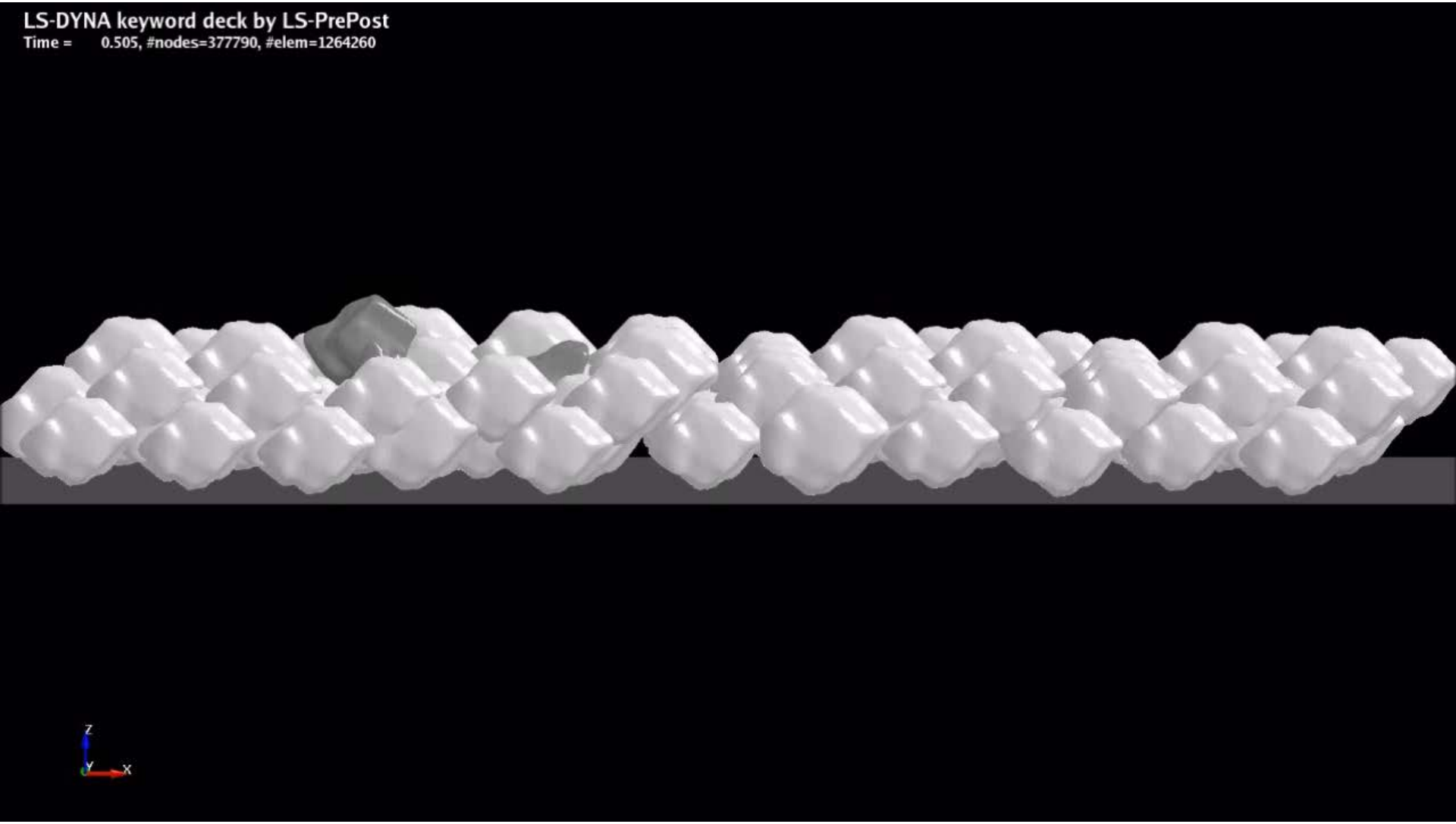
$$V_{CL} = 3.23\, m/s$$

Neill formula

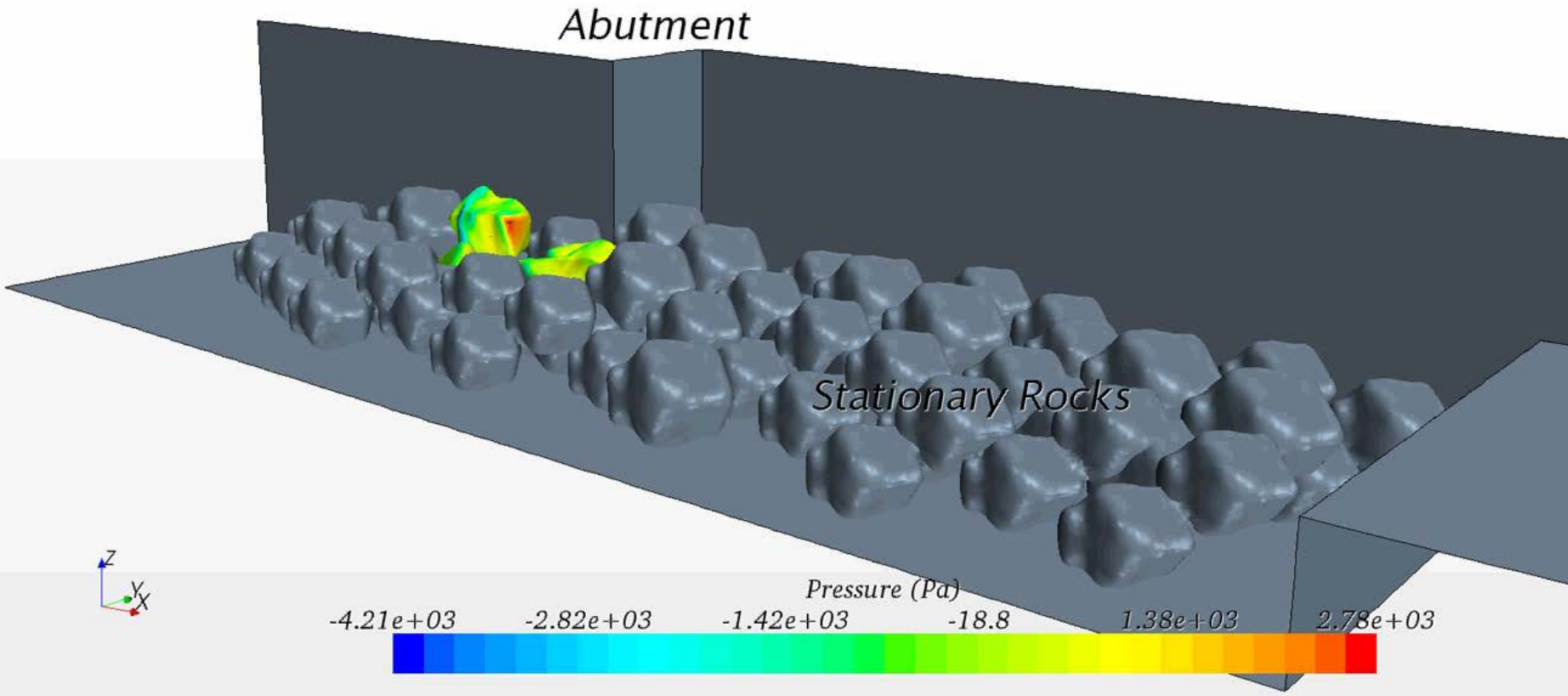
$$V_{CN} = 11.5\, K_U y_2^{1/6} D_{50}^{1/3}$$

