# A Generalized Pressure Load Model on Anti-Slosh Baffles at Different Fill Depths and Slosh Wave Heights

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**Presented at AIAA SciTech 2026**
**Orlando, FL**
**January 12-16, 2026**

# Background

## *Sloshing and Anti-Slosh Baffles in Spacecraft*

- Propellant slosh affects spacecraft stability and tank structural integrity.
- Anti-slosh baffles mitigate undesirable sloshing by increasing damping.
- Baffle spacing and configuration are driven by required damping levels.
- Structural design requires accurate knowledge of slosh-induced pressure loads.
- The resulting slosh-induced forces and moments are critical inputs for GNC modeling and control design

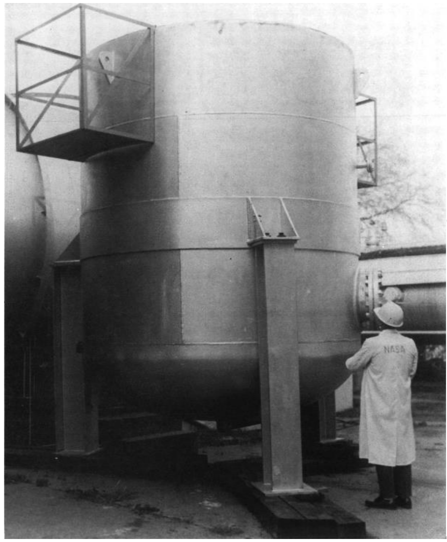
## *Previous Studies*

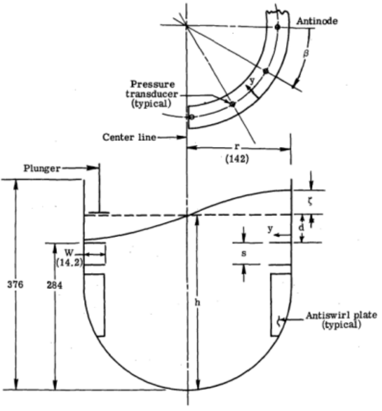
- Liu developed an analytical technique for ring-baffle pressures under irrotational sloshing.
- Davis derived a semi-theoretical expression including fluid acceleration and velocity effects.
- NASA SP-8009 provides a maximum submerged-baffle pressure correlation based on Keulegan–Carpenter.
- NASA TN D-6870 by Scholl et al. experimentally measured pressure distributions and slosh damping.

# Background

## *Experiment Findings*

- NASA TN D-6870 contains the most complete set of baffle pressure test data. It covers a range of depths and values of the velocity (period) parameters.
- At velocity parameters larger than 3.0, all theories seem to predict the pressure well.
- For lower velocity parameters between 0.5 and 3.0, all existing theories underpredict the pressure load (see the right figure as an example)

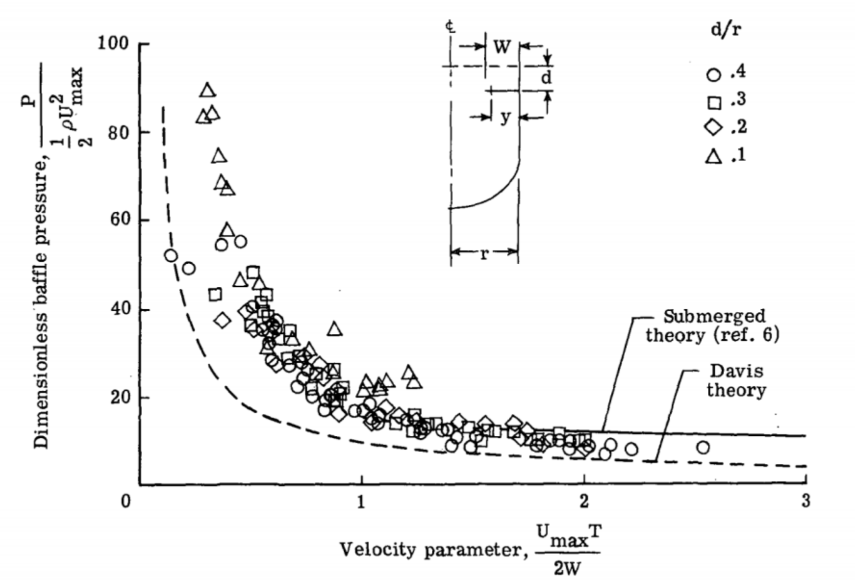




| Test condition | d/r | s/W | y/W | β, deg |
|---|---|---|---|---|
| Single baffle | -0.1 to +0.4 | | 0.25, 0.5, and 0.75 | 0 to 90 |
| Two baffles | 0 to 0.4 | 0.5 to 2.0 | 0.5 | 0 |

## *Objective of This Study*

- The objective is to develop a physically-based pressure load model that accurately matches experimental data across baffle submergence levels.
- Accomplished by deriving a theory of conservative pressure load on a baffle at different wave heights and at different fill depths

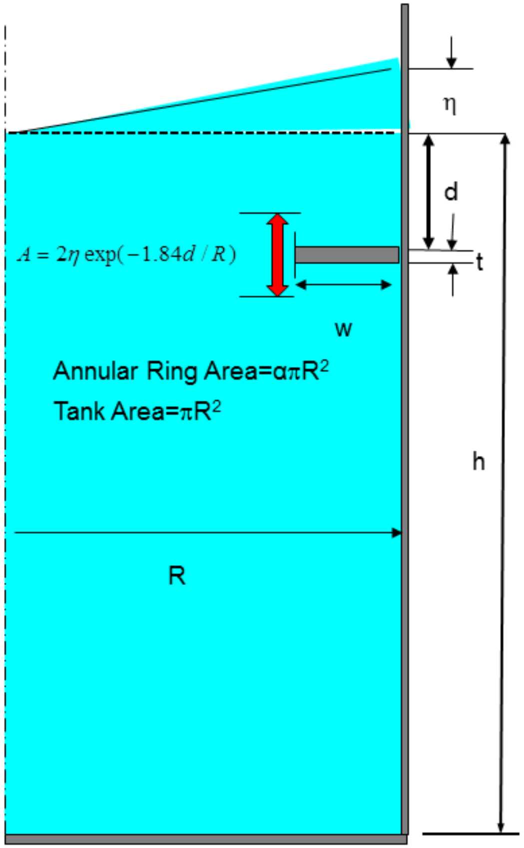


# Slosh Pressure Load Theory

### *Pressure Features During Slosh Dynamics*

- Slosh motion exchanges kinetic and potential energy, producing oscillatory transient pressure on the baffle.
- Pressure consists of static + transient oscillatory components.
- Maximum load occurs when flow phase shift reaches 90° across the baffle.
- Maximum possible pressure:

