Erosion, Scour, and Foundation Design

FEMA
http://www.fema.gov

HURRICANE IKE RECOVERY ADVISORY

Purpose: To discuss how any lowering of the ground surface can affect the ability of a building foundation to resist design loads, and to provide additional guidance for coastal foundation design.

Key Issues

Erosion refers to a general lowering of the ground surface over a wide area.

Scour refers to a localized loss of soil, often around a foundation element.

- Coastal buildings are often subject to flood loads and conditions that do not affect inland buildings. These include waves, high velocity storm surge flow, floodborne debris, and **erosion** and **scour**. This Recovery Advisory will focus on erosion and scour. See FEMA 499, *Home Builder's Guide to Coastal Construction* (2005), Fact Sheets 11 through 15 at: http://www.fema.gov/library/viewRecord.do?id=1570, and FEMA 55, *Coastal Construction Manual* (2000) at: http://www.fema.gov/library/viewRecord.do?id=1671 for discussion of other foundation issues.
- Foundations must transfer all loads imposed on the building into the ground. If the foundation is not strong enough or deep enough to do this, the building will be destroyed. If the foundation embedment into the ground is not sufficient to account for erosion and scour that may occur over the life of the building, the building is vulnerable to collapse under design flood and wind conditions.
- Predicting the incidence, location, and magnitude of coastal erosion and scour is difficult, and present-day building codes and standards do not prescribe clear-cut solutions for designers. Therefore, designers should be conservative with their foundation designs. This means foundations may need to be stronger, deeper, and higher than what has historically been used. Lessons learned from Hurricane Ike and other recent coastal storm events should be incorporated into foundation designs.

Erosion and Scour Basics

Erosion is defined by the International Building Code® (ICC, 2006) as the "wearing away of the ground surface as a result of the movement of wind, water or ice." Section 7.5 of FEMA's *Coastal Construction Manual* describes erosion as "the wearing or washing away of coastal lands." Since the exact configuration of the soil loss is important for foundation design purposes, a more specific definition is used in this Recovery Advisory (see text box and Figure 1).

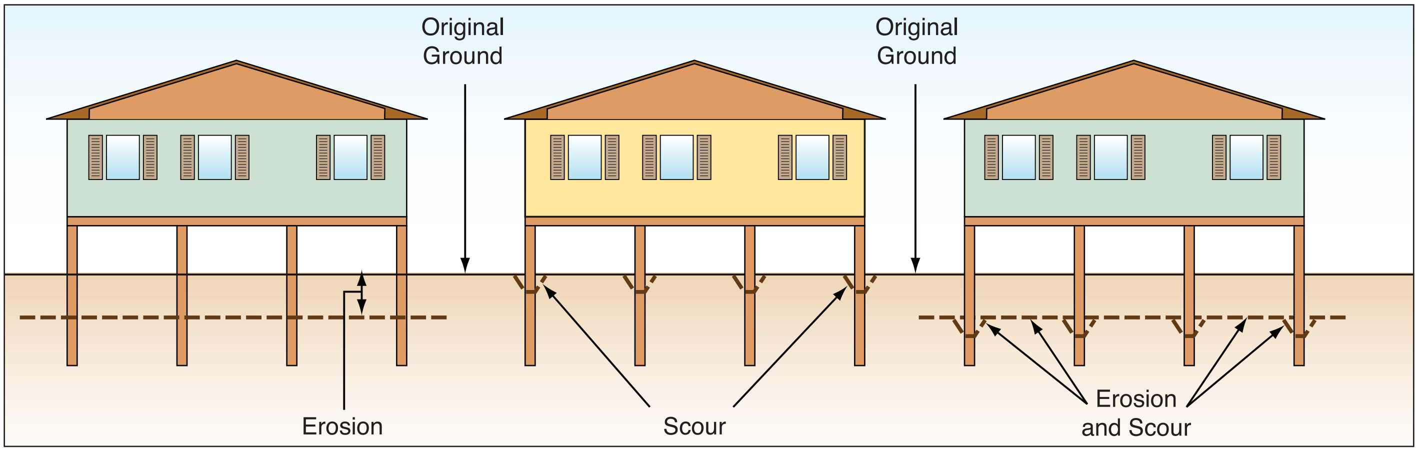

Figure 1. Distinguishing between coastal erosion and scour. A building may be subject to either or both, depending on the building location, soil characteristics, and flood conditions.