$$V_{CN} = 3.31\, m/s$$

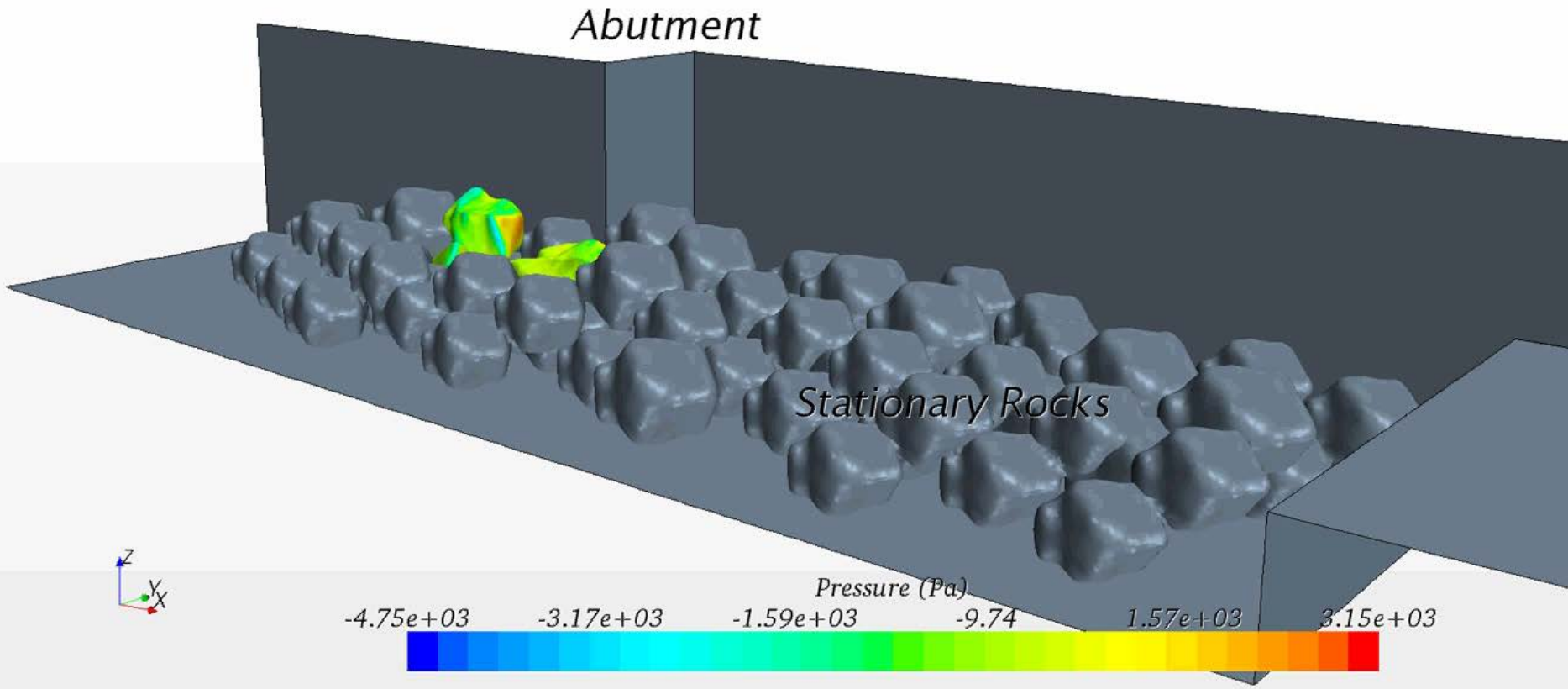
Layout 1 - Case with 3.0 m/s flow



Layout 2 - with abutment - Case with 2.5 m/s flow

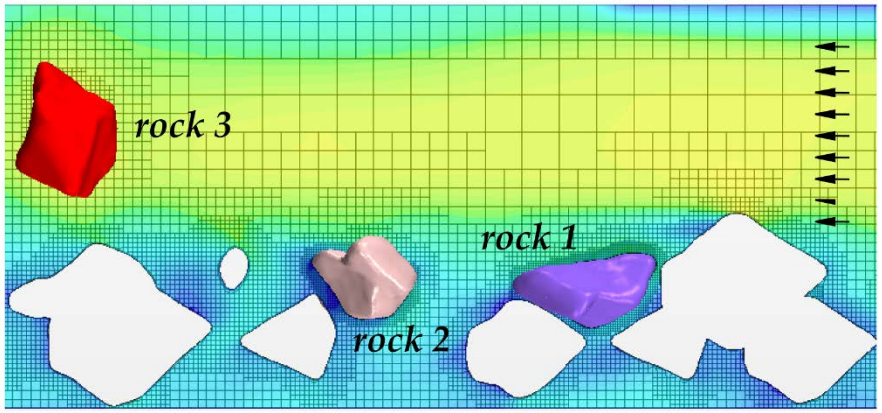


Layout 2 - with abutment - Case with 3.0 m/s flow

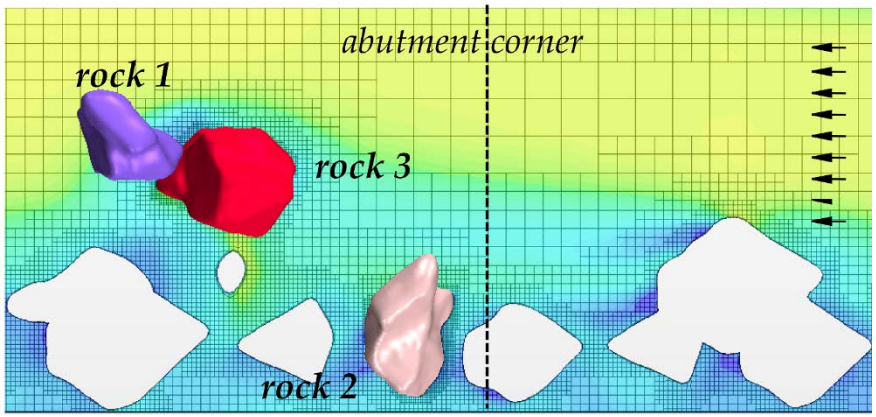


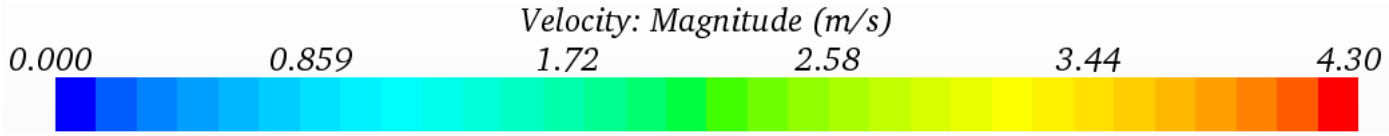
Behavior of rocks in the case study

Layout 1 – 3.0 m/s



Layout 2 – 3.0 m/s



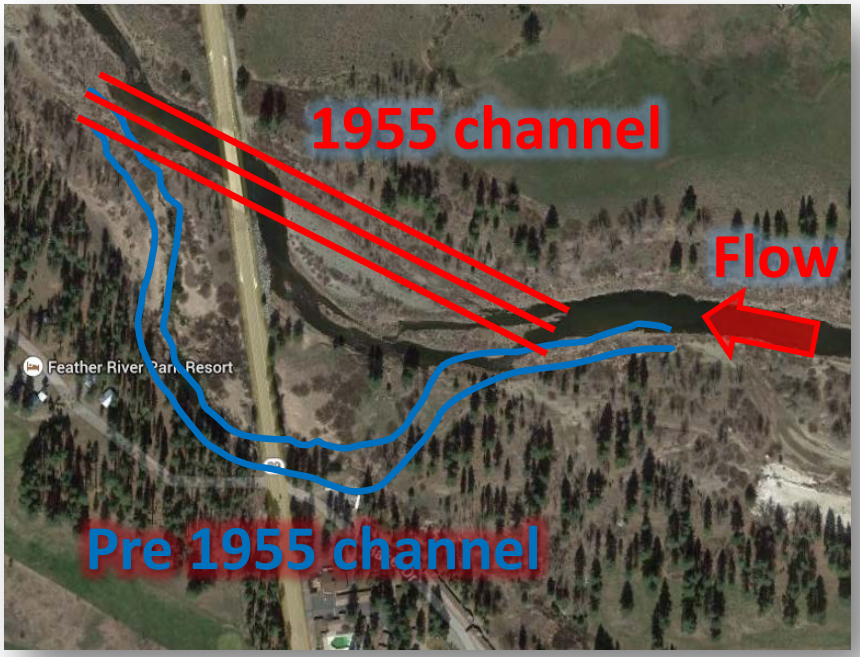


inlet velocity	layout 1	layout 2
2.0 m/s	no motion	no motion
2.5 m/s	local motion of rock 3	local motion of rock 3
3.0 m/s	motion of rock 3 and local motion of rock 2	motion of rock 1 and 3

Application to real river bed case

- The Middle Fork Feather River Bridge located on State Route 89 in Plumas County, Ca.
- When the bridge was built in 1955, the Middle Fork Feather River was realigned.