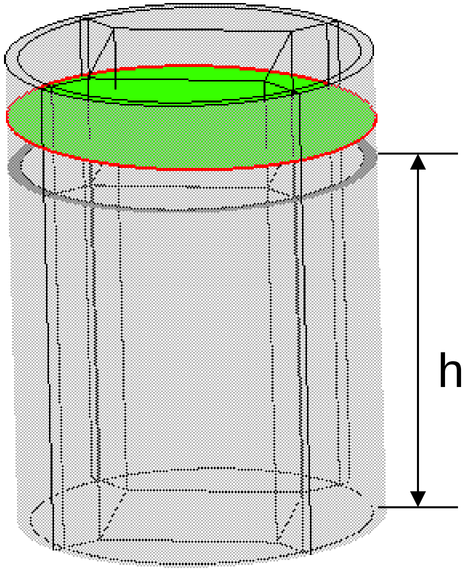
$$\boxed{\Delta p_{max} = \max\left(p_\eta[\sin(\omega t + \theta_1) - \sin(\omega t + \theta_2)]\right) = \sqrt{2}\,\rho g \eta = 1.41\,\rho g \eta}$$

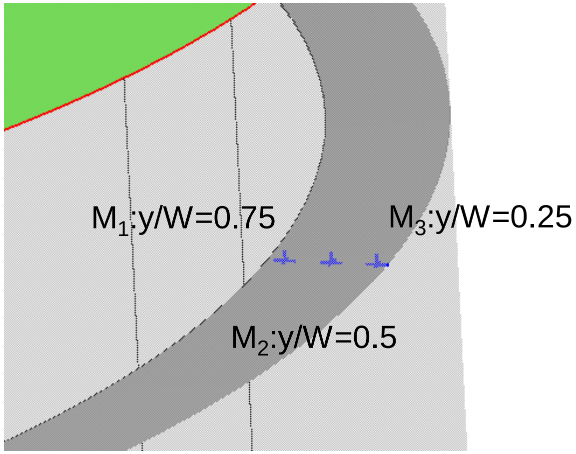


# CFD Verification of Slosh Pressure Load Theory

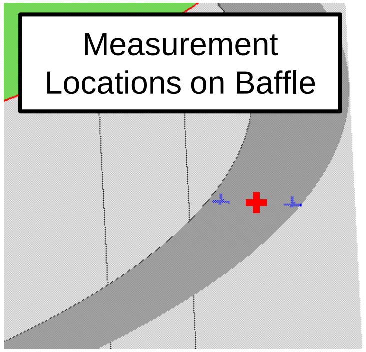
## CFD Model for the Verification of the Pressure Load Theory

- A CFD model has been built to verify the proposed pressure load theory.
  - Loci-Stream/VOF: laminar model, and water and air properties.
- The model has the following parameters:
  - A cylindrical tank; tank radius: R=165”;
  - Baffle location from tank bottom h=2R; baffle width: 12”
  - Liquid: LH2, density: 70.8 kg/m3 ;
  - Initial wave height: η =4”;
  - Total cells: 0.5 million;
  - Liquid fill levels: d/R=0.0; 0.05; 0.1; 0.25
  - Pressure monitor points from tank wall: 0.25W; 0.5W; 0.75W.



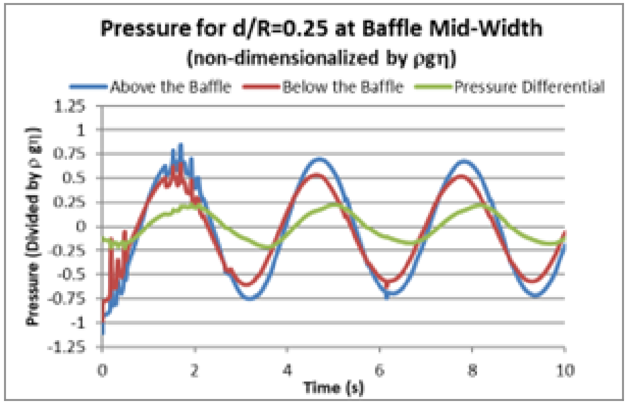


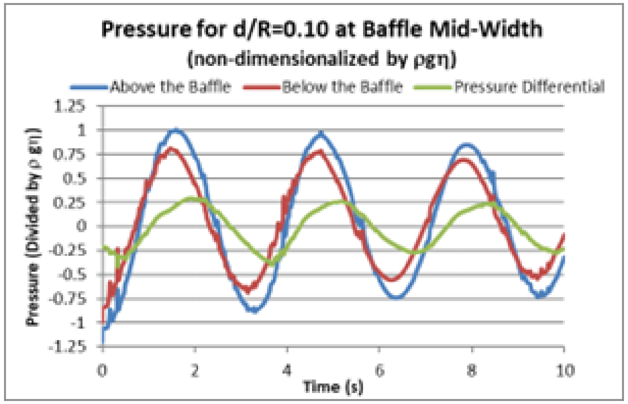
# CFD Verification of Slosh Pressure Load Theory

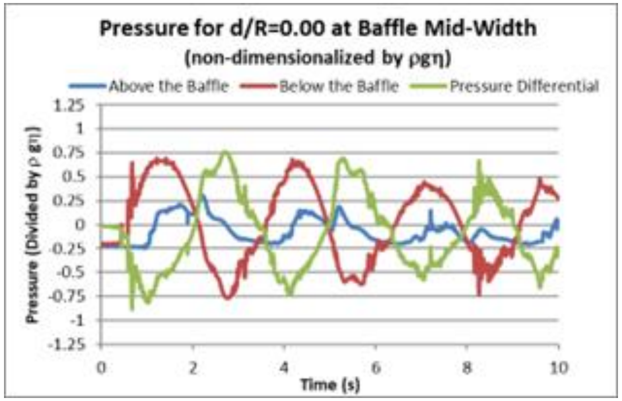

Measurement Locations on Baffle

## *Verification #1: Max local transient pressure magnitude is $\rho g \eta$*

- For the following figures, the pressure is subtracted by the static pressure at the bottom face of the baffle and normalized by the initial wave height of 4”


Pressure for d/R=0.25 at Baffle Mid-Width (non-dimensionalized by ρgη)


Pressure for d/R=0.10 at Baffle Mid-Width (non-dimensionalized by ρgη)


Pressure for d/R=0.00 at Baffle Mid-Width (non-dimensionalized by ρgη)

## *Observations*

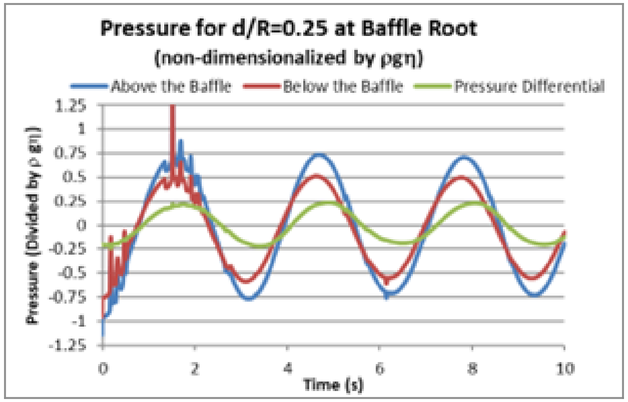
- CFD predicts transient pressures consistent with theoretical expectations.
- Pressure oscillates at the natural slosh frequency.
- Local maxima never exceed ρgη, confirming the theoretical transient pressure bound.