Erosion can occur across a wide range of timeframes – it can be gradual, occurring over a long period of time (many years); more rapid, occurring over a relatively short period of time (weeks or months); or episodic, occurring during a single coastal storm event over a short period of time (hours or days). Figure 2 shows the result of erosion occurring over a long timeframe – buildings that were formerly on upland property, but now stand on the active beach. Figure 3 shows episodic erosion that occurred during Hurricane Ike. In both cases, the recession of the shoreline resulted in a horizontal translation of the beach profile and a lowering of the ground elevation under and near the affected buildings. The closer a building is to the shoreline, the more likely erosion will occur and the greater the erosion depth will be.

Scour occurs when floodwater passes around obstructions in the water column. As the water flows around an object, it must change direction and accelerate. Soil can be loosened and suspended by this process or by waves striking the object, and be carried away. Pilings, pile caps, columns, walls, footings, slabs, and other objects found under a coastal building can lead to localized scour. Scour effects increase with increasing flow velocity and turbulence, and with increasing soil erodibility.

Scour effects are generally **localized**, ranging from small, shallow conical depressions in the sand around individual piles (Figure 4) to larger and deeper depressions around individual piles (Figure 5), to a building-sized shallow depression around a group of piles (Figure 6), to a large and deep depression around a building foundation (Figure 7). Scour depressions like that shown in Figure 7 were observed frequently following Hurricane Ike, and many of these reportedly were 6 to 10' deep and required hundreds of cubic yards of soil to fill. The presence of large, non-frangible concrete slabs and deep grade beams under the buildings may be a contributing factor to the large local scour depressions observed.

In some cases, buildings may settle due to inadequate pile embedment, coupled with some combination of erosion, scour, and soil liquefaction that leads to loss of bearing. This type of failure was observed by the Huricane Ike FEMA Mitigation Assessment Team (MAT) at Surfside Beach, TX (Figure 8) and Holly Beach, LA.

Figure 2. Long-term erosion has caused the shoreline to retreat and has left homes standing on the beach (Surfside Beach, TX). July 2007 Texas General Land Office photo.

Figure 3. Storm-induced erosion beneath an elevated coastal building (Galveston Island, TX, Hurricane Ike).

Figure 4. Local scour around foundation piles (Pensacola Beach, FL, Hurricane Ivan).

Figure 5. Local scour around foundation piles (Holly Beach, LA, Hurricane Ike).

Figure 6. Local scour around a 3rd row house's pile foundation (Bolivar Peninsula, TX, Hurricane Ike).

Figure 7. Extreme local scour around a Gulf-front pile foundation (Bolivar Peninsula, TX, Hurricane Ike).

Figure 8. Differential settlement of buildings thought to be a result of inadequate foundation embedment coupled with erosion, scour, and/or soil liquefaction (Surfside Beach, TX, Hurricane Ike).

Figure 9. Linear scour and erosion patterns aligning with canals and roads (Bolivar Peninsula, TX, Hurricane Ike).

There is one other erosion and scour scenario to consider in foundation design – the loss of soil around or under a building as a result of storm surge flow being channeled or directed across a building site. This process usually takes place where storm surge flow is constrained between large buildings or gaps in shore protection, or when return flow to the sea follows paths of least resistance, such as along canals and roads (Figure 9).

Erosion and Scour – Impacts on Foundations

Erosion and scour have several adverse impacts on coastal foundations:

- Erosion and scour reduce the embedment of the foundation into the soil, causing shallow foundations to collapse and making buildings on deep foundations more susceptible to settlement, lateral movement, or overturning from lateral loads.
- Erosion and scour increase the unbraced length of pile foundations, increase the bending moment to which they are subjected, and can overstress piles.
- Erosion over a large area between a foundation and a flood source exposes the foundation to increased lateral flood loads (i.e., greater stillwater depths, possible higher wave heights, and higher flow velocities).
- Local scour around individual piles or a building foundation will not generally expose foundations to greater flood loads, but linear scour across a building site may do so.

Resisting *higher bending moments* brought about by erosion and scour may necessitate a larger pile cross-section or decreased pile spacing (i.e., more piles) or, in some cases, use of a different pile material (e.g., concrete or steel instead of wood). Resisting increased lateral flood loads brought about by erosion (and possibly by linear scour) would necessitate a similar approach. However, designers must remember that increasing the number of piles or increasing the pile diameter will, in turn, also increase lateral flood loads on the foundation.