- During the winter of 1988, high flows in the realigned portion of the channel overtopped its banks and returned to its original flow path.
- This has caused the Pier 3 pile cap to be undermined and the steel H-piles to be exposed.
- In 2012 riprap consisting of 1 T rocks was installed but was designed based on lower discharge than current estimates.

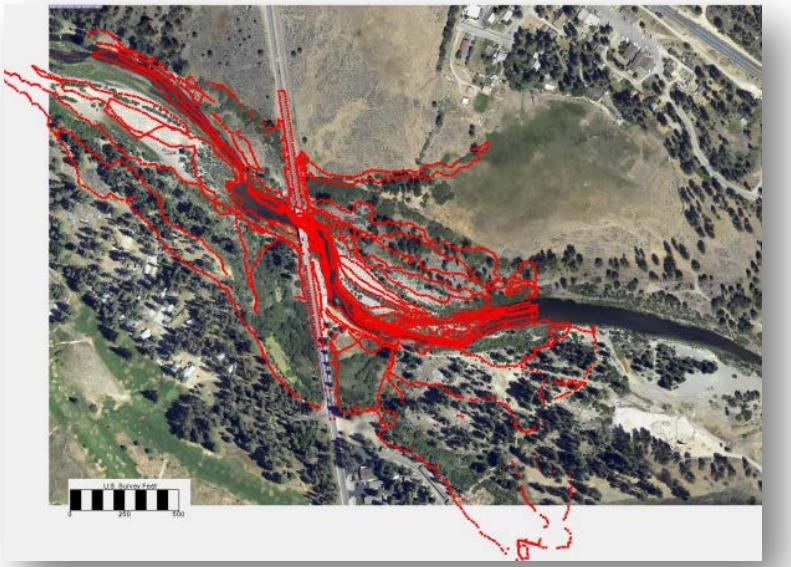
Feather river, CA



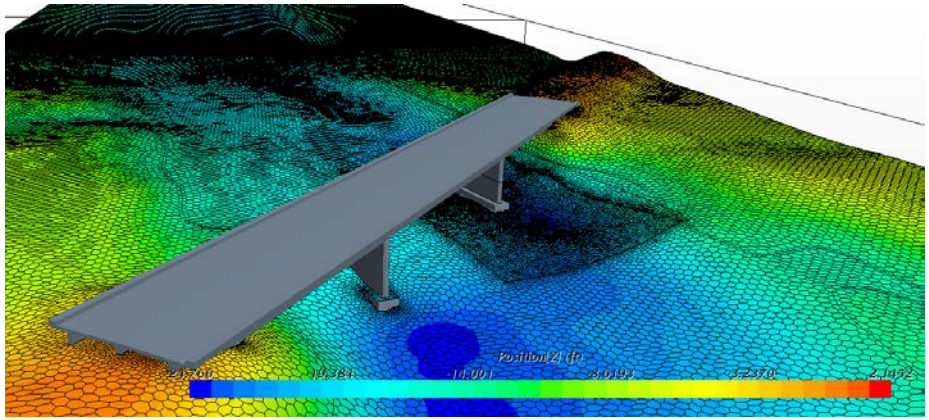
Surveys

- In 2011 a field survey was conducted (GPS and boat survey).
- A follow-up survey was performed after the installation of the riprap.
- SonarMite by Seafloor Systems depthfiner was used in both cases.
- The bathymetry was used to build CAD and CFD models.
- Matlab and MeshLab were used to create meshes from point clouds.

