Figure 2-6 The disruption of velocity flows by large, non-breakaway objects generated extensive scour that undermined vertical foundation members and slabs-on-grade.

2.3 Building Foundation Systems

In assessing the performance of structure foundation systems, the BPAT addressed a variety of issues related to the performance of oceanfront and landward structures: piling and column embedment for structures and their extensions (e.g., utility platforms, decks, porches, and roof overhangs), the grade of lumber used for vertical foundation members, elevation of structures in relation to the flood depth, cross-bracing of vertical support members, and solid perimeter foundation walls on continuous footings. The BPAT also assessed the performance of foundations under manufactured homes and permanently installed RVs.

2.3.1 Piling Embedment for Structural Support

Lack of sufficient embedment of vertical structural foundation members may well have contributed to the collapse of over 100 oceanfront residential buildings (see Figure 2-7). Of those that did not collapse, many were found to be leaning (see Figure 2-8). The majority of these structures met the pre-1986 requirement for an 8-foot embedment of pilings and columns (measured from existing grade). Many front-row houses were placed near or on the landward slope of the frontal dune, where the ground elevations were often 8 to 9 feet m.s.l. As a result, the bottoms of the pilings or columns were at approximately 0 feet m.s.l. (see Figure 2-9)

As noted in Section 1.3.1, the North Carolina State Building Code was revised in 1986 to require that vertical foundation members in erosion-prone areas be embedded 16 feet below existing grade or to -5 feet m.s.l., whichever is shallower. The 1986 requirement was generally successful in protecting structures in areas of low ground elevation, where pilings had to be embedded to -5 feet m.s.l. This is significant because most of the buildings undermined by

Figure 2-7 *Over 100 oceanfront houses were washed off their foundations or completely destroyed.*

Figure 2-8
Many oceanfront houses built prior to current (1986) North Carolina State Building Code requirements were found to be leaning or destroyed.

