Structural Analysis Case Studies of Buildings Damaged during the Tohoku Tsunami

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Basic Objective

- **Perform a series of case studies on different buildings after the 2011 Tohoku Tsunami in order to validate proposed tsunami load characterization procedures for structural design.**

Structural Forces during the Tohoku Tsunami

- **The Tohoku Tsunami presented a range of structural loading conditions and effects.**
- **Focus is on the following:**
  - **Hydrostatic Forces**:
    - **Unbalanced Lateral Forces**
    - **Buoyant Forces**
    - **Additional Loads on Elevated Floors**
  - **Hydrodynamic Drag Forces**:
    - **Lateral Pressures of Tsunami Surge**
  - **Debris Damming**
  - **Tsunami Bore Forces**

Steps in Analysis

1. Estimate the loading type and failure mechanisms for selected structures from field and video observations.

2. Determine/estimate inundation depth and surge/bore velocity from video, field observations and documentation.

3. Theoretically quantify loading on structures.

4. Perform non-linear structural analysis of damaged structures to compute damage based on the theoretical loading.

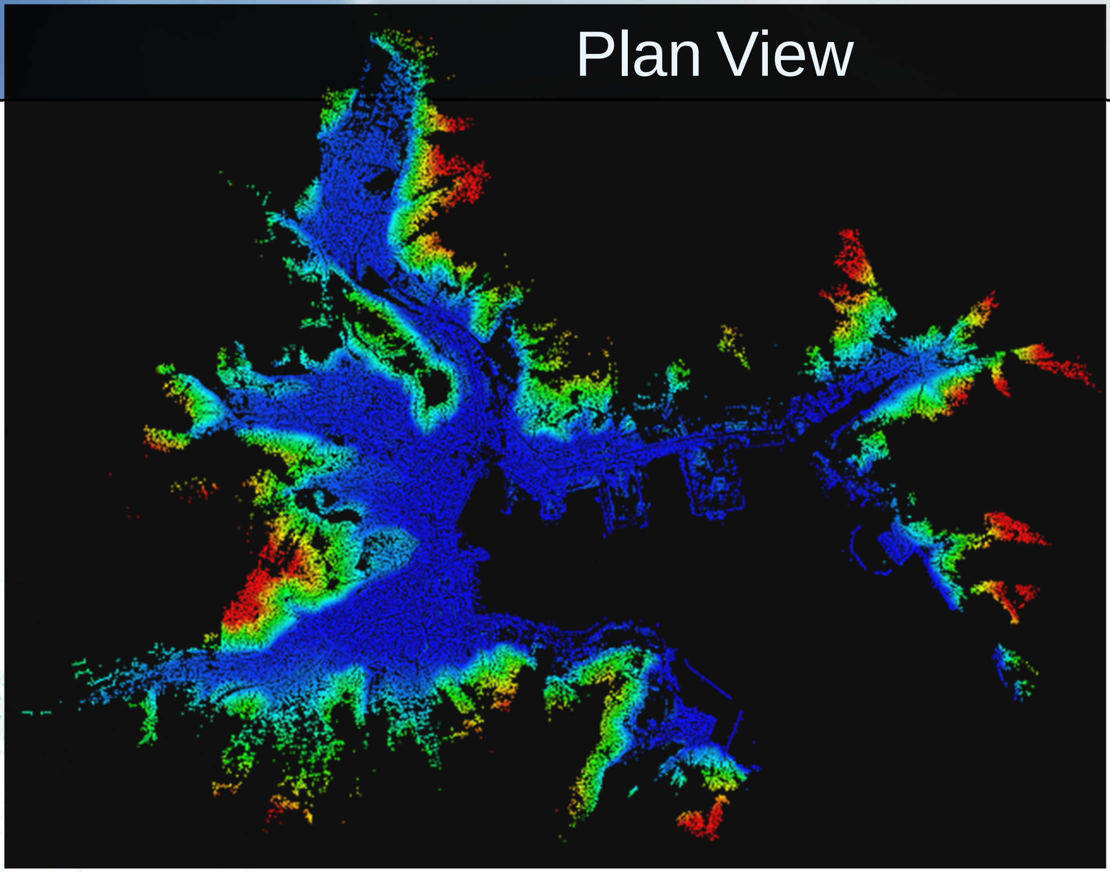
5. Compare computed damage to observed damage from field observations and LiDAR surveys to provide bounds for validation of theoretical loading.