2011 survey GPS and survey points



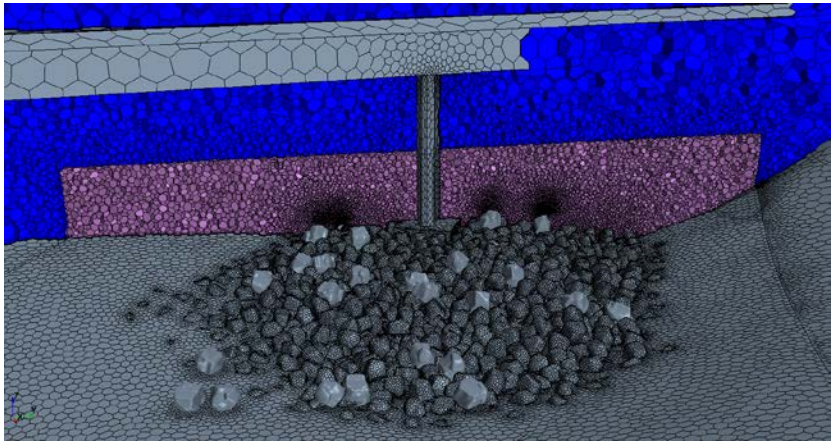
Bathymetry imported to CFD software

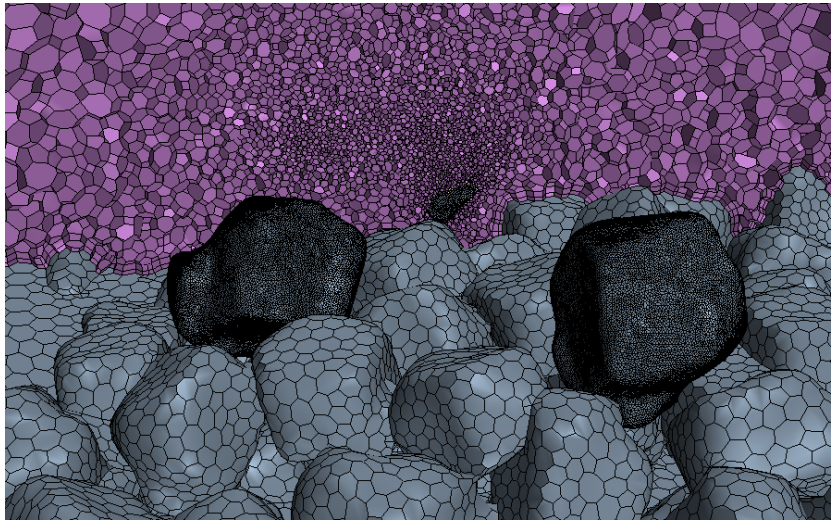


3D CFD models

- STAR-CCM+ software allows for fine gradation of the computational mesh in 3D.
- The mesh is generated automatically with locally defined refinements (3.8 M cells).
- Large areas can be covered within 3D models with a coarser mesh away from area of interest.
- Smaller areas of interest are used for coupling procedures (purple).
- CFD time step: 0.1 sec (for 700 sec).
- Time step for subsequent coupling 0.025 sec