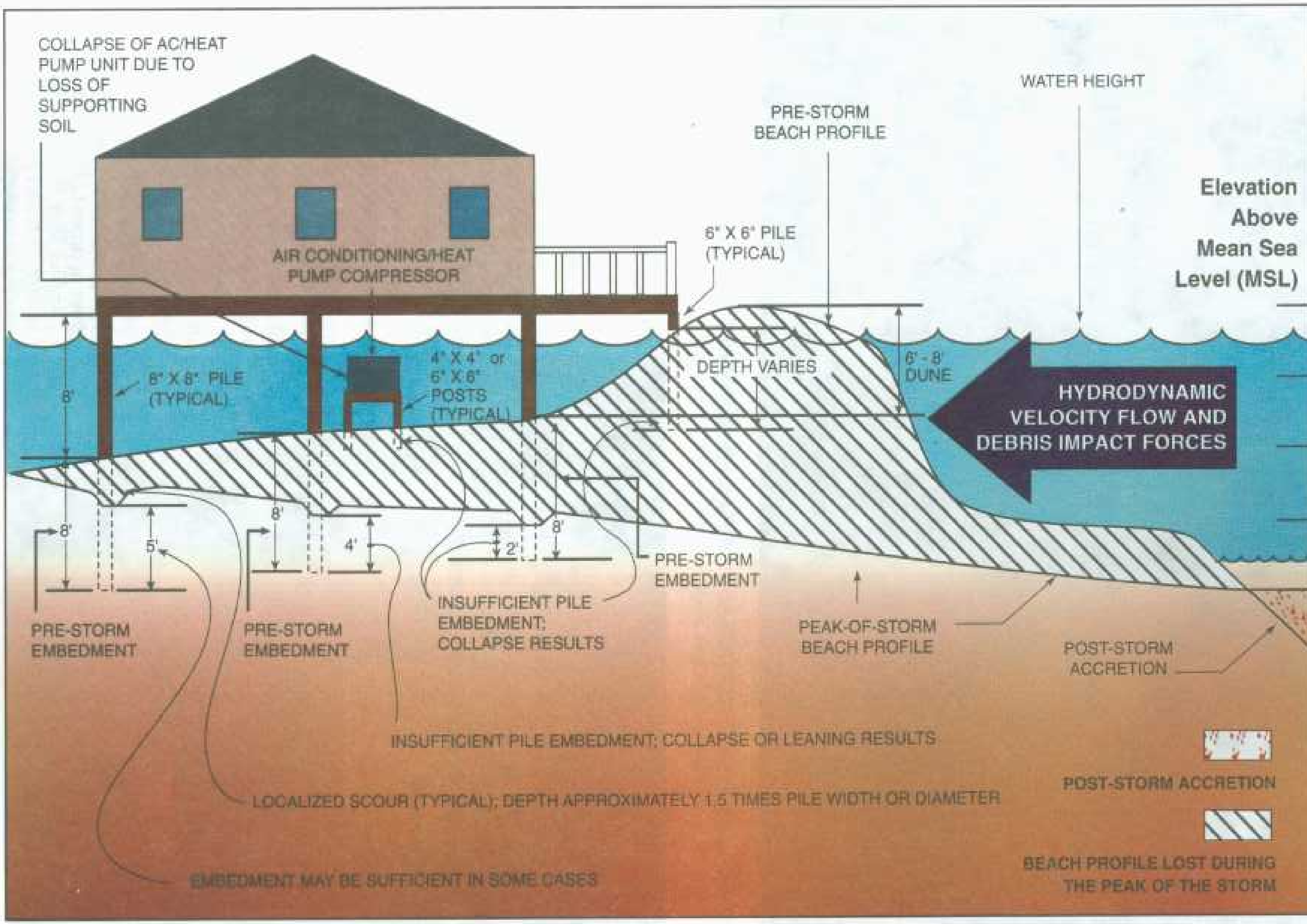

Figure 2-9 *Typical collapse mechanism of post-FIRM building based on pre-1985 embedment requirements in North Carolina coastal areas.*

erosion were in areas where the ground elevations were low. For structures on higher dunes (i.e., where ground elevations exceed 11 feet m.s.l.) the piling embedment requirement changes to only 16 feet below grade. This embedment depth is not sufficient to allow the pilings to survive a similar storm or continuing long-term erosion of moderate to high dunes.

Although post-1986 oceanfront structures generally performed better than oceanfront structures built prior to 1986, several foundations supporting oceanfront structures that were observed to be leaning were suspected of being post-1986 (see Figure 2-10). The remaining embedment depth of the foundation members beneath these structures was not determined by the BPAT; however, for example, with a pre-storm grade of 11 feet m.s.l., erosion of approximately 6 vertical feet to an elevation of approximately 5 feet m.s.l., and localized scour of an additional 1 vertical foot, the vertical foundation members should still have been embedded approximately 9 feet below grade during the height of the storm. This depth should have been sufficient to prevent leaning in many cases. One possible explanation is that the pilings under these leaning structures did not meet the current embedment depth requirement.

To follow up on this issue and investigate the effects of the current North Carolina State Building Code requirements on the performance of foundation pilings, FEMA contracted with Woodward-Clyde Federal Services (W-C) to determine piling embedment depths for oceanfront buildings on Topsail Island, North Carolina, where Hurricanes Bertha and Fran damaged a number of structures. Using aerial photographs, W-C identified 205 post-1986 oceanfront buildings. Of the identified buildings, 92 percent had not sustained any significant foundation damage. The remainder had pilings that were damaged or leaning. W-C conducted tests to determine the embedment depths of selected pilings under 11 of the identified buildings,

Figure 2-10 *One of several buildings observed to be leaning landward that were suspected of having been constructed to current North Carolina State Building Code requirements.*

including 7 leaning buildings, and found that over 80 percent of the tested pilings did not meet the 1986 embedment requirement. The testing procedure and the findings are presented in a separate report prepared by W-C. The Executive Summary from the W-C report is contained in Appendix C of this report. Recommendations based on W-C's findings are presented in Section 3.1.1.

2.3.2 Piling Embedment for Decks, Porches, and Roof Overhangs

Lack of sufficient embedment of vertical foundation members for decks, porches, and roof overhangs attached to oceanfront and landward residential buildings resulted in the collapse of several hundred of these building extensions (see Figure 2-11).