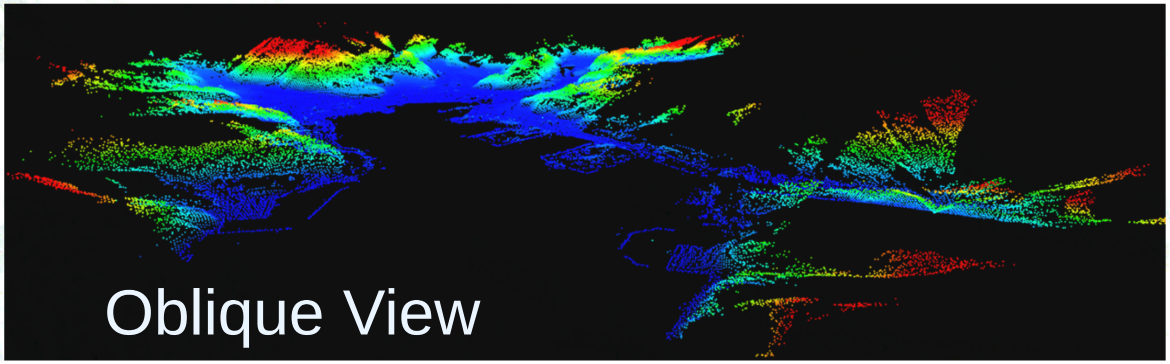
LiDAR – Building Deformation

Michael Olsen,
Shawn Butcher &
Evon Silvia,

Oregon State
University

LiDAR – Onagawa Topography



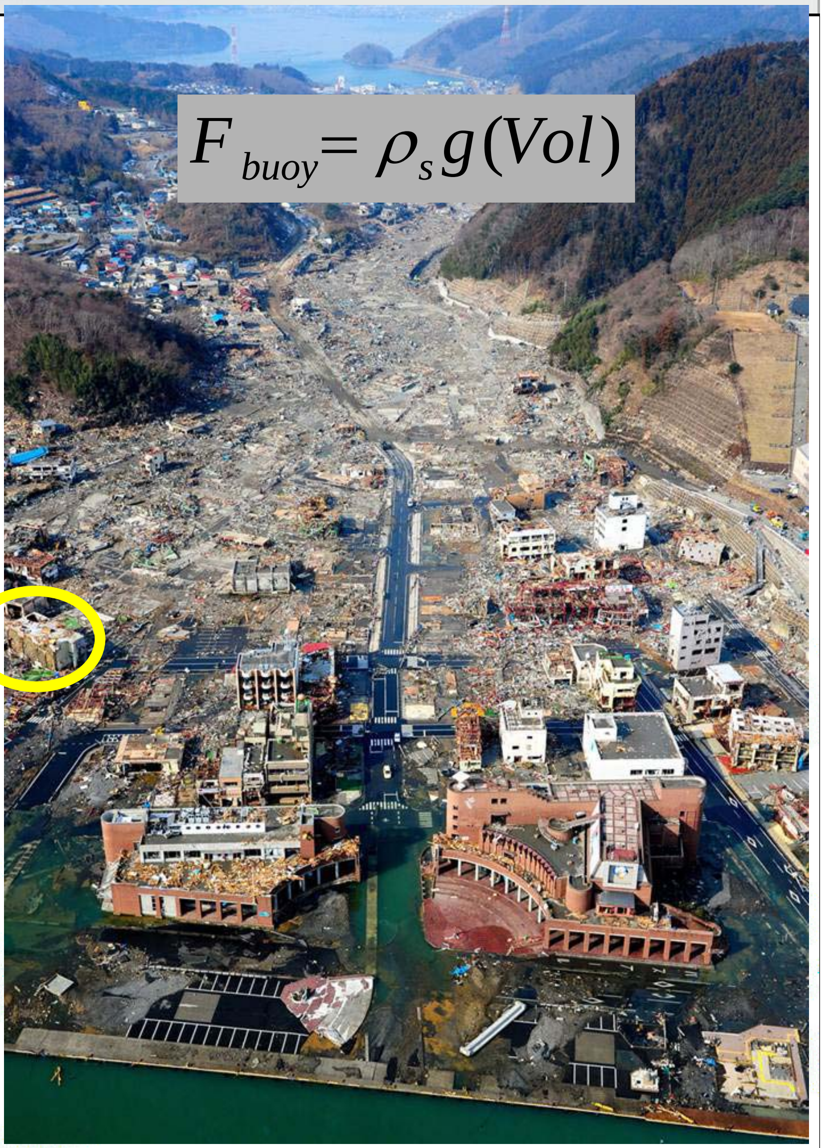


Michael Olsen, Shawn Butcher & Evon Silvia,

Oregon State University

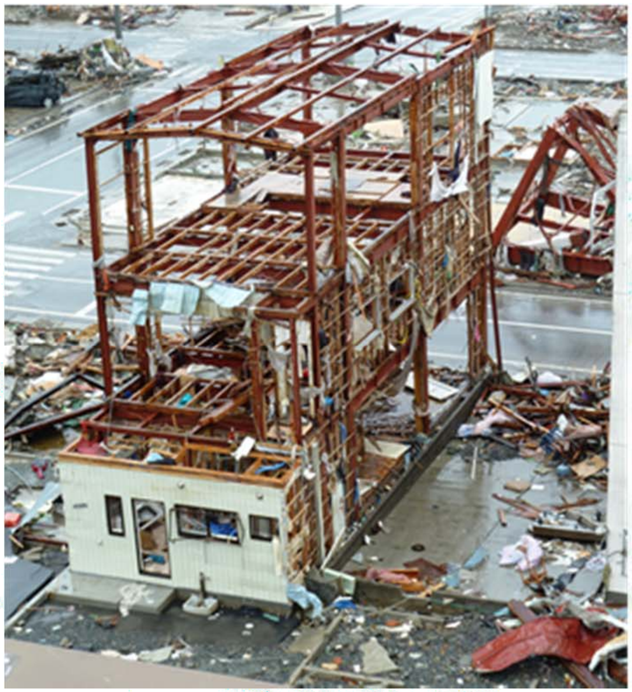
Hydrostatic Forces – Buoyancy of Warehouse Building - Onagawa

