Type of Damage or Failure Mechanism	Location	Structure	Top of Structure Elev. (m above MSL))	Approximate Runup Elev. (m above MSL)	Fig. #
Scour	Shizagawa	Tsunami Wall		+15.2	**56**
	Arahama Beach	Shoreline Dike	+5	+12.2	**57**
	Arahama Beach	Restroom Building	+5	+12.2	**58**
	Natori Beach	Shoreline Dike	+5	+9	**59**
	Otsuchi	Tsunami Wall	+5	+9	**63**
	Taro	Tsunami Wall			**64**
	Kojirahama	Tsunami Wall			**65**
	Omoto	Barrier Wall			**66**
Erosion	Rikuzentakata	Beach & Seawall		+19	**68**
	Oya	Beach & Revetment		+15	**69**
	Koizumihama Beach	Beach & Seawall		+19.6	**70**
	Otsuchi	Port & Tsunami Wall		+8	**71**
Abutments End Effects	Tanohata	Road Abutment			**72**
	Rikuzen Takada	Road Abutment			**73**
	Utatsu	Bridge Abutment			**74**
	Fudai	River Gate			**75**
Subsidence	Kojirahama Port	Port Infrastructure		+17.8	**76**
	Kesennuma Port	Port Infrastructure		+8	**77**
	Onagawa Port	Port Infrastructure		+18	**78**
	Gamo Tidal Flats	Tidal Flats		+6.1	**79**

3.1 Tsunami Overtopping without Structural Failure

A number of the coastal structures withstood wave forces despite having been overtopped. Structures can survive tsunami wave runup and overtopping if

(a) The structure's design capacity is not exceeded (shear stresses and/or bending stresses within design limits of the structure's members)
(b) Adequate protection prevents landward or seaward scour
(c) Adequate protection deters turbulent and supercritical flows
(d) Impact loads do not damage the structure
(e) The structure can withstand buoyant uplift forces and lateral overturning forces
(f) The structure has a significantly low profile such that the tsunami passes over its top with little or no structural damage due to any resultant hydrodynamic forces.

Figures 19 – 22 show examples of structures that withstood wave runup and overtopping.

Figure 19. Arahama Beach shoreline dike — Minor damage to top pavement/backside concrete slope; scour on landward side of dike

Figure 20. Naruse River north entrance jetty — Damage to a small section of the river revetment, as indicated by the work crane; no damage to the jetty itself

Figure 21. Taro tsunami wall — No substantial damage to section shown

Figure 22. Shizugawa, fishing port bridge — No damage observed

3.2 Tsunami Overtopping with Structural Damage or Failure

Tsunami wave runup and overtopping that cause structural damage and even failure typically result from hydrostatic and hydrodynamic loads that

(a) Exceed the structure's design capacity (shear stresses and/or bending stresses exceeding design limits of the structure's members)
(b) Scour the landward and/or seaward sides of the structure, or its end points, resulting in failure due to loss in foundation earth support
(c) Produce excessive turbulent and supercritical flows resulting in failure

(d) Produce impact loads such as hydrodynamic drag forces, impulsive forces, debris acting as projectiles that either strike the structure or cause debris damming resulting in damage
(e) Produce excessive buoyant forces that uplift and move the structure from its foundation
(f) Produce excessive lateral loading that result in the structure's overturning

The examples shown in Figures 23 – 26 all exhibit various combinations of these loads. In Figure 26, for example, the wall sections at Kojirahama experienced overturning due to lateral loading. However, the landside scour that occurred during overtopping and the added buoyancy in the units from the airspace of a built-in tunnel on their landside face exacerbated damages caused by overturning.

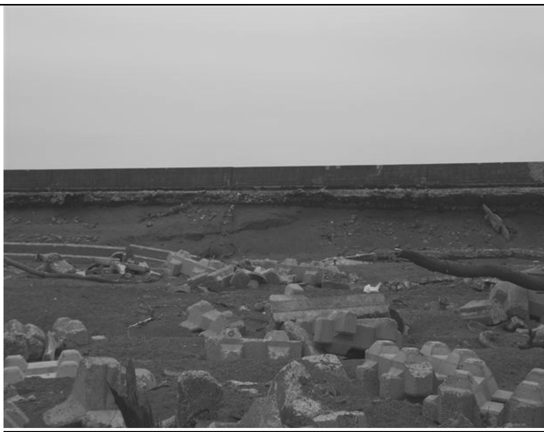

Figure 23. Noda Tsunami Seawall (old wall) —Backside erosion/concrete armor units tossed over wall; wall sections broken off