Resisting *increased unbraced lengths* brought about by erosion and scour will require additional embedment of the foundation into the ground.

To illustrate these points, calculations were made to examine the effects of erosion and scour on foundation design for a simple case – a 32' x 32', two-story house (10' story height), situated away from the shoreline and elevated 8' above grade on 25 square timber piles (spaced 8' apart), on medium dense sand. The house was subjected to a design wind event with a 130-mph (3-second gust) wind speed and a 4' stillwater depth above the uneroded grade, with storm surge and broken waves passing under the elevated building. Lateral wind and flood loads were calculated in accordance with ASCE/SEI 7-05 *Minimum Design Loads for Buildings and Other Structures* (model codes and related prescriptive standards, such as the International Building Code (IBC), the International Residential Code® (IRC®), and ICC-600 *Standard for Residential Construction in High Wind Areas*, are based on ASCE 7 loads). For this illustration, the piles were analyzed under lateral wind and flood loads only; dead, live and wind uplift loads were neglected. If these neglected loads are included in the analysis, deeper pile embedment and possibly larger piles may be needed.

Three different timber pile sizes (8" square, 10" square, and 12" square) were evaluated using pre-storm embedment depths of 10', 15', and 20', and five different erosion and scour conditions (Erosion = 0' or 1'; Scour ranges from 2.0 times the pile diameter to 4.0 times the pile diameter). The results of the analysis are shown in Table 1. A shaded cell indicates the combination of pile size, pre-storm embedment, and erosion/scour does not provide the bending resistance and/or embedment required to resist lateral loads. The reason(s) for a foundation failure is indicated in each shaded cell, using "P" for failure due to bending and overstress within the pile and "E" for an embedment failure from the pile/soil interaction. An unshaded cell with "OK" indicates bending and foundation embedment criteria are both satisfied by the particular pile size/pile embedment/erosion-scour combination.

Table 1. Example foundation adequacy calculations for a two-story house supported on square timber piles and situated away from the shoreline, storm surge and broken waves passing under the building, 130-mph wind zone, soil = medium dense sand. Shaded cells indicate the foundation fails to meet bending (P) and/or embedment (E) requirements.

Pile Embedment Before Erosion and Scour	Erosion and Scour Conditions	Pile Diameter, a		
		8 inch	10 inch	12 inch
10 feet	**Erosion = 0, Scour = 0**	**P, E**	**E**	**OK**
	Erosion = 1 foot, Scour = 2.0 a	**P, E**	**E**	**E**
	Erosion = 1 foot, Scour = 2.5 a	**P, E**	**E**	**E**
	Erosion = 1 foot, Scour = 3.0 a	**P, E**	**E**	**E**
	Erosion = 1 foot, Scour = 4.0 a	**P, E**	**P, E**	**E**
15 feet	**Erosion = 0, Scour = 0**	**P**	**OK**	**OK**
	Erosion = 1 foot, Scour = 2.0 a	**P**	**OK**	**OK**
	Erosion = 1 foot, Scour = 2.5 a	**P**	**OK**	**OK**
	Erosion = 1 foot, Scour = 3.0 a	**P**	**OK**	**OK**
	Erosion = 1 foot, Scour = 4.0 a	**P, E**	**P, E**	**E**
20 feet	**Erosion = 0, Scour = 0**	**P**	**OK**	**OK**
	Erosion = 1 foot, Scour = 2.0 a	**P**	**OK**	**OK**
	Erosion = 1 foot, Scour = 2.5 a	**P**	**OK**	**OK**
	Erosion = 1 foot, Scour = 3.0 a	**P**	**OK**	**OK**
	Erosion = 1 foot, Scour = 4.0 a	**P**	**P**	**OK**

Review of the table shows several key points:

- Increasing pile embedment will not offset foundation inadequacy (bending failure) resulting from too small a pile cross-section or too weak a pile material.
- Increasing pile cross-section (or material strength) will not compensate for inadequate pile embedment
- Given the building and foundation configuration used in the example, the 8" square pile is not strong enough to resist the lateral loads resulting from the 130-mph design wind speed under any of the erosion and scour conditions evaluated, even if there is no erosion or scour. Homes supported by 8" square timber piles, with embedment depths of 10' or less, will likely fail in large numbers when subjected to design or near-design loads and conditions. Homes supported by deeper 8" piles may still be lost during a design event due to pile (bending) failures
- The 10" square pile is strong enough to resist bending under all but the most severe erosion and scour conditions analyzed.
- The 12" pile is the only pile size evaluated that satisfies bending requirements under all erosion and scour conditions analyzed. The 12" pile works with 10' of embedment under the no erosion and scour condition. However, introducing as little as 1' of erosion, and scour equal to twice the pile diameter, was enough to render the foundation too shallow.
- 15' of pile embedment is adequate for both 10" and 12" piles subject to 1' of erosion and scour up to three times the pile diameter. However, when the scour is increased to four times the pile diameter (frequently observed following Hurricane Ike), 15' of embedment is inadequate for both piles. In general terms, approximately 11' of embedment is required in this example house to resist the loads and conditions after erosion and scour are imposed.
- The 12" pile with 20' of embedment was the only foundation that worked under all erosion and scour conditions analyzed. This pile design may be justified for the sample house analyzed when expected erosion and scour conditions are unknown or uncertain.

WARNING

The results in Table 1 should not be used in lieu of building- and site-specific engineering analyses and foundation design. The table is for illustrative purposes only and is based upon certain assumptions and simplifications, and for the combinations of building characteristics, soil conditions, and wind and flood conditions described above. Registered design professionals should be consulted for foundations designs.

NFIP and Building Code Requirements

One of the requirements of **Section 60.3(a)(3)** of the NFIP regulations that applies to all flood hazard zones (V, VE, V1-30, A, AE, A1-30, AO, AH, etc.) within the Special Flood Hazard Area (SFHA) is:

> "If a proposed building site is in a flood-prone area, all new construction and substantial improvements shall be designed (or modified) and adequately anchored to prevent flotation, collapse, or lateral movement of the structure resulting from hydrodynamic and hydrostatic loads, including the effects of buoyancy."

A requirement in **Section 60.3(e)(4)** states that all new construction and substantial improvements in V zones must be elevated on pilings and columns so that:

> "(i) the bottom of the lowest horizontal structural member of the lowest floor (excluding the pilings or columns) is elevated to or above the base flood level; and
>
> (ii) the pile or column foundation and structure attached thereto is anchored to resist flotation, collapse and lateral movement due to the effects of wind and water loads acting simultaneously on all building components.
>
> Water loading values used shall be those associated with the base flood. Wind loading values used shall be those required by applicable State or local building standards. A registered professional engineer or architect shall develop or review the structural design, specifications and plans for the construction, and shall certify that the design and methods of construction to be used are in accordance with accepted standards of practice for meeting the provisions of paragraphs (e)(4)(i) and (ii) of this section."

The International Residential Code (2006) has similar requirements:

> "**R324.1.1 [Flood Resistant Construction] Structural systems**. All structural systems of all buildings and structures shall be designed, connected and anchored to resist flotation, collapse or permanent lateral movement due to structural loads and stresses from flooding equal to the design flood elevation.
>
> **R324.3.3 [Coastal high-hazard areas] Foundations**. All buildings and structures erected in coastal high-hazard areas shall be supported on pilings or columns and shall be adequately anchored to such pilings or columns. Pilings shall have adequate soil penetration to resist the combined wave and wind loads (lateral and uplift). Water loading values used shall be those associated with the design flood. Wind loading values used shall be those required by this code. Pile embedment shall include consideration of decreased resistance capacity caused by scour of soil strata surrounding the piling. Pile systems design and installation shall be certified in accordance with Section R324.3.6. Mat, raft or other foundations that support columns shall not be permitted where soils investigations that are required in accordance with Section R401.4 indicate that soil material under the mat, raft or other foundation is subject to scour or erosion from wave-velocity flow conditions.
>
> Buildings and structures, and all parts thereof, shall be constructed to support safely all loads, including dead loads, live loads, roof loads, flood loads, snow loads, wind loads and seismic loads as prescribed in this code. The construction of buildings and structures shall result in a system that provides a complete load path capable of transferring all loads from their point of origin through the load-resisting elements of the foundation."

Thus, designers are responsible for ensuring that a foundation for a building in any flood hazard area must be adequate to support a building under applicable design loads and load combinations. Designers must consider the effects of erosion and scour when foundations are designed. Designers must certify the foundations.