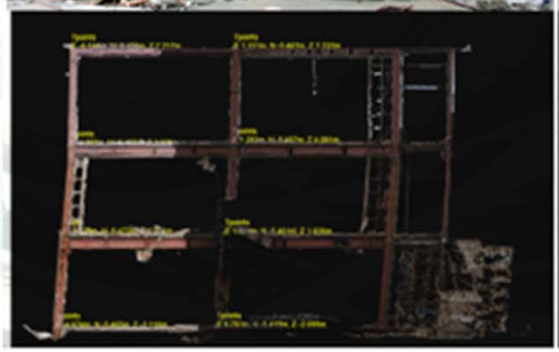
- Total weight estimated at 9000 kN
- Floated due to sealed refrigerated space on ground floor
- Lifted off foundations (piles with minimal tensile capacity) at inundation depth of around 7 m

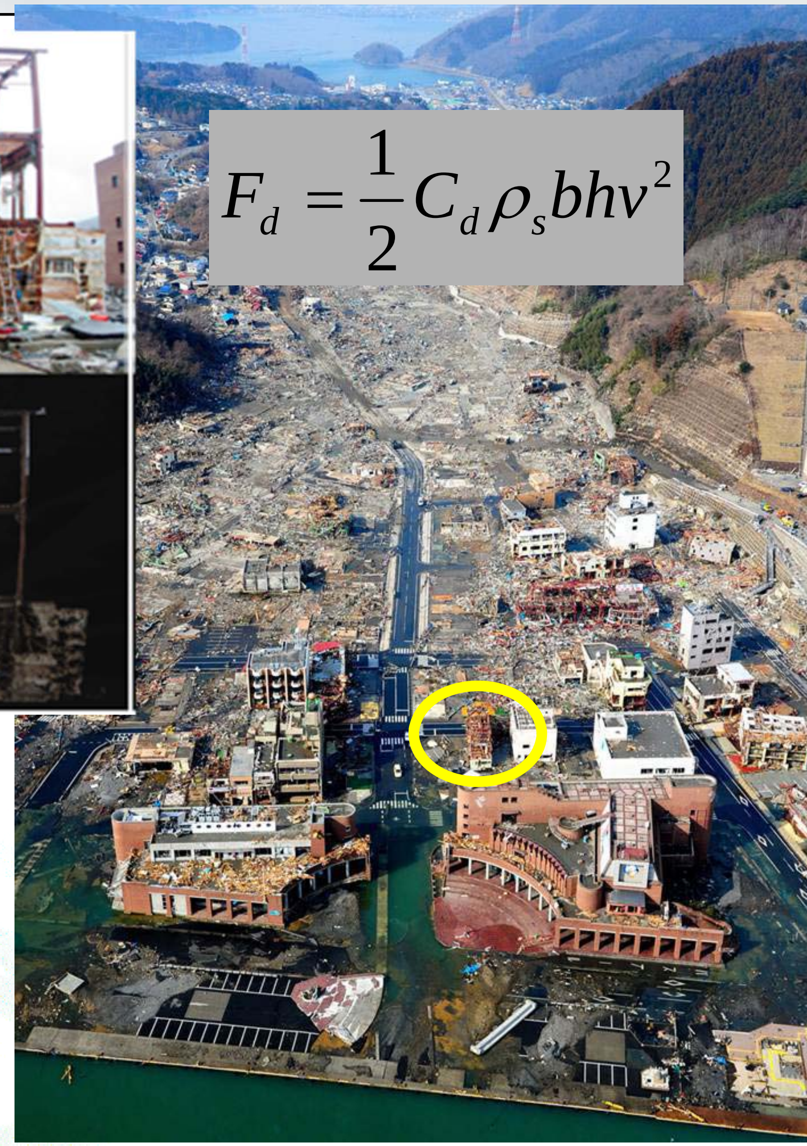


$$F_{buoy} = \rho_s g(Vol)$$

Hydrodynamic Forces – Steel Structure - Onagawa



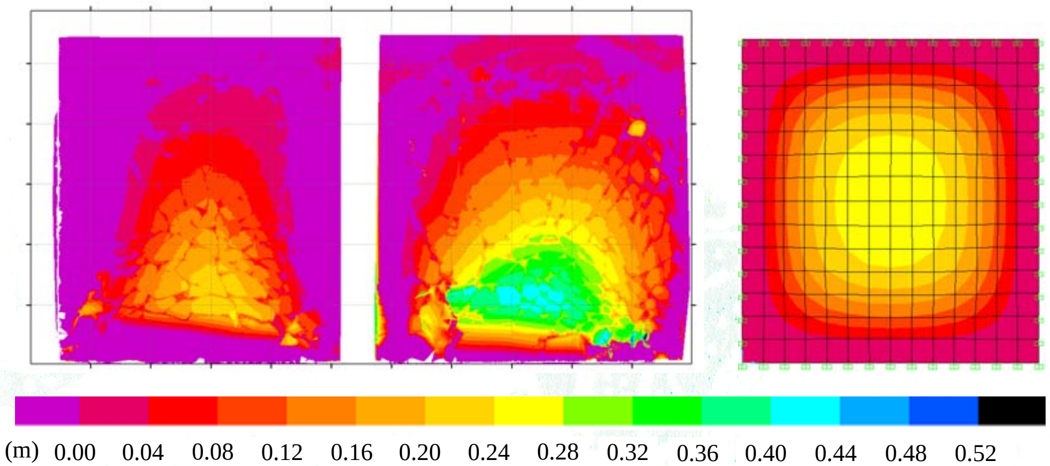




$$F_d = \frac{1}{2} C_d \rho_s b h v^2$$

- **Flow velocity = 7.5 m/s**
- **Inundation = full height of structure**
- **Yielding/Plastic hinging in columns**
- **60% blockage of projected face of structure sufficient to yield the columns based on hydrodynamic force equation**