Oceanfront Residential Buildings

Vertical foundation members supporting unroofed decks did not have to meet the pre-1986 State Building requirement for 8-foot piling embedment, nor do they have to meet the post-1986 requirement for 16-foot embedment. Vertical foundation members for covered porches and roof overhangs are supposed to meet the criterion applied to the foundation members for the main structure. The BPAT found that vertical foundation members for decks, porches, and roof overhangs were often embedded to a depth of only 2 to 6 feet below existing grade (see Figure 2-12).

Decks, porches, and roof overhangs were often built on the seaward side of oceanfront structures and were therefore often embedded into the frontal dune (see Figure 2-9). With embedments of only 2 to 6 feet into the dune, the bottoms of the pilings or columns were often at elevations of 4 to 8 feet m.s.l. The remaining embedment depth of those deck, porch, and roof overhang supports that survived the hurricane appears to be as little as 1 to 2 feet in many cases.

Figure 2-11 *The BPAT observed several hundred decks and porches that collapsed as a result of insufficient foundation support.*

Figure 2-12 *Example of building constructed to current North Carolina State Building Code requirements with insufficient embedment of piles/columns under two-story deck.*

Figure 2-13 *Embedment of deck supports into frontal dune was often shallow. After erosion of the dune, the bottom of the support for this deck was left several feet above grade.*

Since these supports are usually seaward of main structures, they are subject to amounts of storm surge, velocity flow, wave action, vertical erosion, and localized scour at least as great as those that affect the main structure (see Figure 2-13).

In the areas where decks, porches, and roof overhangs were observed, erosion was approximately 7 vertical feet, to an elevation of approximately 4 feet m.s.l. Localized scour of an additional vertical foot would result in total loss of embedment to an elevation of 3 feet m.s.l. during the peak of the storm (see Figure 2-9). When vertical foundation members lost their ability to support the structure above, the deck, porch, or roof overhang often collapsed, damaging the structure to which it was attached and becoming waterborne debris that was then carried into the main structure or nearby structures (see Figure 2-14). This damage may have contributed to the collapse of some buildings.

For decks, porches, and roof overhangs to have survived, their supporting vertical members would have to have had a post-storm embedment of approximately 8 feet below grade. The findings of the team regarding decks, porches, and roof overhangs are particularly important because it appears that the construction of multilevel decks and porches supporting roof overhangs is becoming increasingly popular in oceanfront architecture (see Figure 2-15). Usually, these building extensions are larger and more complex than required solely for building access.

LANDWARD RESIDENTIAL BUILDINGS

Decks, porches, and roof overhangs supported by vertical foundation members were observed to have been installed on many landward homes on barrier islands. In general, these building extensions were not protected from localized scour caused by velocity flow. The loss of

Figure 2-14 Storm-generated debris impacted nearby structure.

Figure 2-15 As shown by this post-Fran photograph taken at Figure Eight Island, North Carolina, a current architectural trend is the construction of multistory decks supporting roof overhangs.

supporting soil due to scour often left vertical foundation members of decks, porches, and roof overhangs unable to resist the velocity flow, wave action, and debris impact forces that occurred in coastal areas (see Figure 2-16). Vertical foundation members were found to not be embedded to the same depth as the main building supports. It was reported that the North Carolina State Building Code requires vertical supports for the main structure outside of a V Zone to be embedded 8 feet below existing grade, but that no such requirement was enforced for building extensions such as decks and, in some instances, porches and roof overhangs.

2.3.3 Debris Impact on Vertical Foundation Members

Debris observed by the BPAT included 8-inch x 8-inch pilings up to 20 feet long (see Figure 2-14), round 6-inch diameter posts, septic tank sections (see Figure 2-17), materials from collapsed adjacent houses, the remains of collapsed decks (from the house impacted and from adjacent and other nearby oceanfront houses — see Figure 2-18), and portions of collapsed fishing piers. An extreme example of debris impact is shown in Figure 2-19. Although debris impact generally was not suspected of causing significant failure of vertical foundation members, it did damage foundation cross-bracing, as discussed in Section 2.3.6.