# CFD Verification of Slosh Pressure Load Theory

## *Verification #2: Phase Shift Across the Baffle*

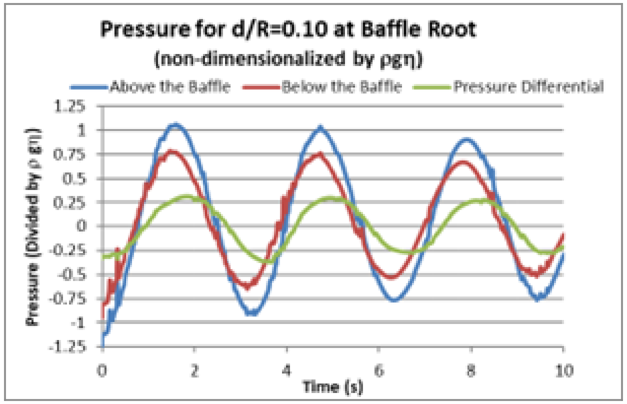
- We propose that the pressure load is:

$$p_{top} = p_\eta \sin\left(\omega t + \theta_{top}\right); \qquad p_{bottom} = p_\eta \sin(\omega t + \theta_{bottom})$$



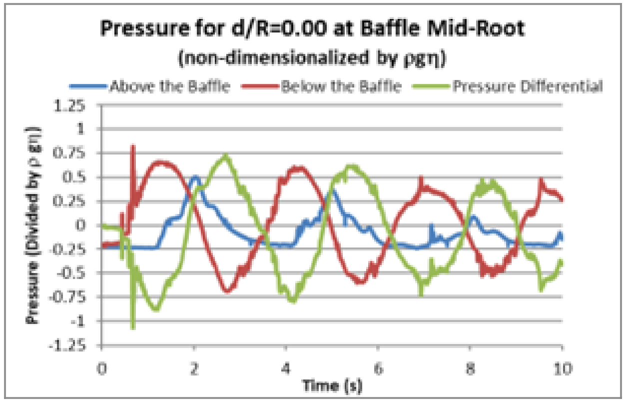
Pressure for d/R=0.25 at Baffle Root

(non-dimensionalized by ρgη)



Pressure for d/R=0.10 at Baffle Root

(non-dimensionalized by ρgη)



Pressure for d/R=0.00 at Baffle Mid-Root

(non-dimensionalized by ρgη)

## *Observations*

- Pressure above and below the baffle is not in phase.
- Phase shift increases as fill depth decreases.
- The phase shift arises from viscous damping and flow separation effect across the baffle.
- Maximum phase shift approaches 90°, consistent with theory.
- Larger phase shift → higher effective damping.

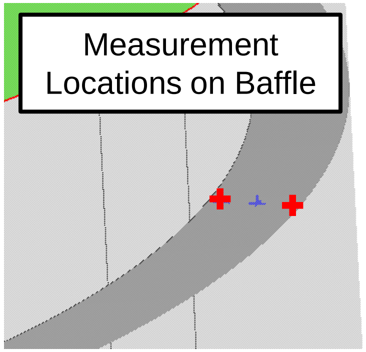
# CFD Verification of Slosh Pressure Load Theory

## *Verification #3: Max pressure load is* $1.41\,\rho g \eta$

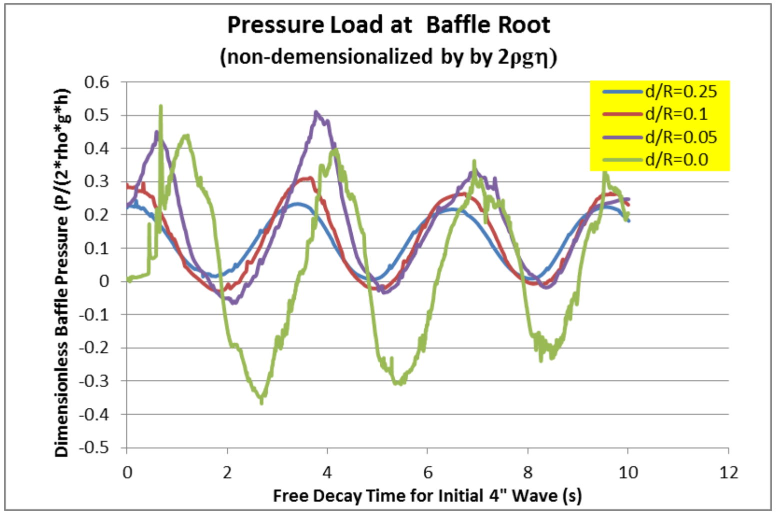
- We assume that the pressure phase differs across the baffle.

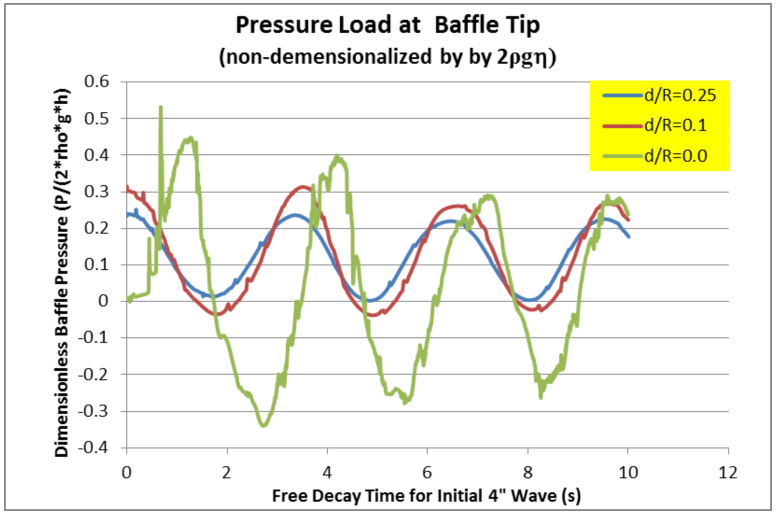
$$\Delta p = p_\eta\left[\sin\left(\omega t + \theta_{top}\right) - \sin\left(\omega t + \theta_{bottom}\right)\right]$$

- The maximum value is $1.41\rho g\eta$ when $(\theta_{top} - \theta_{bottom}) = 90^o$