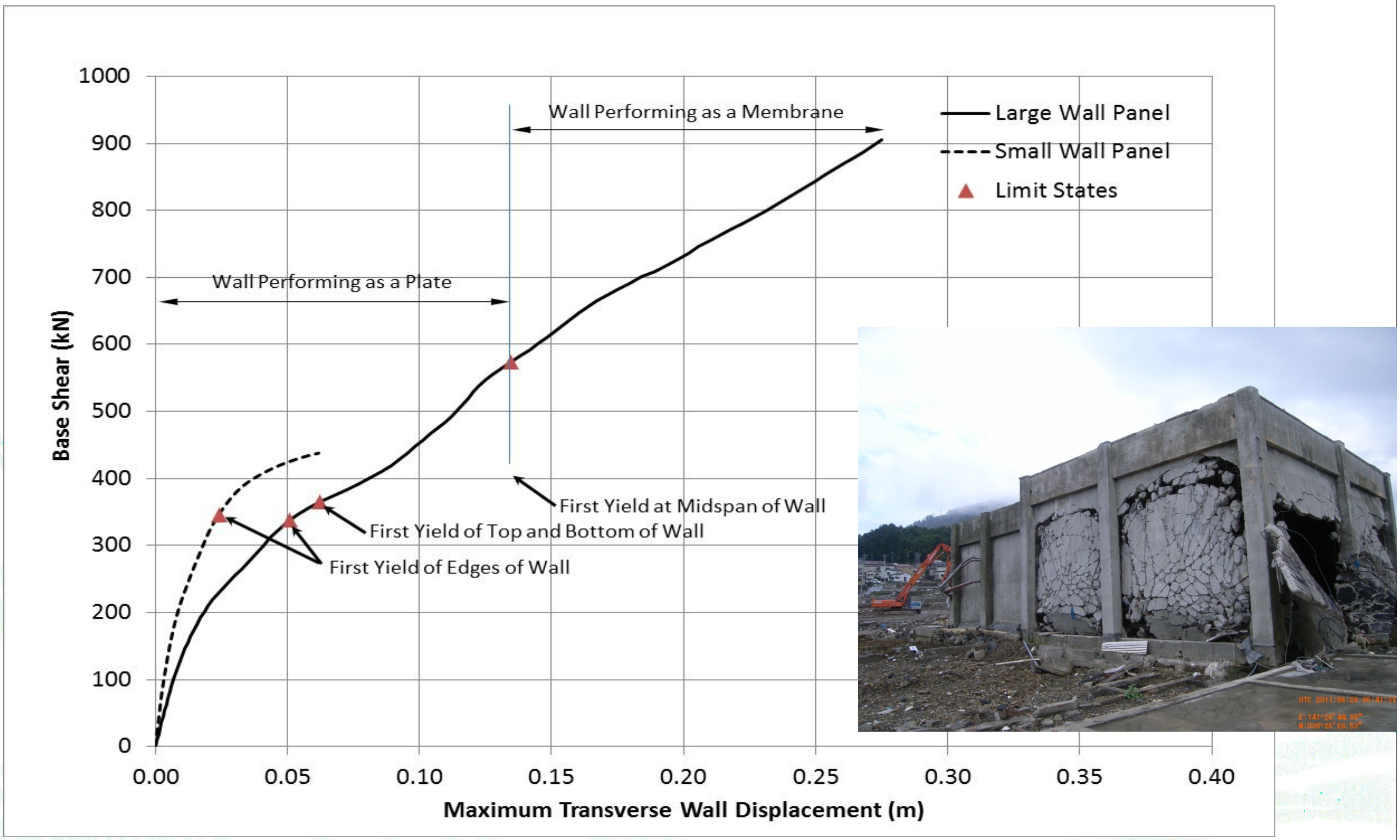
Stagnation Pressure – Concrete Structure - Onagawa



- **Flow velocity = 7.5 m/s**
- **Inundation = full height of structure**
- **Pressure sufficient to fully yield larger wall segments.**
- **Pressure sufficient to partially yield smaller wall segments but not completely fail them.**

$$p = \frac{1}{2}\rho_s v^2$$

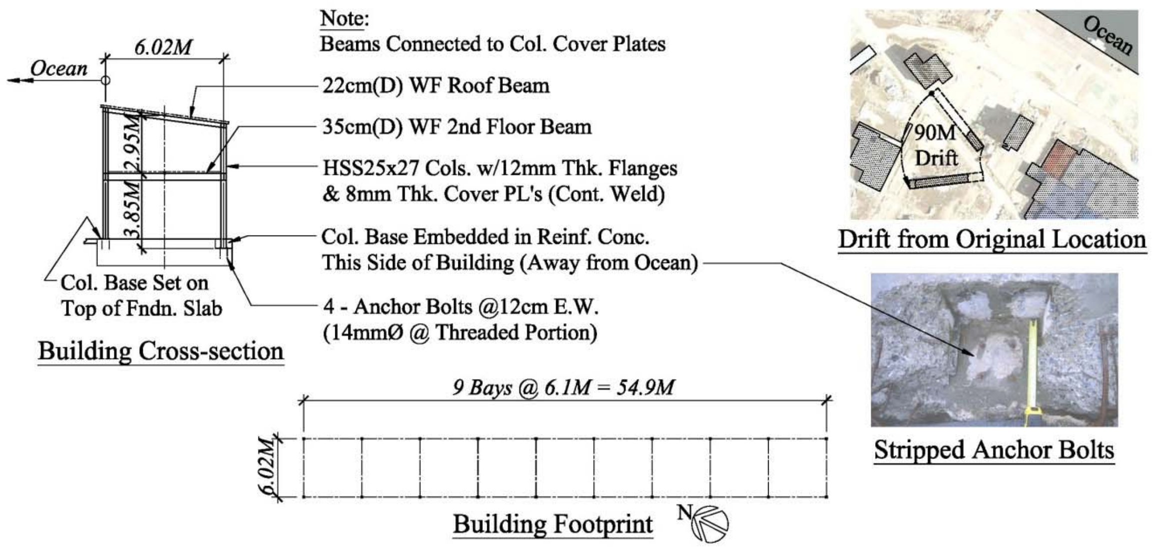
Stagnation Pressure – Concrete Structure - Onagawa



