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
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

Plan View

Michael Olsen,
Shawn Butcher &
Evon Silvia,

Oregon State
University

Oblique View
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

\[ F_{\text{buoy}} = \rho_s g (Vol) \]
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

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

Graph showing the relationship between base shear (kN) and maximum transverse wall displacement (m). The graph includes two lines: one for large wall panels and another for small wall panels. Key points include:

- Wall Performing as a Plate
- Wall Performing as a Membrane
- First Yield at Midspan of Wall
- First Yield of Top and Bottom of Wall
- First Yield of Edges of Wall

Limit States are indicated by triangles on the graph.
- 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
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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

\[ F_h = \frac{1}{2} \rho_s gb (h_1^2 - h_2^2) + \frac{1}{2} C_d \rho_s bhv^2 \]
Hydrostatic and Hydrodynamic Forces - Tourist Center - Rikuzentakata

- Forms membrane prior to complete failure

![Graph showing total water pressure vs. maximum transverse wall displacement](image)
Bore Impact Forces – Minami Gamou Wastewater Treatment Plant
Bore Impact Forces – Minami Gamou Wastewater Treatment Plant

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

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

\[
h_r = g \frac{1}{3} (v_j h_j)^{2/3}
\]
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.