Figure 24. Noda Tsunami Seawall (new wall) — Backside erosion with loss of precast concrete panels; one upper section of wall sheared off

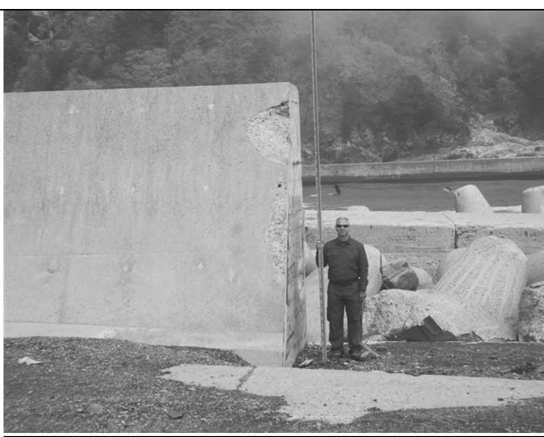

Figure 25. Omoto Port breakwater — 3.5m high x 56m long section of wall sheared off

Figure 26. Kojirahama tsunami wall — Five wall sections overturned due to landside scouring resulting in 74m-breach

3.3 Tsunami Uplift Forces

When tsunami waves completely or partially submerge a structure, or when they pass underneath a structure resulting in entrapment of the waves on the underside of the structure (i.e., bridge decks, piers), the structure experience uplift forces due to the hydrostatic buoyancy including effects of excessive pore pressure and hydrodynamic forces. The hydrodynamic forces result from the vertical difference in the dynamic pressure forces over the surface of the structure, and the Bernoulli (aerodynamic) effect as water flows around the structure (Figure 27). The uplift forces reduce the structure's total effective dead weight, which may affect the structure's resistance to overturning and sliding (Figure 28). Excessive tsunami-induced uplift forces can lift a structure from its foundation, especially when the structure does not have sufficient anchorage. Figures 29 – 35 show examples of structures subjected to tsunami uplift forces.