Hydrodynamic Forces – Steel Warehouse Structure - Kessenuma

- **Two story warehouse**
- **Flow velocity = 5.5 m/s**
- **75% walls remained at ground floor and 50% remained at 2nd floor**
- **Foundation anchor bolt shear strength exceeded at 5.6 m inundation depth**
- **Building translated and rotated about its longitudinal axis.**

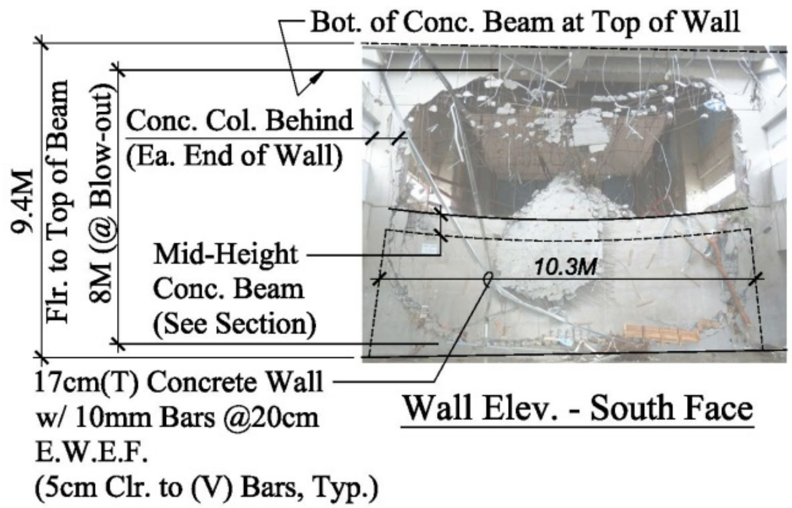
$$F_d = \frac{1}{2} C_d \rho_s b h v^2$$



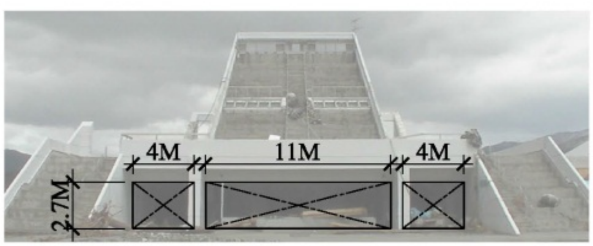
Hydrostatic and Hydrodynamic Forces - Tourist Center - Rikuzentakata

Hydrostatic and Hydrodynamic Forces - Tourist Center - Rikuzentakata

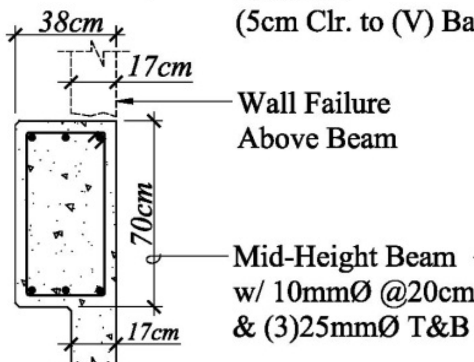
Wall Elevation
Looking East
(Robertson)