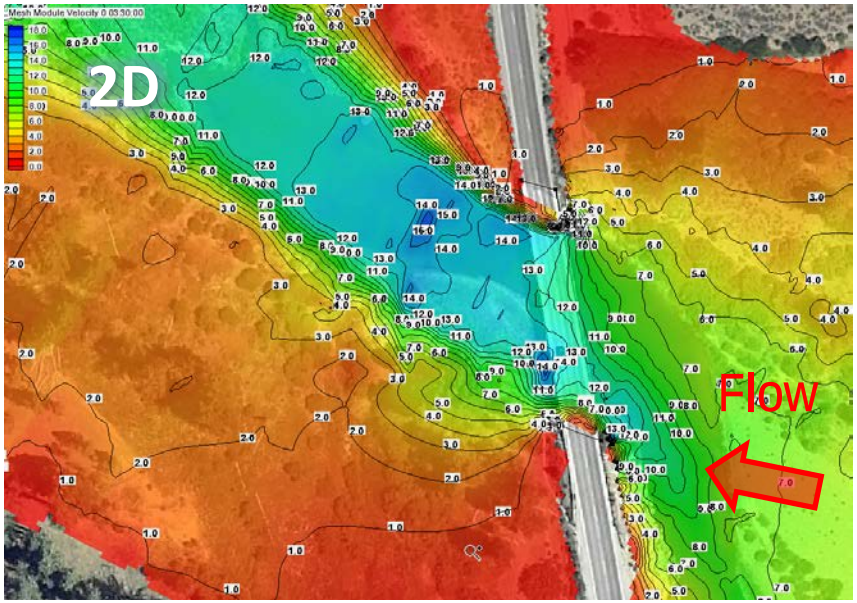
Separate regions with varying mesh

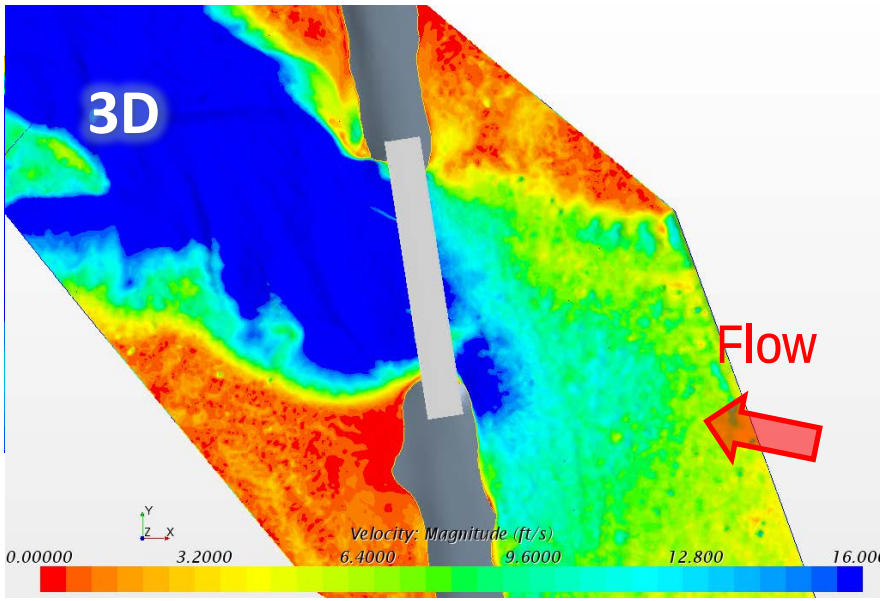




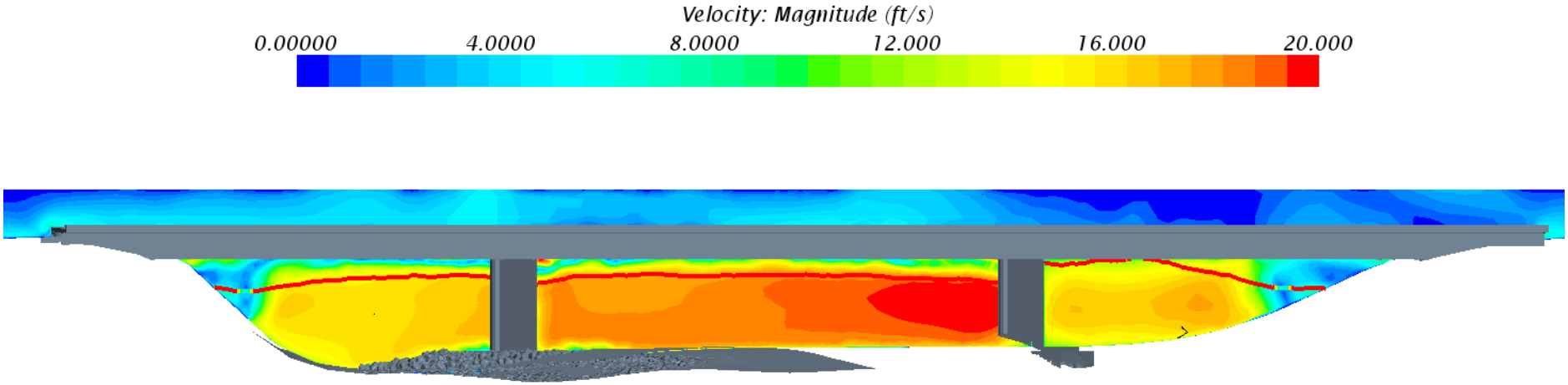
Analysis results

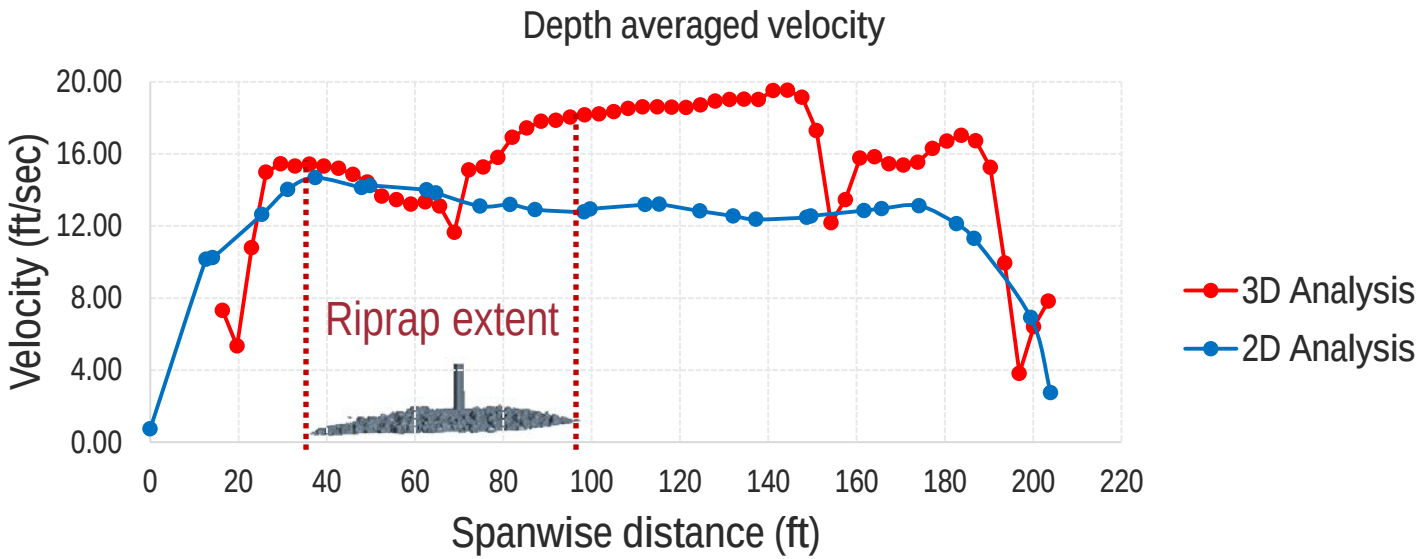
- 2D analysis performed in TUFLOW.
- 100-year discharge of 30,100 cfs used.
- 2D analysis predicted overtopping of the bridge (3D did not).
- Design velocity required adjustment for that.
- HEC23 was used to assess stability of riprap.
- 1 T rocks were determined sufficient for Q50.
- However, the 1 Ton rock is undersized both adjacent to and away from the pier for the Q100.



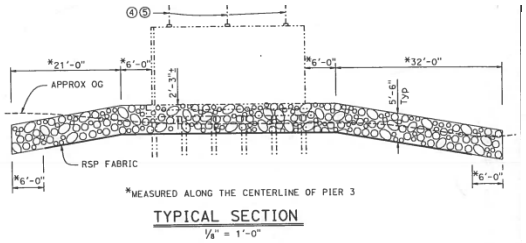


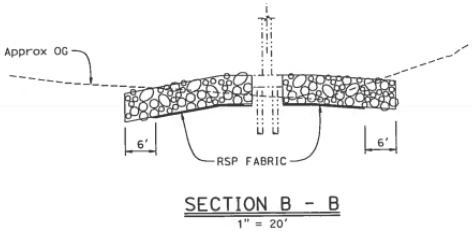
Velocity under the bridge



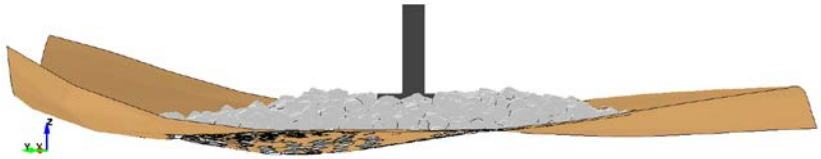


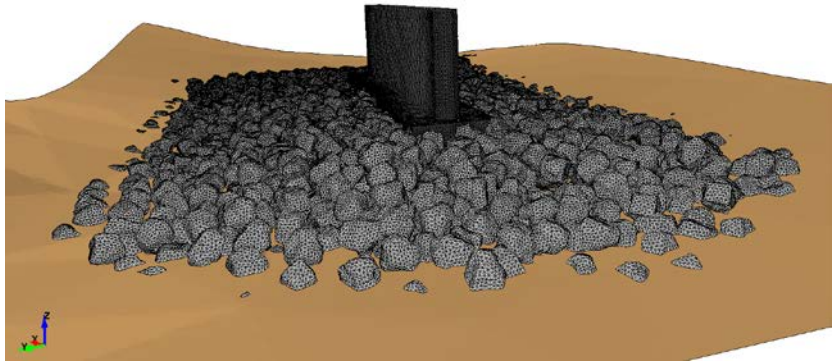
Initial riprap layout





- For the initial models the design drawings were used.
- Over 2,500 rocks were included in the CFD model.
- At first they all are considered as non-movable.
- Subsequently movable rocks are placed in the areas where high forces are expected.
- The first coupled simulations used 0.4 ton rocks that will move to verify the onset of motion computation