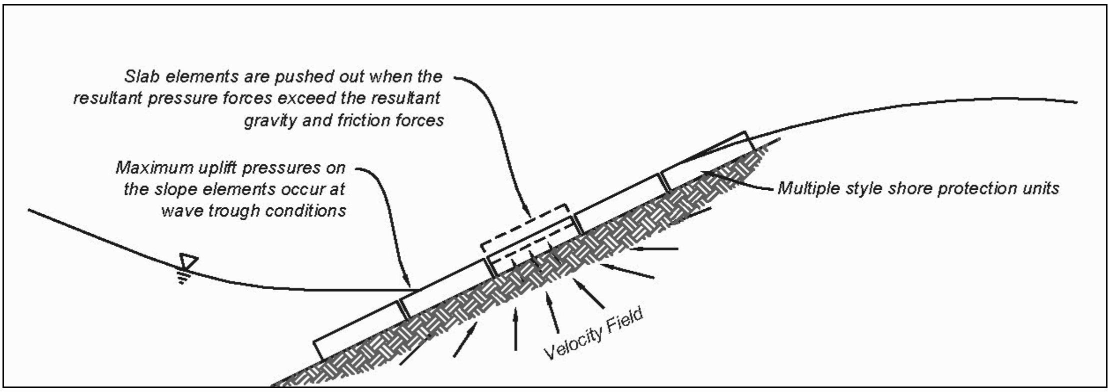

Figure 27. Hydrostatic uplift forces

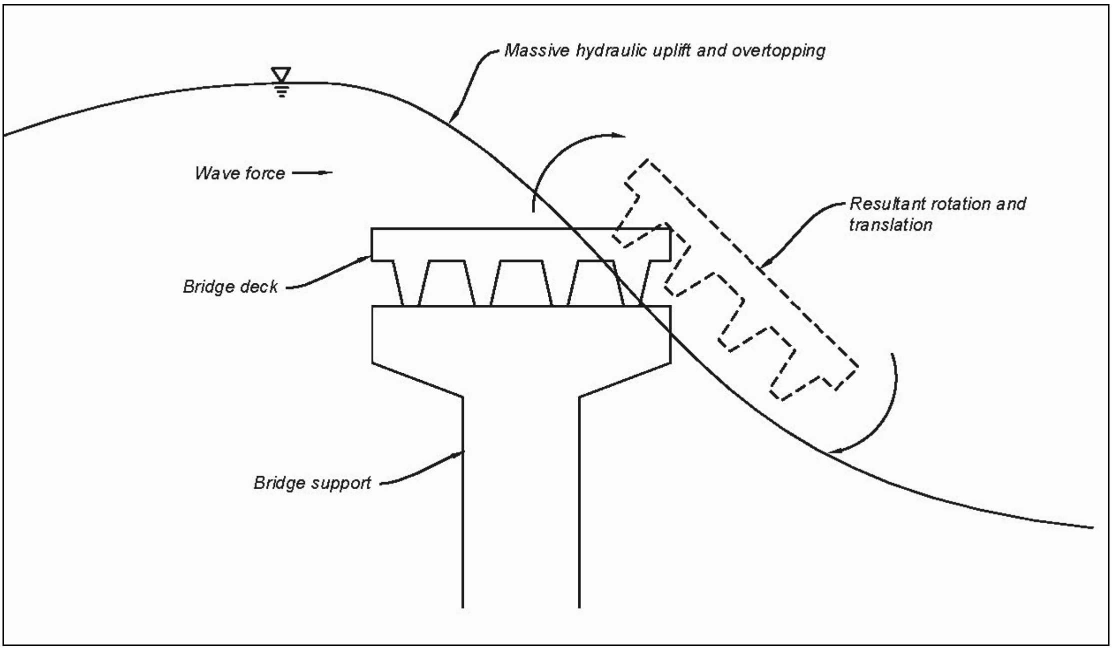

Figure 28. Hydraulic uplift and overtopping

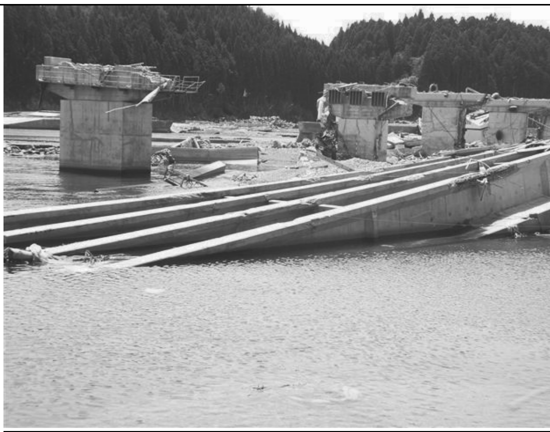

Figure 29. Utatsu Port Bridge — Bridge deck uplifted off its foundation piers and overturned

Figure 30. Taro Miyato Bridge — Bridge deck uplifted off its foundation piers and overturned

Figure 31. Otsuchi Bridge — Bridge deck (not visible) uplifted off its foundation piers

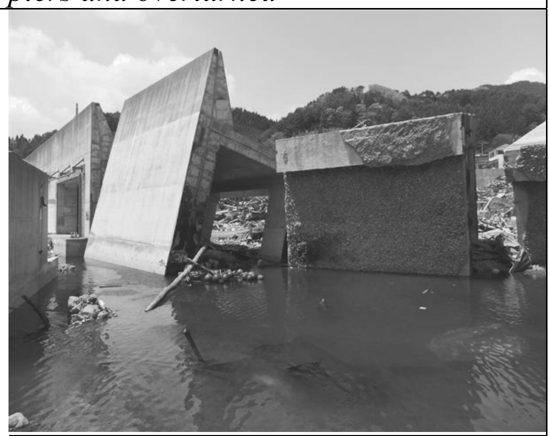

Figure 32. Kojirahama tsunami wall — Five wall sections (12.5m x 8.5m x 10 – 12m long, 74m in total length) scoured on landward side, uplifted, and rotated/overturned

Figure 33. Noda barrier wall — Panels of inland side of wall detached and washed inland

Figure 34. Oya Station — Panels behind seawall uplifted; scour inland of seawall

Figure 35. Onagawa — Tank and building overturned; significant subsidence experienced throughout the area during the earthquake

3.4 Movement of Structure from Its Foundation due to Sliding, Rotation, and Overturning

A structure requires a strong foundation and an adequate anchoring system. In the absence of either, a tsunami's hydrostatic lateral and buoyant loading as well as hydrodynamic loading and foundation scouring can result in the structure's movement off its foundation. When forces exceed the capacity of the anchoring to the foundation, a structure can fail through sliding, rotation, or overturning. Figures 36 – 39 show examples of structures moved from their foundations.