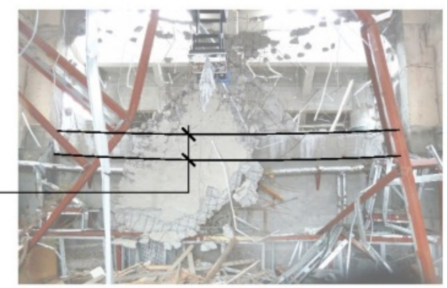
Wall Elev. - South Face



South Elevations
Indicating Openings to Ocean



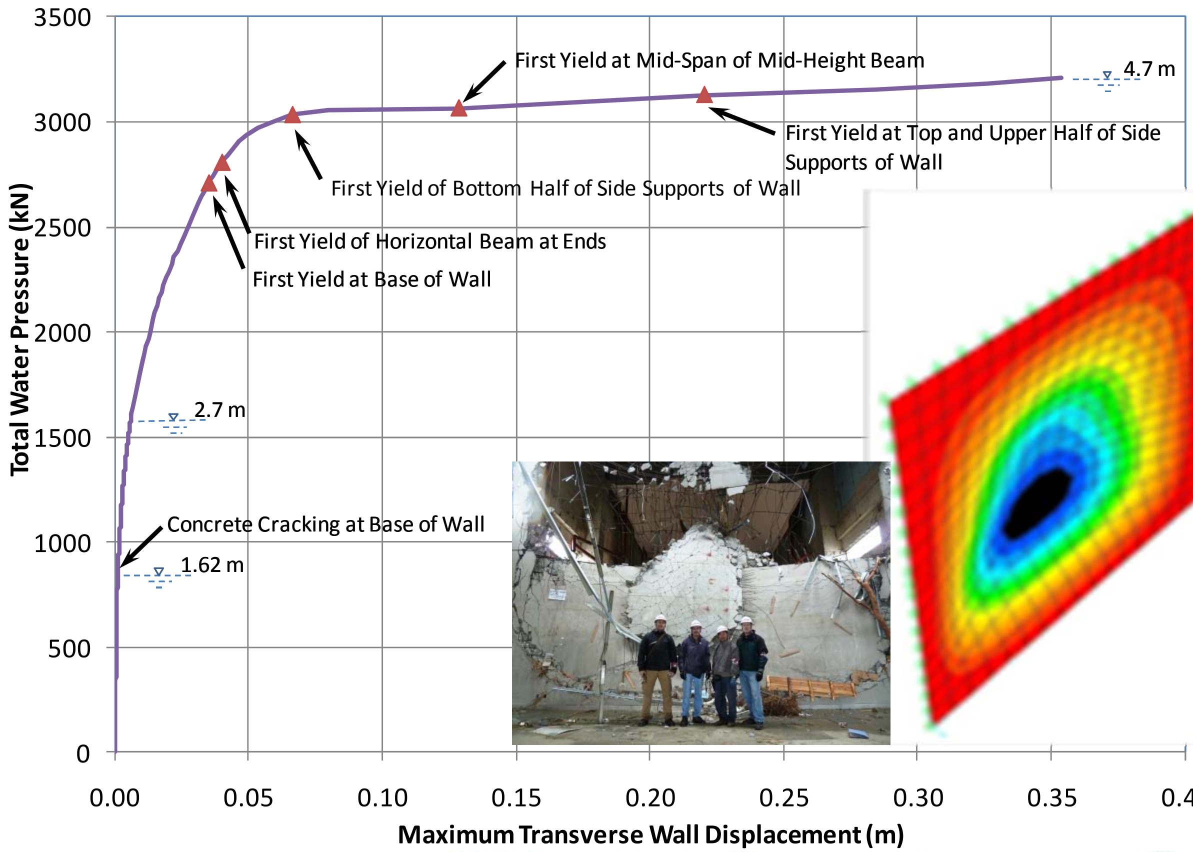
Section thru
Mid-height Beam

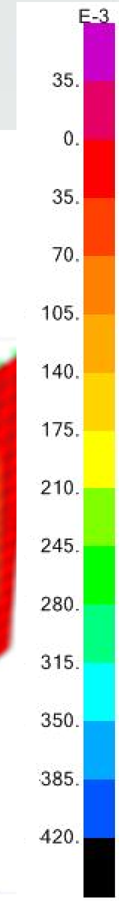


Wall Elev. North Face

Hydrostatic and Hydrodynamic Forces - Tourist Center - Rikuzentakata

- Flow velocity
  = 7.5 m/s
- Inundation depth
  = 10.5 m
- Combination of hydrostatic and hydrodynamic forces
- Force sufficient to completely fail wall well beyond ultimate strength