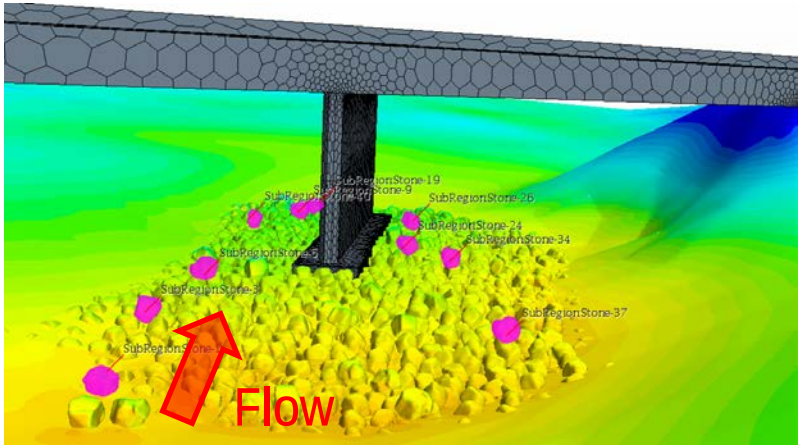


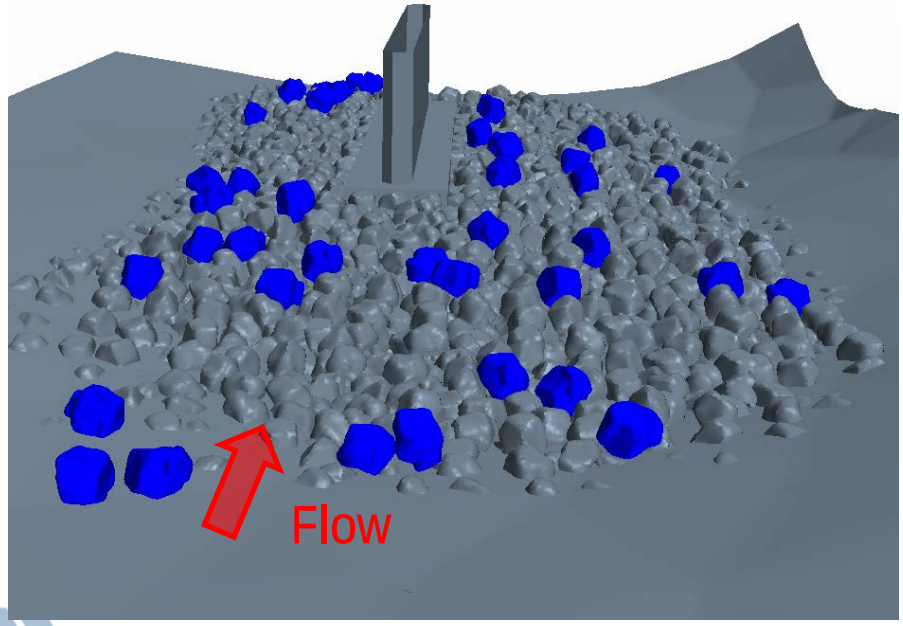


Movable rocks in Star-CCM+ model

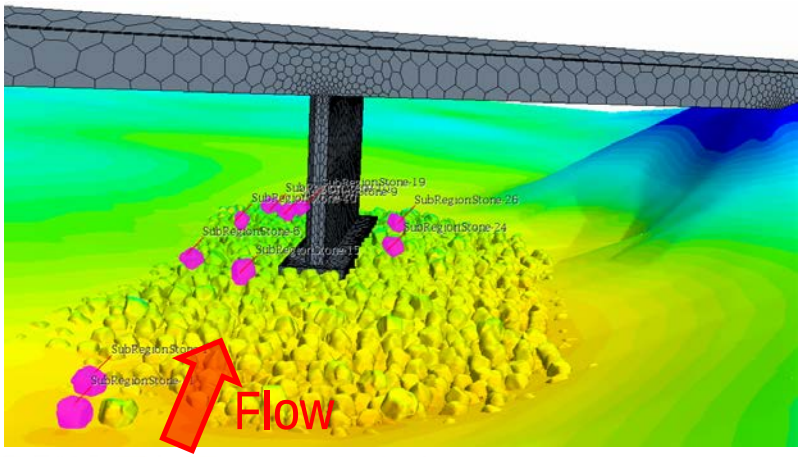
- Movable rocks were distributed randomly.
- Currently up to about 100 movable rocks can be modeled.
- A lot of information can come from pure CFD analysis.