Measurement Locations on Baffle



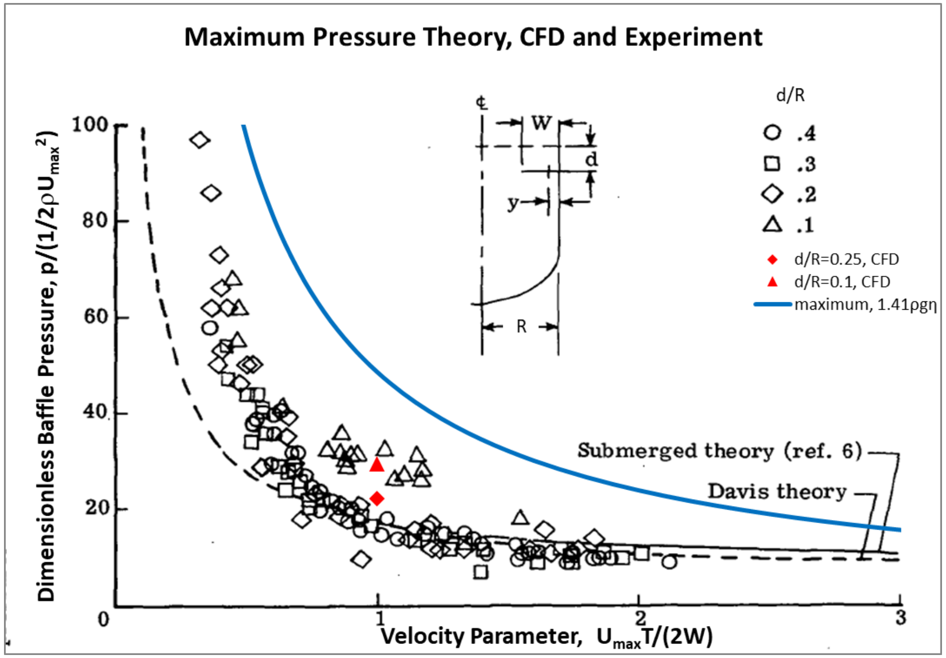


## *Observations*

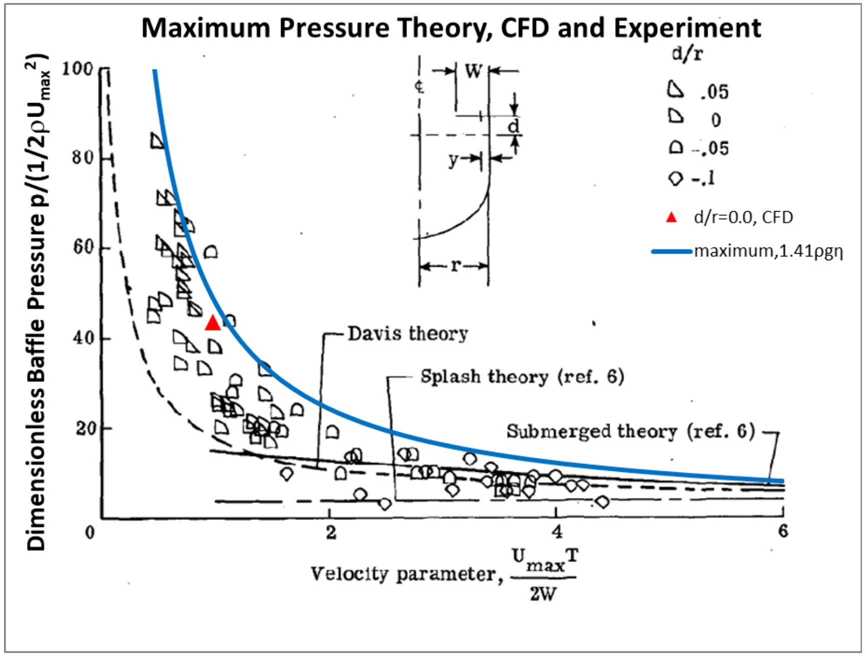
- Just as expected, none of the computed pressure load is higher than $1.41\rho g\eta$ (0.707 in the dimensional form) at different fill levels.

# Validation of Slosh Pressure Load Theory and CFD near baffle root of y/W=0.25

**For Submerged Baffles: d/R >=0.1**



**For the Near-Surface Baffles: d/R < 0.1**

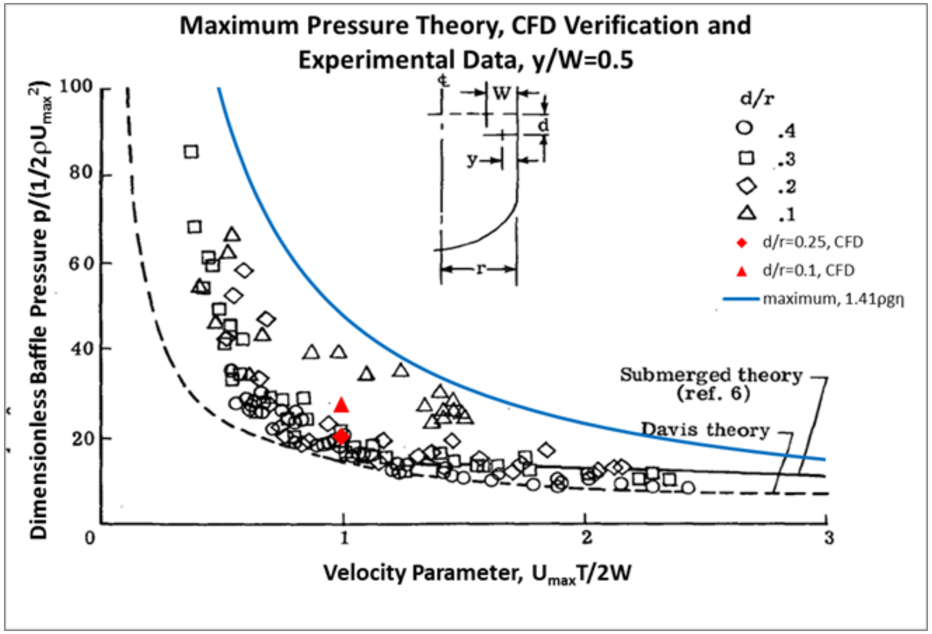


## *Observations*

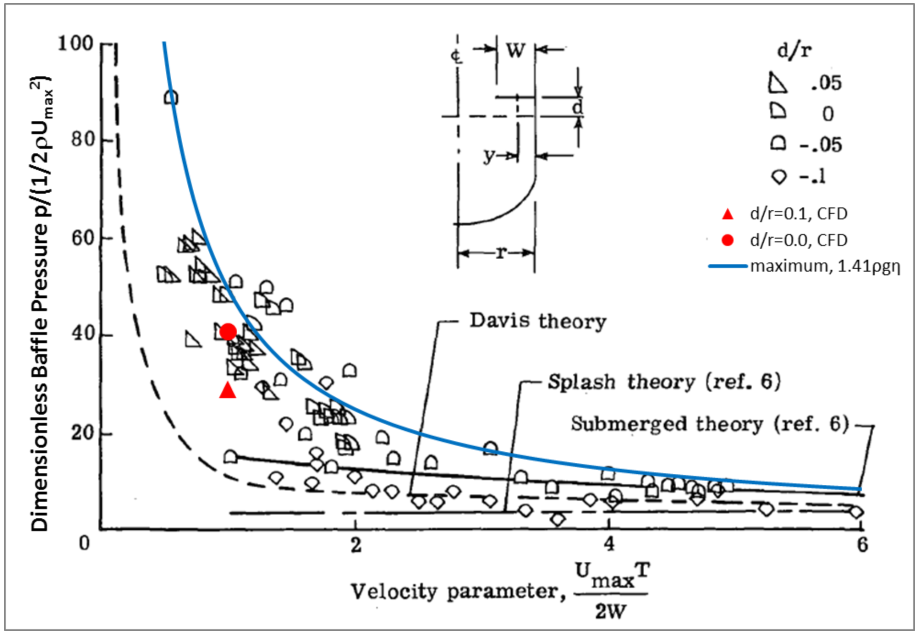
- CFD pressure traces show excellent agreement with experiment and the predicted transient bounds.
- The maximum differential pressure remains below the theoretical $\sqrt{2}\,\rho g\eta$ limit.
- Confirms validity of proposed model for submerged and near-surface cases.