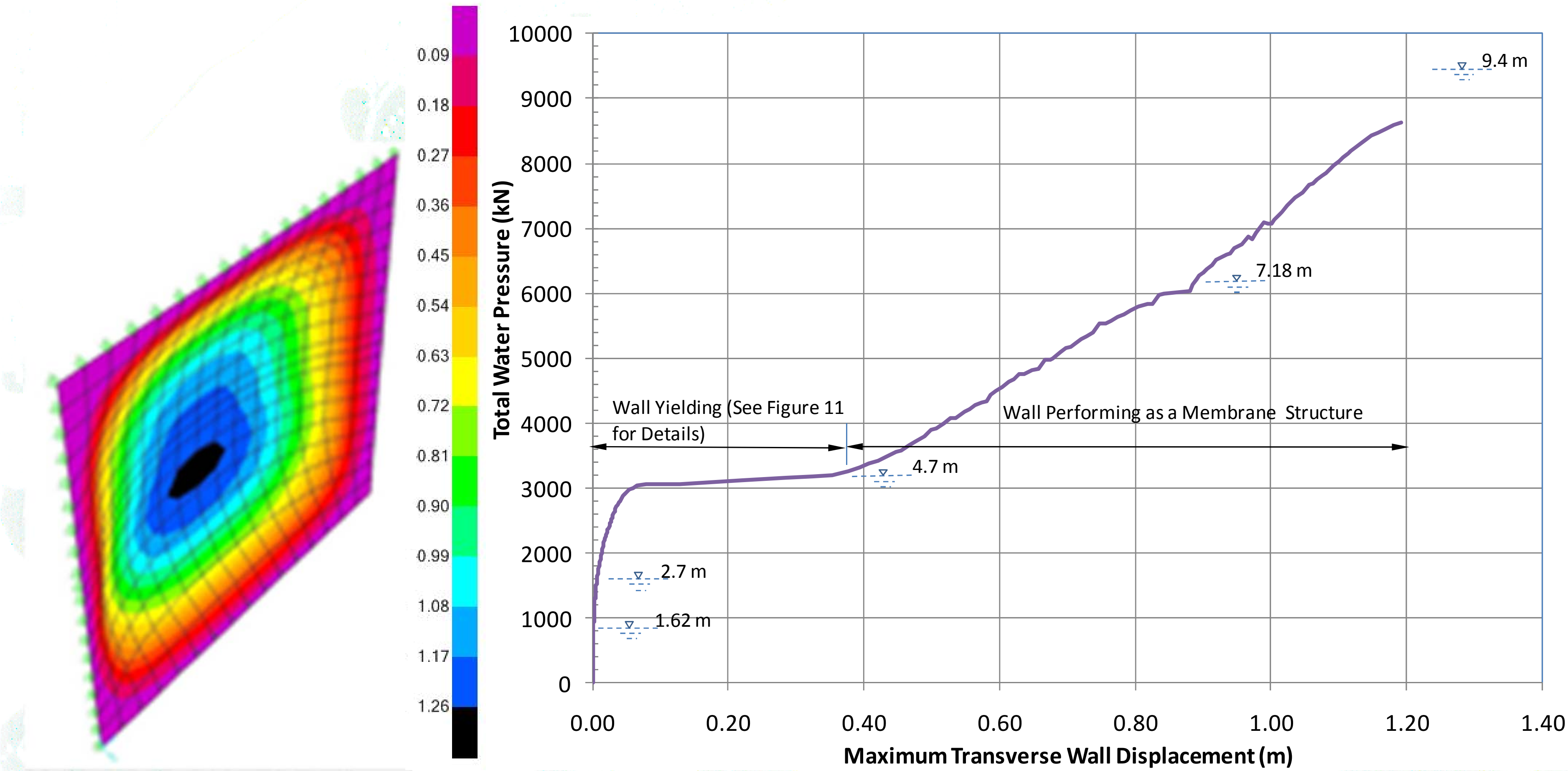




$$F_h = \frac{1}{2}\rho_s g b({h_1}^2 - {h_2}^2) + \frac{1}{2}C_d \rho_s b h v^2$$

Hydrostatic and Hydrodynamic Forces - Tourist Center - Rikuzentakata

- **Forms membrane prior to complete failure**



Bore Impact Forces – Minami Gamou Wastewater Treatment Plant

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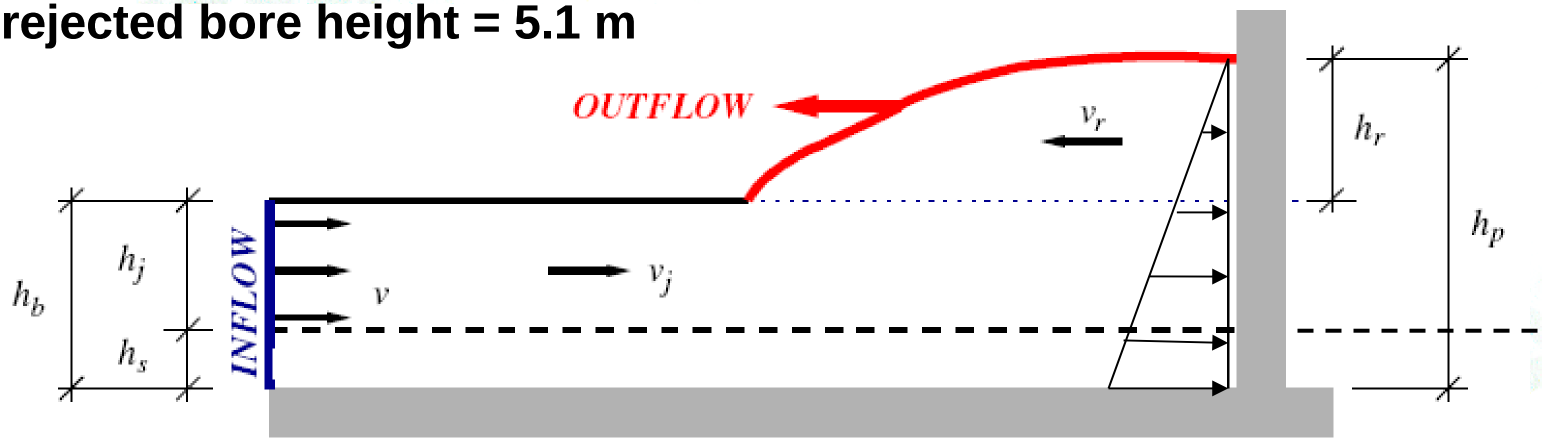
Theoretical Bore Force (Robertson and Packowski, 2011)

- **Flow velocity = 6.5 m/s**
- **Static water height = 0.5 m**
- **Bore height = 6.0 m**
- **Calculated rejected bore height = 5.1 m**