Rocks with largest Z force

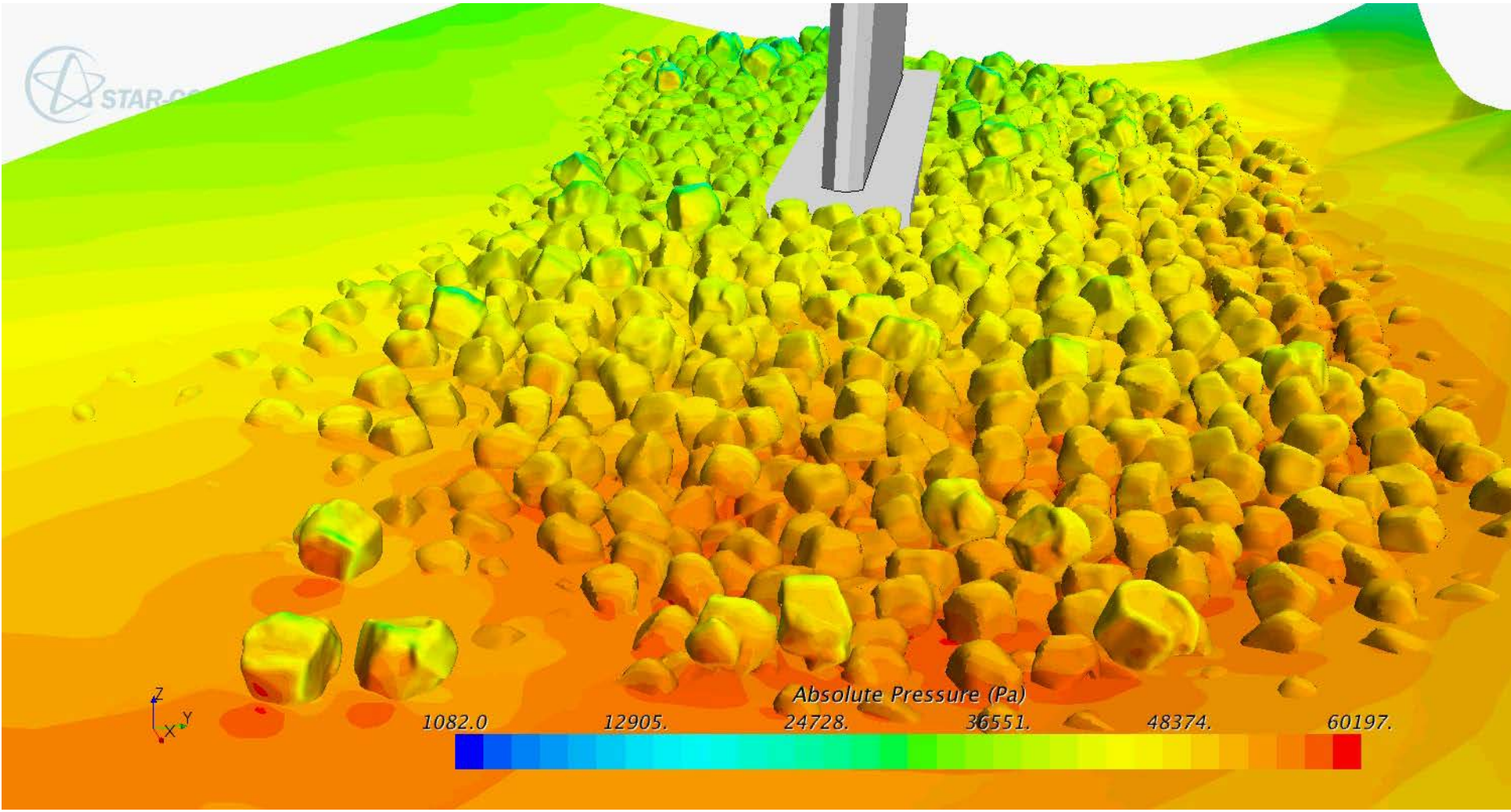




Rocks with largest X force



Animation from coupled CFD+CSM simulation



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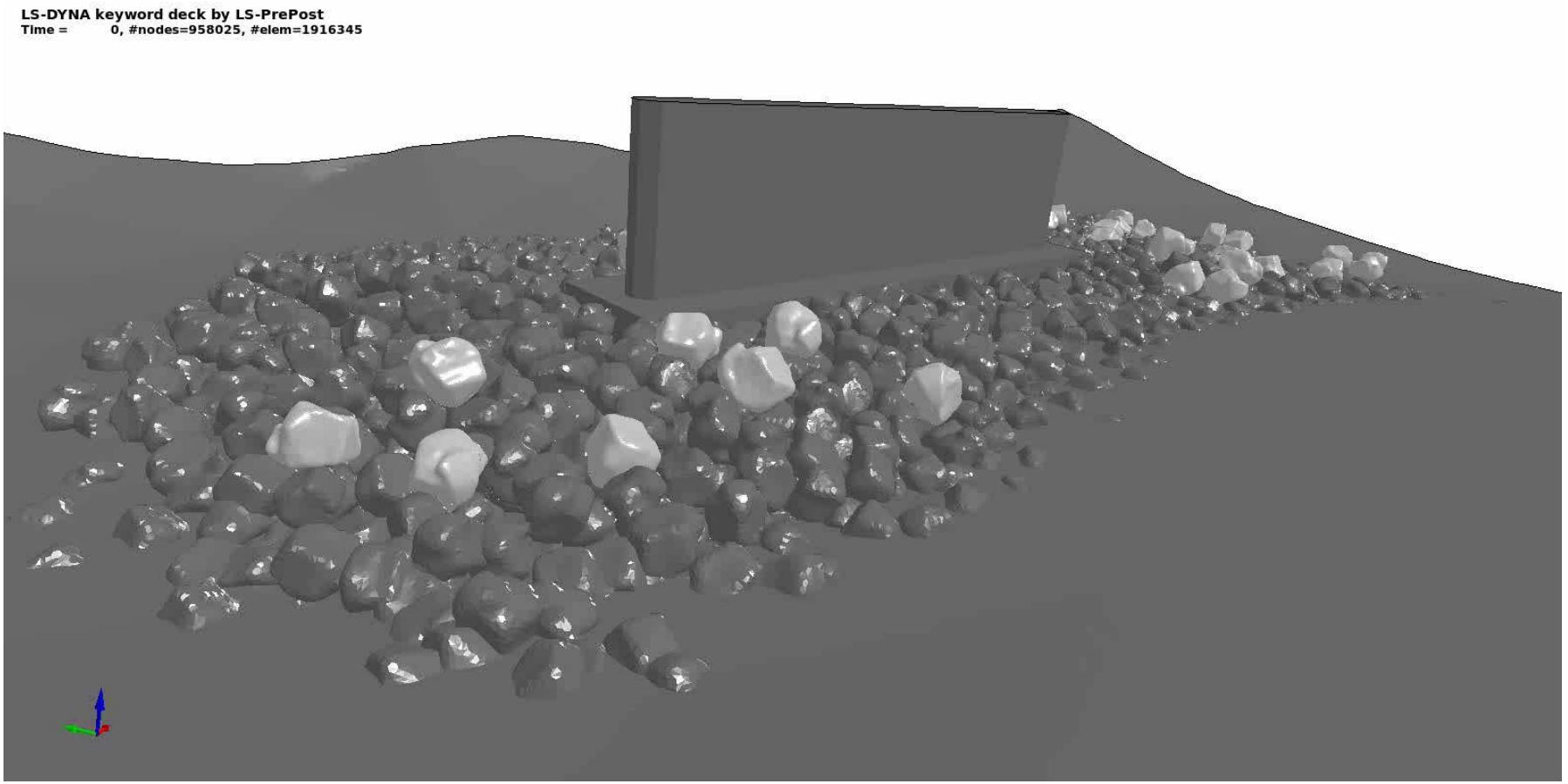
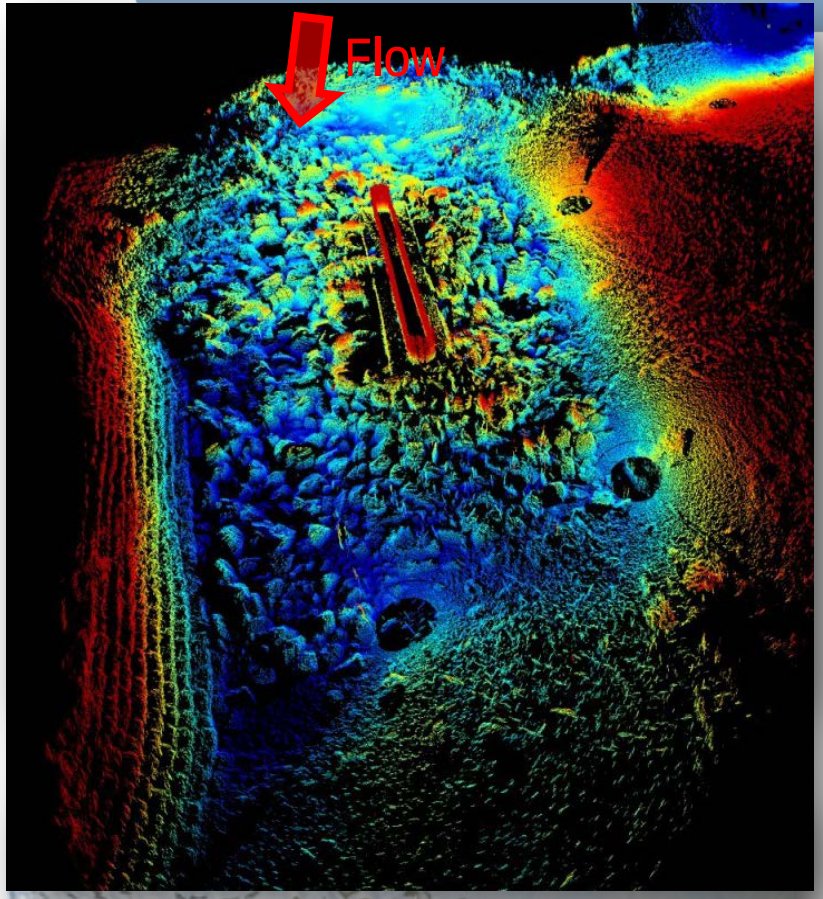
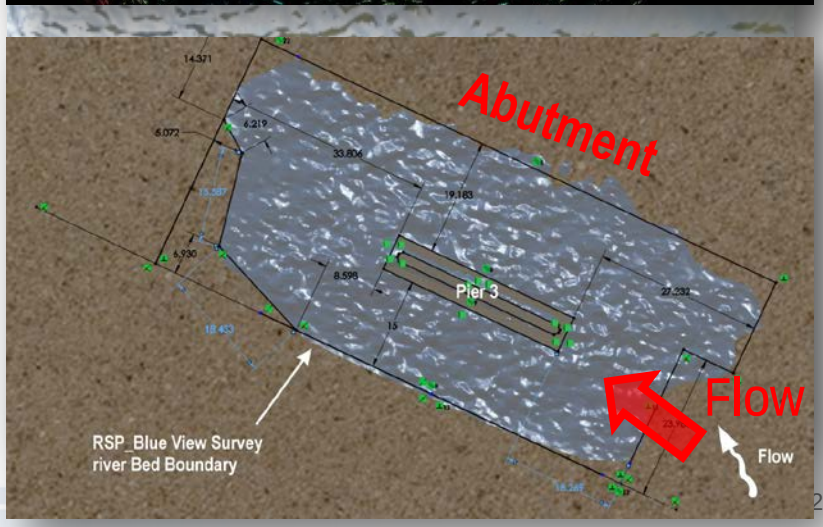


Riprap geometry update

- Three different technologies were performing scanning of the bed.
- High resolution data have been collected.
- The data together with the pictures have been used to update the extent of the riprap in the numerical models.