3.5 Impact Loads

In addition to hydrostatic and uplift forces, tsunamis subject coastal structures to impact loads during inundation. Forces include unsteady hydrodynamic drag forces, impulsive forces, debris impact forces, and debris damming forces. Water flowing around a structure applies hydrodynamic drag forces to the structure. The drag forces are a combination of the lateral forces caused by the pressure forces from the moving mass of water and the friction forces generated as the water flows around the structure (see figure, next section). Impulsive forces are very short duration loads caused by the leading edge of a surge of water impinging on a structure. As the surge passes through a structure, all structural components receive the brunt of impulsive forces — applied sequentially but not at the same time. Debris impact forces are short duration loads due to the impact of large floating objects that act as projectiles and strike individual structural components. Debris damming increases the exposed surface area and thus increases the hydrodynamic loading on the structure. Figures 40 – 43 show structures subjected to impact loads.

Figure 36. Otsuchi tsunami wall — Wall sections (54m in total length) scoured on landward side, slid off foundation, and rotated/overturned

Figure 37. Kojirahama tsunami wall -- The shallow foundation keyway is visible in underside of the overturned unit on the right of the photo

Figure 38. Koizumihama Beach tsunami seawall — Seawall completely destroyed from hydrodynamic/impact loading and beach scour; seawall sections slid off foundation, rotated, and overturned

Figure 39. Onagawa building — Three-story concrete building overturned off its foundation; underside visible slab on grade without piling or footings

	
Figure 40: Noda tsunami seawall (old wall) — Broken off concrete portions of seawall; 2m x 2m x 0.8m concrete armor units tossed 75m inland over the wall	*Figure 41: Noda tsunami seawall (new wall) —Sheared off top precast concrete section of seawall with insufficient steel rebar vertical/horizontal connections*
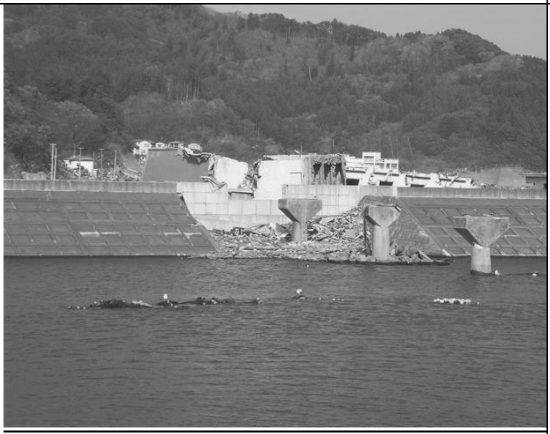	
Figure 42: Otsuchi tsunami seawall — Ripped out section of tsunami wall where the supported bridge deck intersected and is now missing from uplift/impact)	*Figure 43: Onagawa tank structure — Collapsed tank ripped off its foundation (Note: Storage tanks, often partially full, commonly float because their fluid contents are usually less dense than water.)*

3.6 Hydrostatic Pressures

Structures submerged or partially submerged during tsunami inundation are subjected to hydrostatic pressures (see Figure 27). The net hydrostatic force in the vertical direction, the buoyancy force, is equal to the volume of the fluid displaced by the structure times the specific weight of the fluid. The buoyancy force reduces the total dead weight of a structure and therefore reduces its resistance to sliding and overturning. A difference in the hydrostatic pressures in the horizontal direction, acting on the front and back surfaces of the structure, creates a net lateral pressure force, which will also impact the stability of the structure and its resistance to movement. Figure 44 shows this failure mechanism. Figures 45 – 50 show examples of structures that failed due to this mechanism.