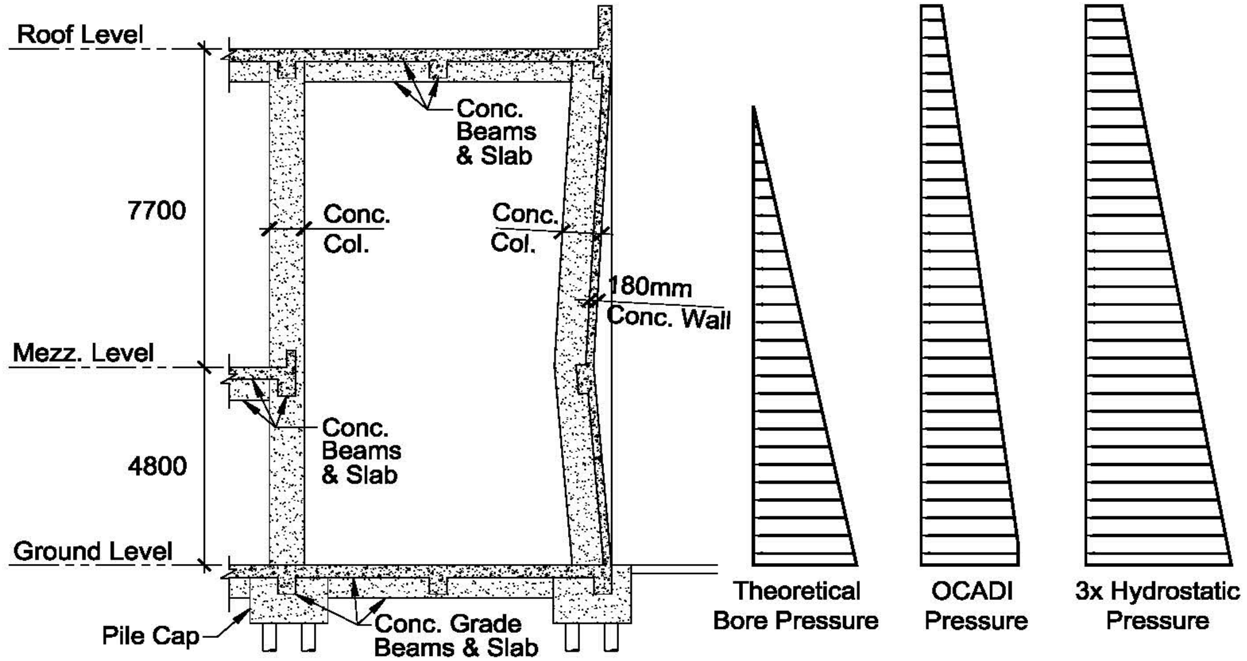
$p=2F_b/h_p$

$$F_b = \rho_s\left(\frac{1}{2}gh_b^2 + h_j v_j^2 + g^{1/3}(h_j v_j)^{4/3}\right)$$

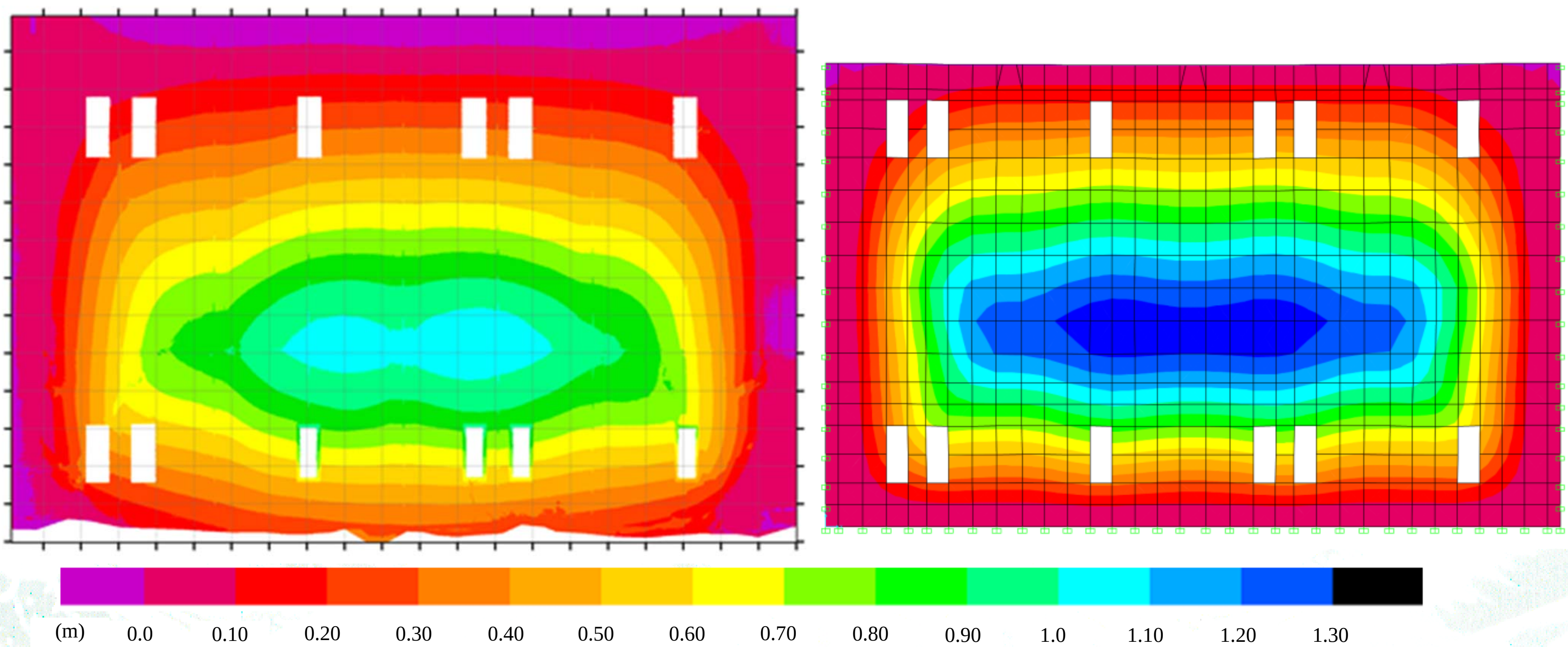
$$h_r = g^{-\frac{1}{3}}(v_j h_j)^{\frac{2}{3}}$$

Bore Impact Forces – Minami Gamou Wastewater Treatment Plant

- **Comparison with Different Bore Pressures used in Tsunami Standards**



Bore Impact Forces – Minami Gamou Wastewater Treatment Plant



Conclusions

- **There are tools available for reliable structural load characterization of different loading conditions**
- **LiDAR was a useful tool in capturing structural post-tsunami deformations along with other field survey techniques.**