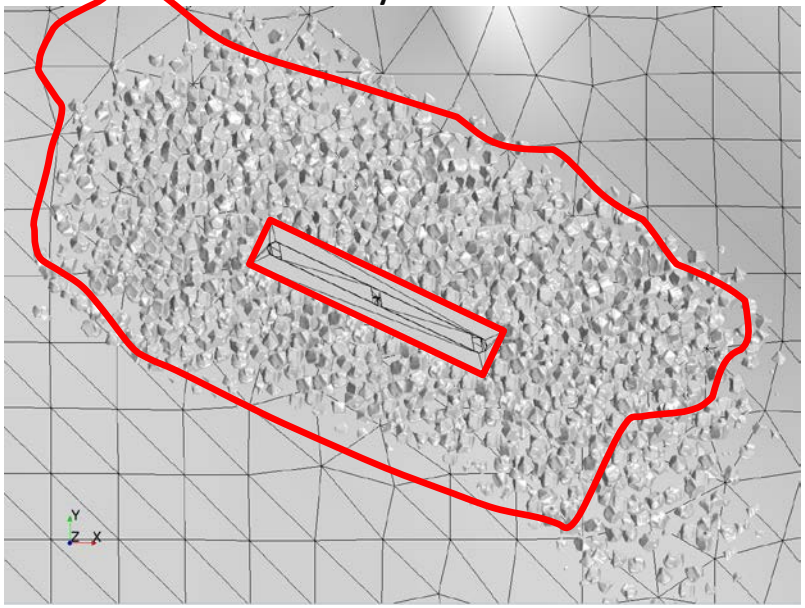




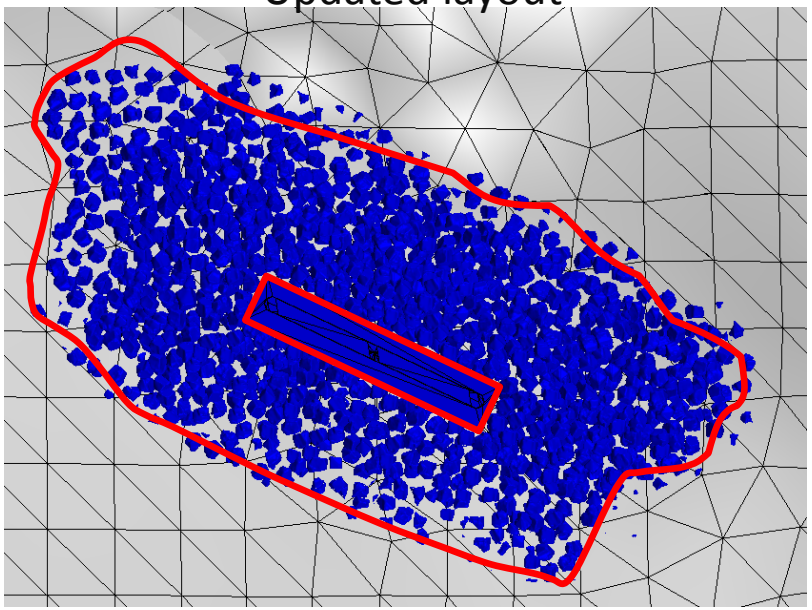
Current status

- Currently a CFD model with “as is” riprap extent is under development.
- 40 movable rocks with mass from 0.4 to 1 T are placed randomly.
- Although up to 100 rocks can be modeled in the coupled simulations, body interaction models are being developed for STAR-CCM+ by CD-adapco that will allow for simulating the entire event in just one software package.

Old layout



Updated layout



Acknowledgements

- Kornel Kerenyi, Turner-Fairbank Highway Research Center (TFHRC) for funding this research,
- Jerry Shen, TFHRC for very helpful comments and coordinating the work,
- Oscar Suaznabar, and other team members from TFHRC for providing the geometry of rocks and the CAD model of river bathymetry,
- Kevin Flora, California DOT for providing bathymetry, 2D Analysis results and other data on the Feather River location and a ton of good comments…
- All other people who were involved in the work.

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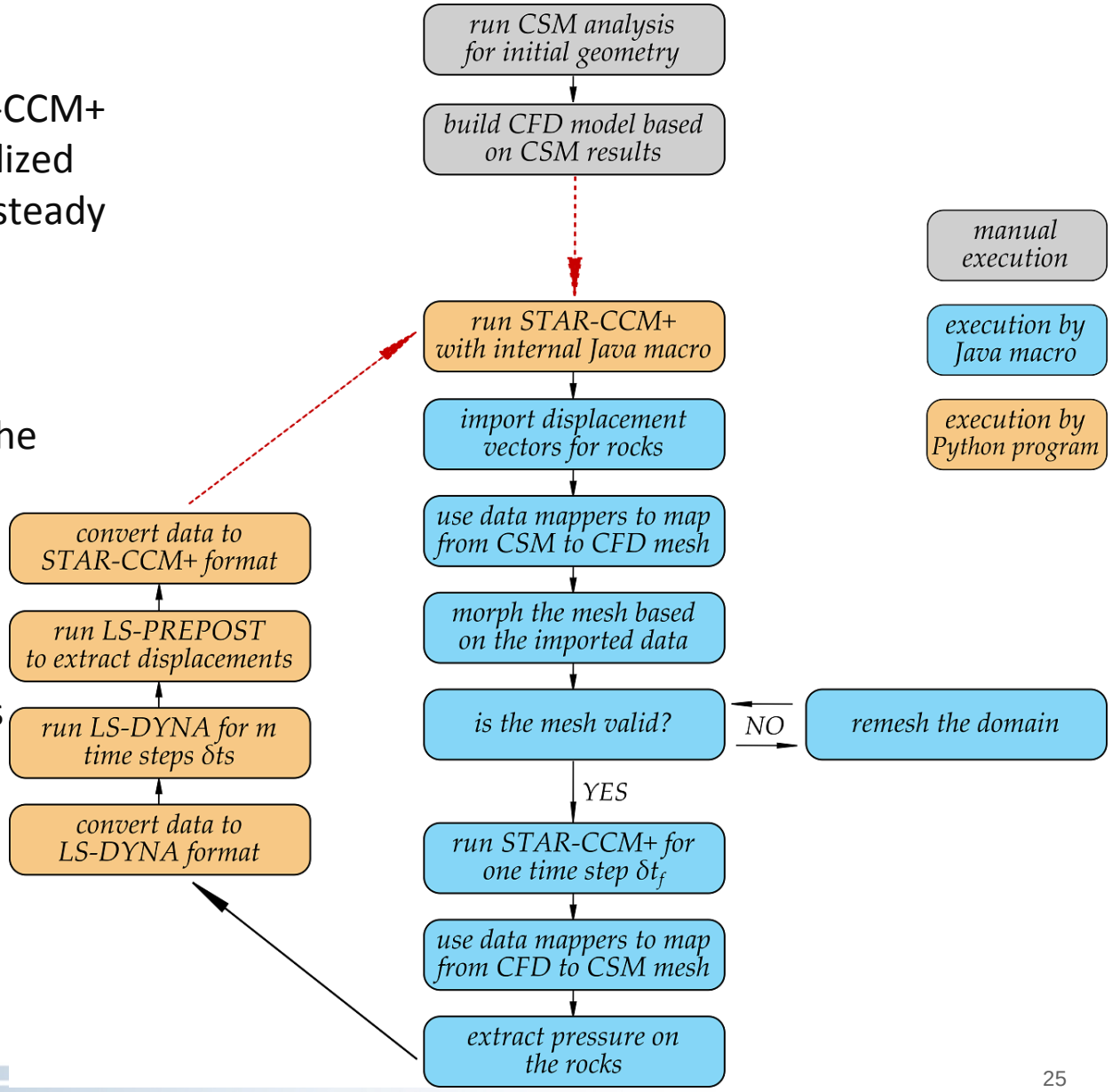
Thank you!

Extra slides

Current implementation of coupled workflow

- Both LS-DYNA and STAR-CCM+ models need to be initialized separately until pseudo steady conditions are achieved.
- A Python program subsequently executes the loop for loose coupling.
- A Java macro controls operation of the internal components of the STAR-CCM+ software.



Case with a pier and 8 movable rocks