# Validation of Slosh Pressure Load Theory and CFD near baffle root of y/W=0.50

**For Submerged Baffles: d/R >= 0.1**



**For the Near-Surface Baffles: d/R < 0.1**



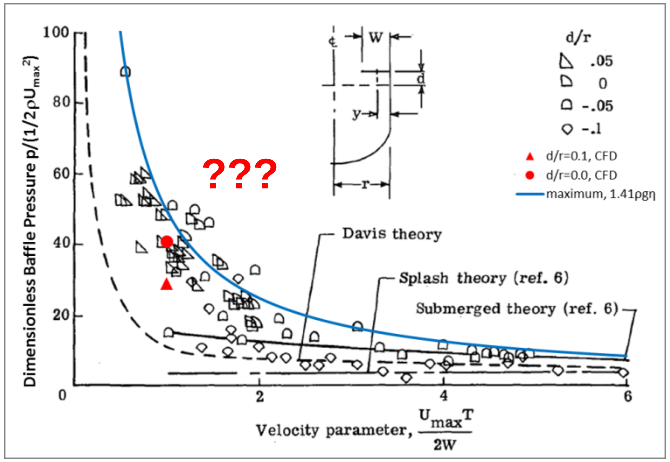
## *Observations*

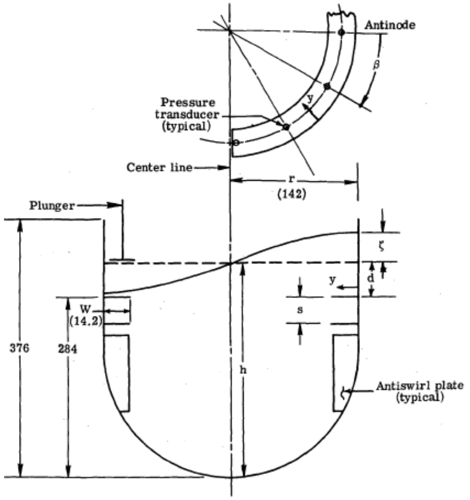
- Maximum differential pressure remains below theoretical √2 ρgη limit for all the submerged baffles.
- For the exposed fill levels, there some points that are higher than the proposed theory.
- It will be shown in the following charts that the non-conservative pressure is due to the splash of liquid on the baffle, and their impact is localized and has a time scale much smaller than slosh period.

# CFD Verification of Local High Collision Pressure at Low Fill Level

**Stephen and Scholl NASA TN D-6870, 1972**

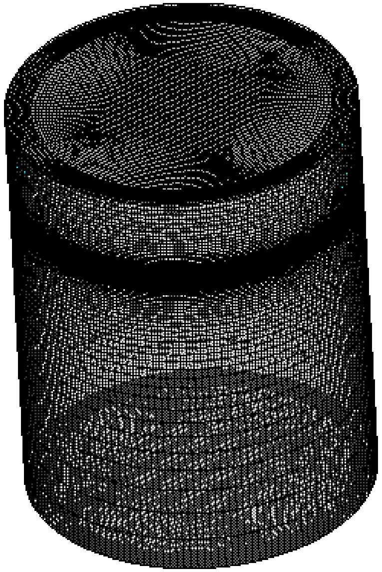
- **Well-defined geometry and material property**
- **Data for rigid baffle have been used for validation previously of nonlinear damping equation at different flow regime**
- **R=56”, W=5.6”; W/R=0.1**
- **t/W=0.022**
- **d/R=-0.1, to 0.4**



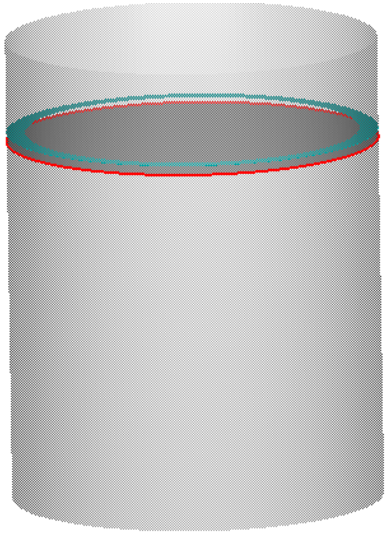


| Test condition | d/r | s/W | y/W | β, deg |
|---|---|---|---|---|
| Single baffle | -0.1 to +0.4 | | 0.25, 0.5, and 0.75 | 0 to 90 |
| Two baffles | 0 to 0.4 | 0.5 to 2.0 | 0.5 | 0 |

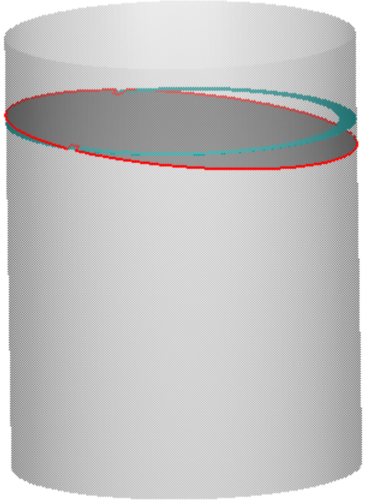
Experimental Setup



Simulation Mesh



Fill Level d/R=-0.05



Initial wave height $\eta/R=0.1$

# CFD Verification of Local High Collision Pressure at Low Fill Level

**Stephen and Scholl NASA TN D-6870, 1972**

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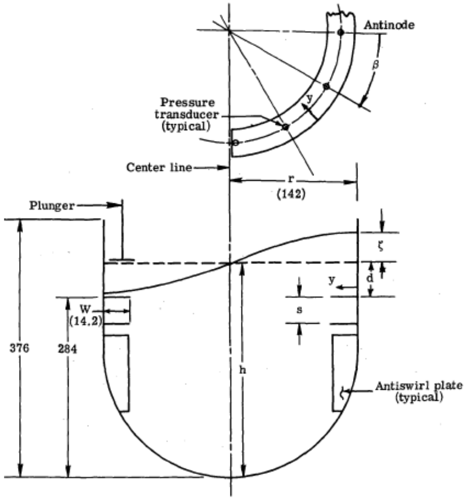
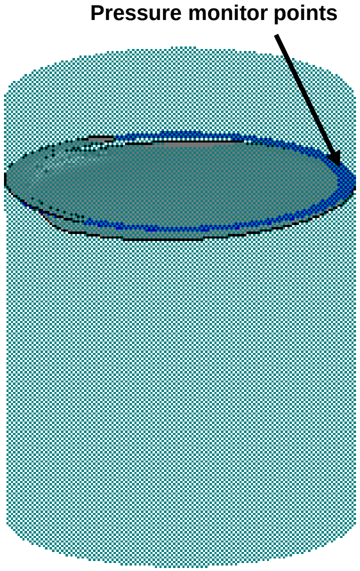
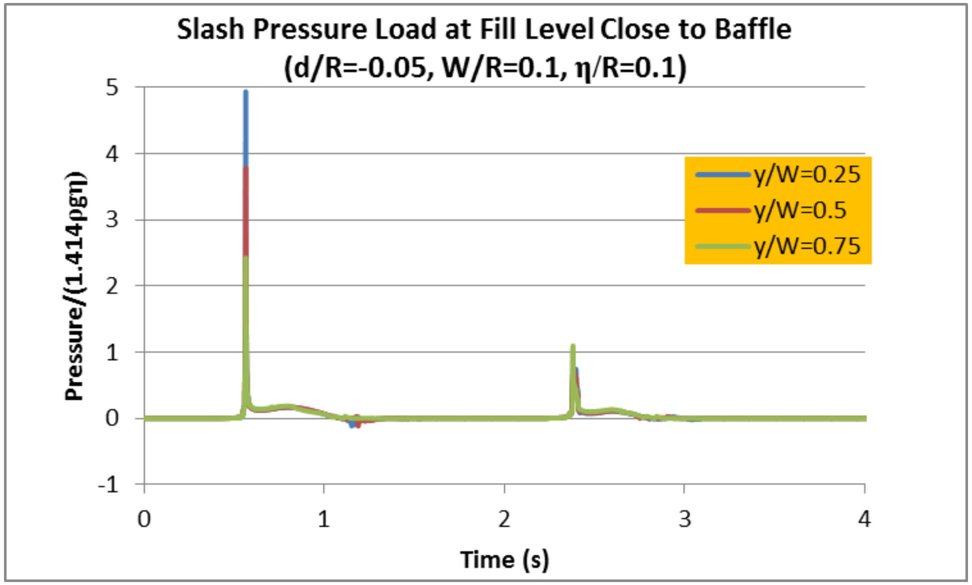