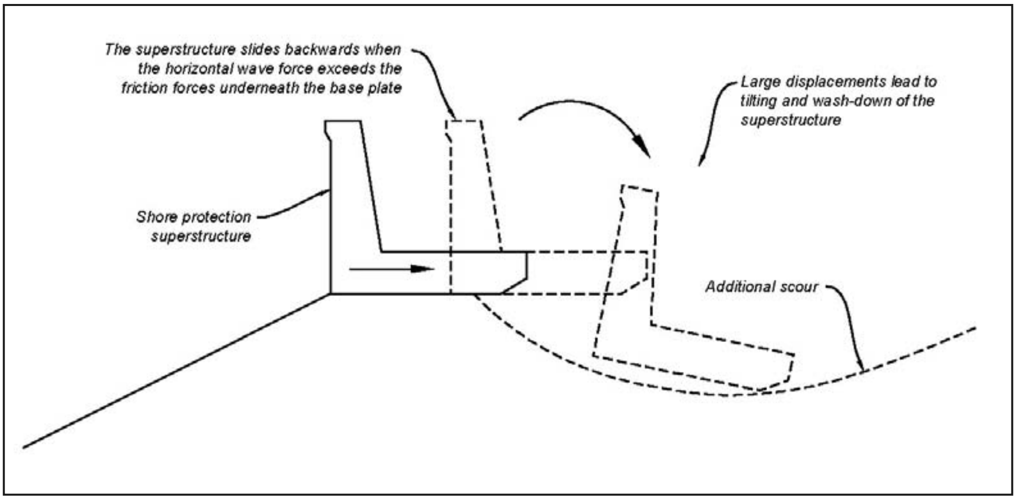

Figure 44. Structural displacement, sliding, rotation, and movement

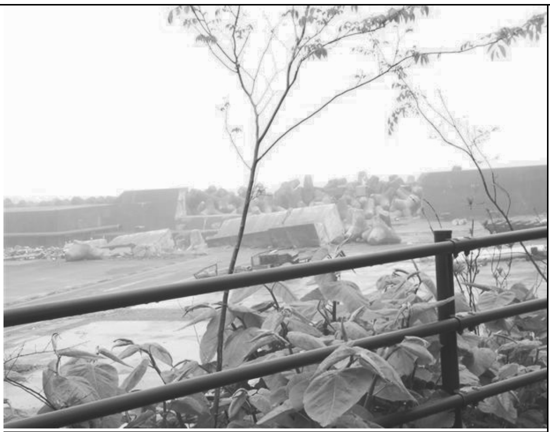

Figure 45. Otanabe (Fudai) breakwater — Caisson breakwater sections and concrete armor units moved inland off their rubble mound foundation due to combination of hydrostatic and hydrodynamic loads on seaward side

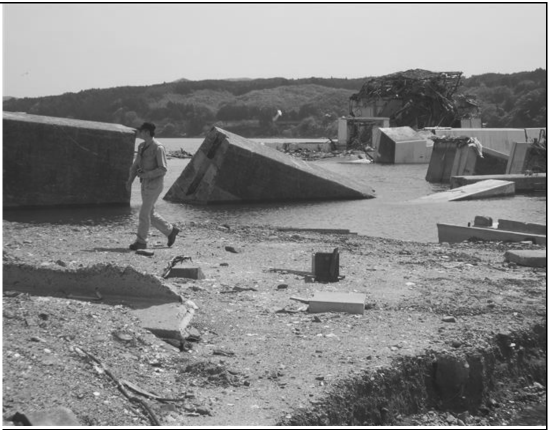

Figure 45. Otanabe (Fudai) breakwater — Caisson breakwater sections and concrete armor units moved inland off their rubble mound foundation due to combination of hydrostatic and hydrodynamic loads on seaward side

Figure 47. Natori Beach shoreline dike — Collapsed sections of seaward facing concrete paver units due to combination of hydrostatic and hydrodynamic loads on seaward side and overtopping scour of landward side

Figure 48. Natori Beach shoreline dike — Complete collapse of landward facing concrete paver units due to combination of hydrostatic and hydrodynamic loads on seaward side and overtopping scour of landward side

Figure 49. Utatsu — Effects of flow obstruction (Greater area facing flow is subject to higher hydrostatic and hydrodynamic forces.)

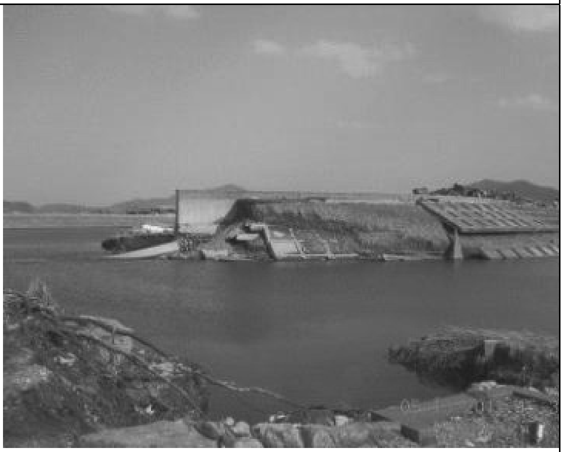

Figure 50. Otsuchi — Concrete panels removed due to flow behind wall; caused scour of earthen fill and structural failure of the wall

3.7 Supercritical Flows

Due to extremely long wave periods, tsunami waves typically appear as fast-moving turbulent bores when propagating towards the shore. Due to the immense volume of displaced water movement and the high energy involved, supercritical flows typically occur during the tsunami runup at flow obstructions such as walls and dikes, and particularly during the tsunami backrush (draw-down). This high-discharge, supercritical runup and backrush flow provides a mechanism for massive beach erosion and erosion around the foundations of coastal structures (Figures 51 – 54).