2.3.4 Grade of Lumber Used for Timber Pilings and Cross-Bracing

To resist coastal flood forces, timber pilings depend largely on their dimensions and depth of embedment, but another important factor is the grade of lumber used. Lower grades of lumber may have knots, cracks, or other imperfections that contribute to failure when the piling is acted on by water and debris impact forces. For example, Figure 2-20 shows a failed timber

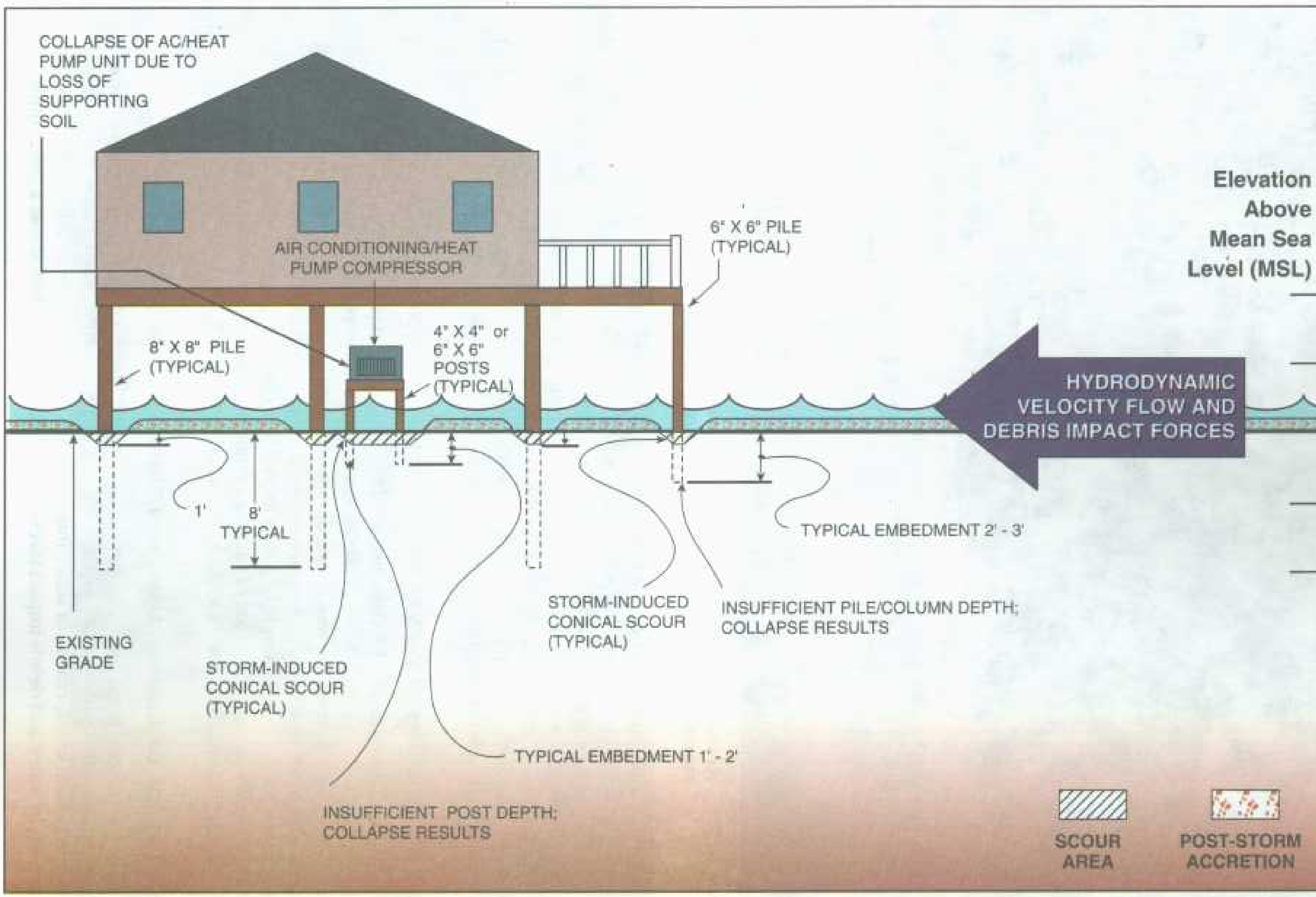

Figure 2-16 *Typical failure of deck / roof overhang and air conditioning / heat pump compressor platform for landward home.*