## Observations

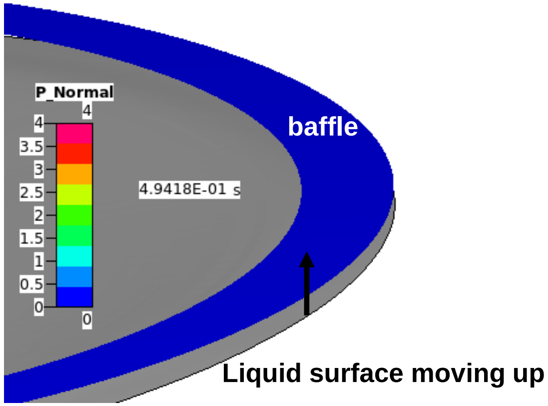
- **When the liquid fill level is close to the baffle, or when d/R is small, if the wave height is larger than the fill level (η/R> d/R), liquid will splash to the baffle.**
- **In addition to the increase of slosh damping, collision of liquid with baffle produces short-duration, localized pressure pulses up to 5X the proposed maximum slosh pressure.**

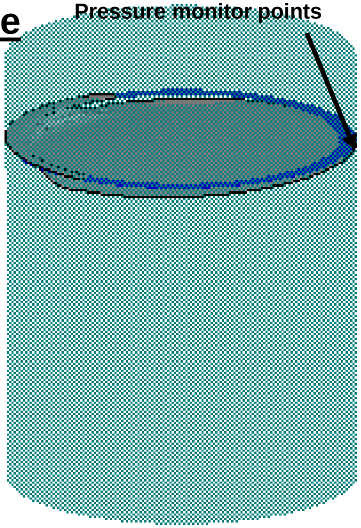
## Questions

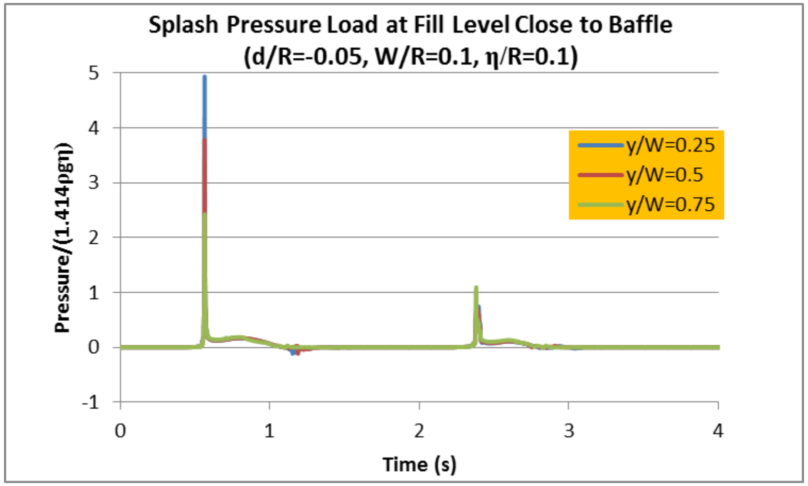
- **Spatial distribution of the pressure spike? Any impact on the pressure load? Impact on the total slosh force? Implication on the pressure measurement? Implication on the proposed pressure theory?**
- **Will assess from CFD solution.**

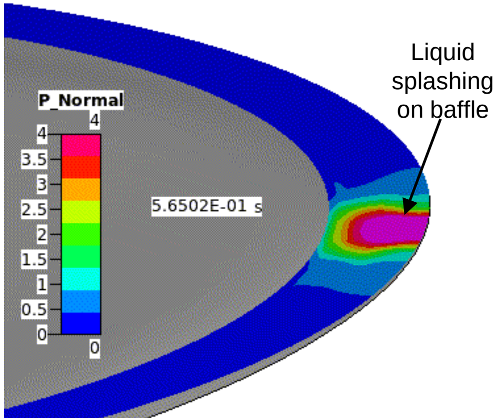
# CFD Verification of Local High Collision Pressure at Low Fill Level

## Spatial Distribution of Splash Pressure

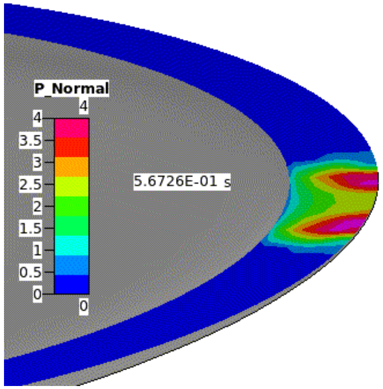




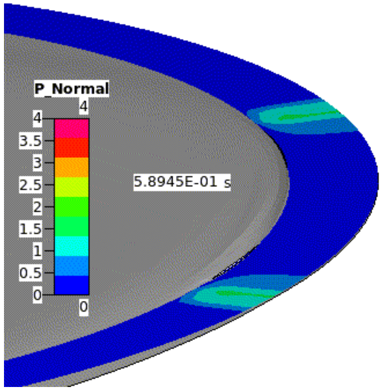




**High pressure in the region of liquid contact with baffle**



**As free surface continues moving up, the high pressure region moves away from the center, and follows the instantaneous contact point.**



**The pressure at the monitor region reduces to low value. The splash-impact pressure rapidly decays**

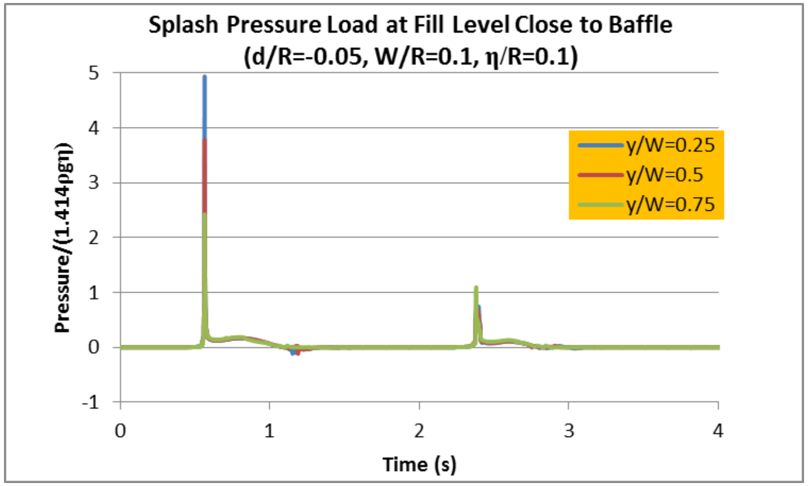
The high collision pressure is localized and has a time scale much smaller than slosh period

# CFD Verification of Local High Collision Pressure at Low Fill Level

The local high collision pressure is localized and has a time scale much smaller than slosh period

## #1. *Implication to Experimental Data*

- **Higher-than-expected measured pressures at d/R = –0.05, 0.0, 0.05 are likely due to splash impacts.**
- **These short-duration spikes should not be interpreted as slosh loads, which are cycle-averaged phenomena**

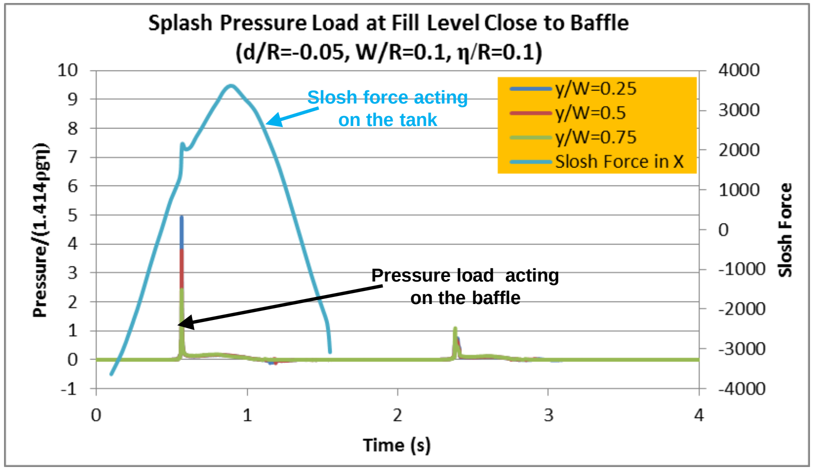

Splash Pressure Load at Fill Level Close to Baffle
(d/R=-0.05, W/R=0.1, η/R=0.1)

## #2. *Implication to Proposed Theory*

- **Proposed maximum slosh pressure model remains valid**

## #3. *Implication to Pressure load Acting on the Baffle*

- **Splash involves very small liquid mass → negligible effect on total slosh force.**
- **Therefore, splash pressure does not affect baffle design based on slosh loads.**


Splash Pressure Load at Fill Level Close to Baffle
(d/R=-0.05, W/R=0.1, η/R=0.1)

Slosh force acting on the tank

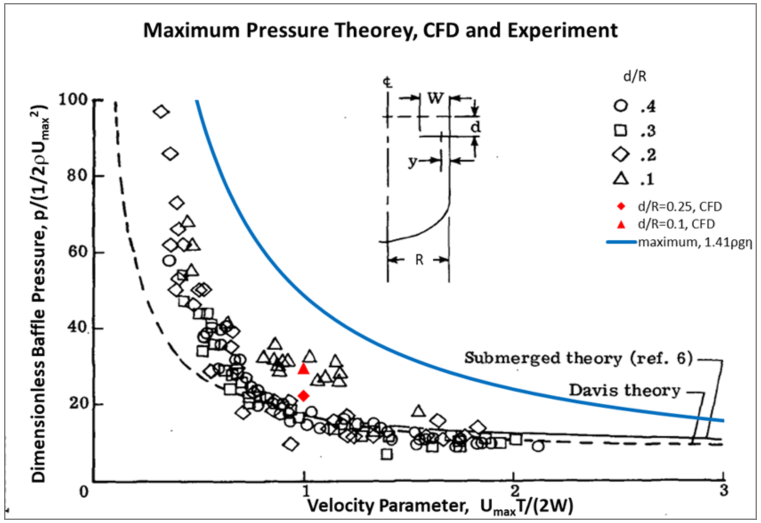
Pressure load acting on the baffle

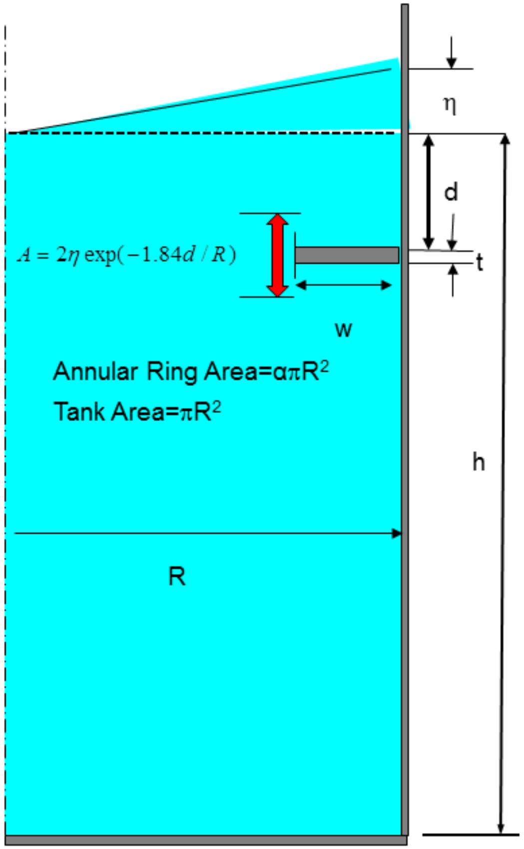
The proposed maximum pressure is validated even for the case when liquid fill level is close to the baffle and high pressures are detected from experimental data.

# Generalized Depth Model

***Observation from Experimental Data***

- Pressure load decease with the increase of fill depth d/R



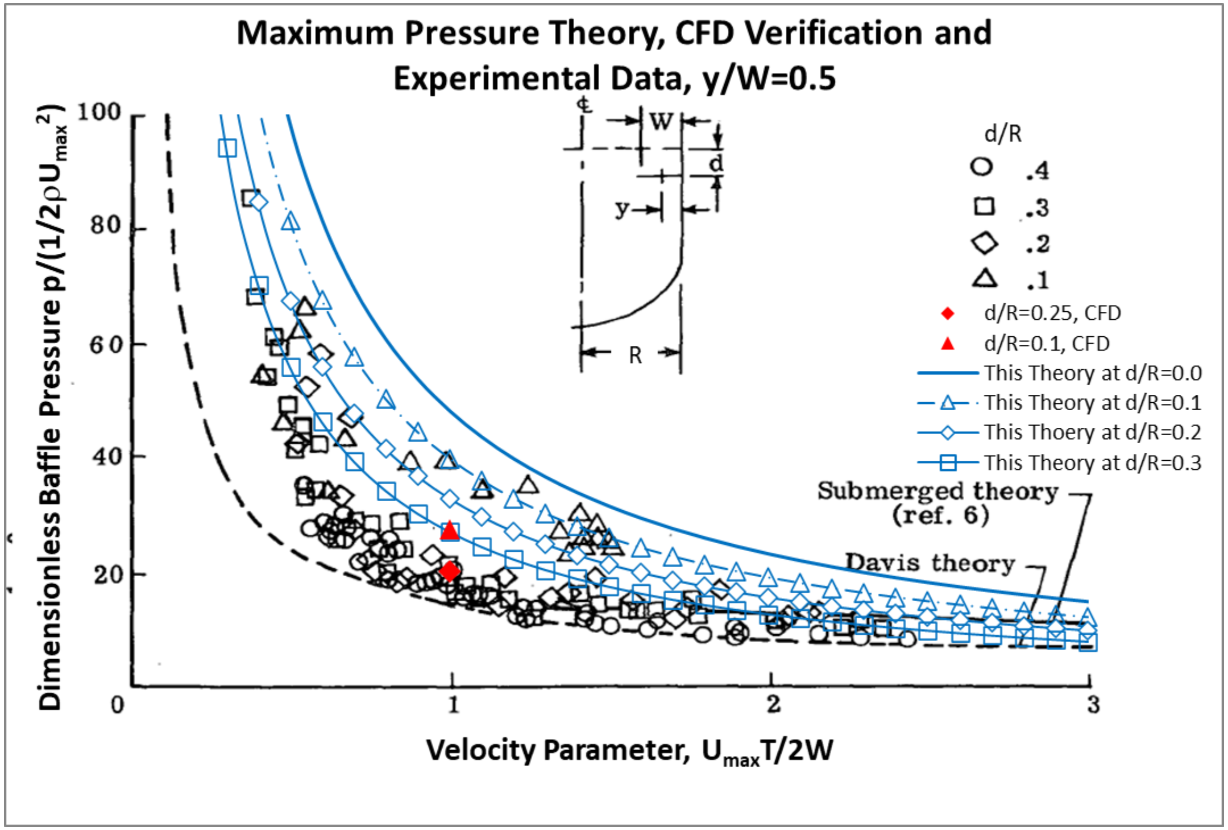


***Particle movement amplitude decreases with depth***

$$\eta_d = \eta * exp(-1.84\frac{d}{R})$$

***Generalized Pressure Load Model:*** $\Delta p = \sqrt{2}\rho g \eta exp(-1.84\frac{d}{R})$

# Validation of Generalized Depth Model



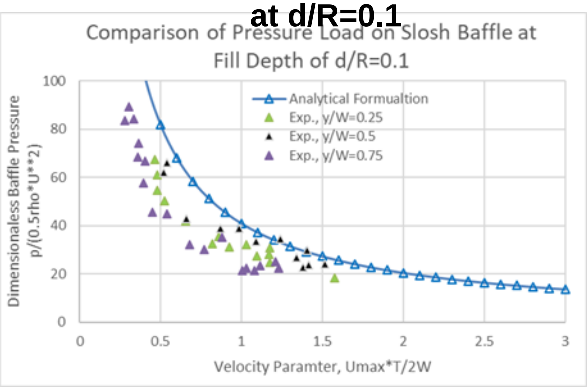
Maximum Pressure Theory, CFD Verification and Experimental Data, y/W=0.5

### *Observations:*

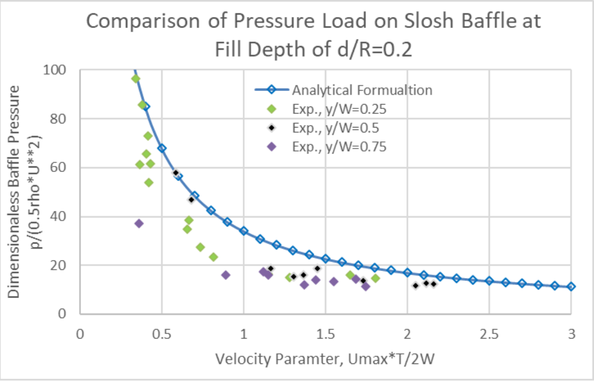
- Matches experimental trend
- Maximum load at d/R = 0
- Decreases with depth

# Full Validation of Across Depths

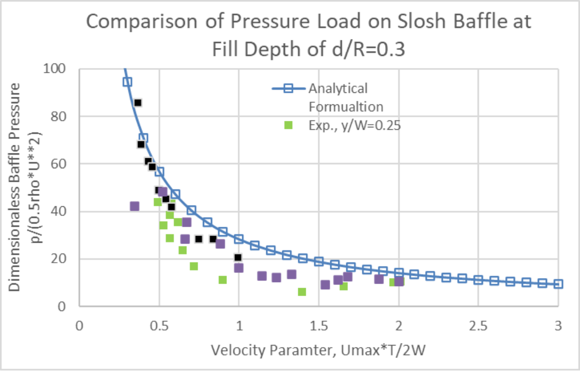
**at d/R=0.1**



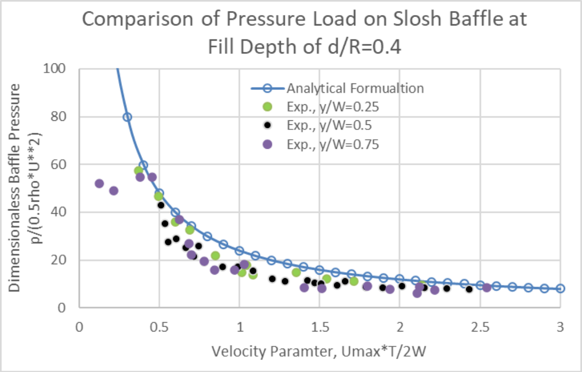
**at d/R=0.2**



**at d/R=0.3**



**at d/R=0.4**



## *Comparison at Four Depth Ratios*

- d/R = 0.1, 0.2, 0.3, 0.4
- Theory envelopes all submerged cases
- Consistent across y/W = 0.25, 0.5, 0.75
- Provides a unified and conservative prediction framework for submerged-baffle pressure loads.

# Contributions

- ✓ Derived a **maximum slosh pressure model**
- ✓ Extended to **general fill depths and wave heights**
- ✓ Verified theoretical model with VOF CFD
- ✓ Validated with **experimental data**
- ✓ Identified splash vs. slosh regimes
- ✓ Provided a **conservative, unified pressure-load prediction tool**

# Conclusion

***A Generalized Pressure Load Model for Baffle Design Has Been Developed***

- Maximum transient pressure ≤ $\rho g \eta$
- Maximum differential load ≤ $\sqrt{2}\,\rho g \eta$
- Theory valid across all **submerged conditions**
- Generalized model captures **depth dependence**

***Applicable to***

- Structural design
- GNC modeling
- Slosh analysis

***Provides a simple, robust engineering formula***