There may also be other (State or local) foundation design and certification requirements.

Erosion and Scour Design Guidance

Given that the design requirements listed above are performance requirements, designers must translate those into practice. This can be difficult with respect to estimating erosion and scour conditions at a particular site, since definitive guidance for estimating coastal erosion and scour is not present in building codes and standards.

FEMA's *Coastal Construction Manual* (FEMA, 2000) provides some information and guidance, but even this should be considered preliminary and subject to improvement as we learn more from post-storm investigations. The pertinent CCM sections and guidance are summarized below:

> *CCM* Section 7.5: this section summarizes the causes of erosion, its impacts on coastal lands and buildings, and how it is measured. Section 7.5.2.5 discusses local scour. One key point is a procedure outlined in the note on page 7-28 and illustrated in *CCM* Figure 7-66 – three steps that a designer should use to estimate future ground elevations and flood conditions at a site:
>
> > Step 1: determine the most landward shoreline location expected during the life of the building
> >
> > Step 2: define the lowest expected ground elevation during the life of the building
> >
> > Step 3: define the highest expected BFE during the life of the building
>
> *CCM* Section 7.8.1.4 discusses FEMA's current procedures for estimating storm-induced erosion.

Designers in Texas and Louisiana can obtain erosion data and other related information from various state agencies (see References).

> *CCM* Section 7.9.2 discusses how designers can update an obsolete flood hazard description for a site by accounting for long-term (Step 1 above) and storm-induced erosion (Step 2 above). *CCM* Figure 7-67 (Figure 10) provides an example, illustrating the use of published long-term erosion information and simple storm erosion calculations to estimate future ground elevations at a building site.
>
> *CCM* Section 11.6.11 discusses local scour and presents a simple method for calculating erosion around a single pile. The method predicts the depth of a scour depression below the eroded ground elevation

is equal to 2.0 times the pile diameter, unless non-erodible soil lies beneath the ground surface (Figure 11).

Designers should use the CCM scour depth relationship (Smax = 2.0 a) with caution. Observations after Hurricane Ike showed scour exceeded twice the pile diameter at many locations. This could have been due to deeper scour depths around entire pile foundations (Figures 6 and 7), or to the presence of concrete slabs and deep grade beams that channeled flow between the bottom of the slab and the soil, or to other factors. Given the uncertainty over the exact cause of local scour during Hurricane Ike, foundation designs for reconstruction along the Gulf shoreline should be very conservative, and an assumed scour depth of 6 to 8' would not be unreasonable. Designers should investigate local soils and Hurricane Ike-induced scour at nearby locations before selecting a scour depth. Post-hurricane aerial photographs, such as those obtained after Hurricane Ike by NOAA and USGS (see References) will provide a good source of data for designers.

The *CCM* mentions linear scour channels occurring between large buildings or in-line with roads, canals, and drainage features (see *CCM* Section 8.3.2), but does not provide design guidance for estimating linear scour depths. As was the case with local scour, designers should utilize post-hurricane data when they estimate linear scour likelihood and depth.

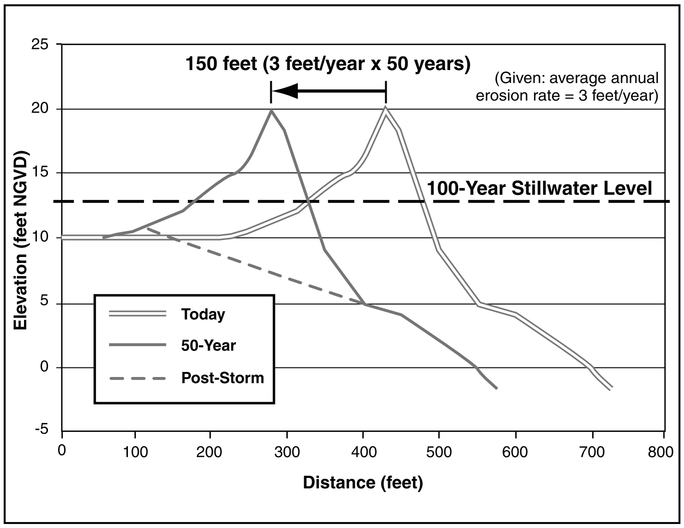

Figure 10. CCM Figure 7-67 illustrating a simple procedure to account for long-term erosion and storm erosion.

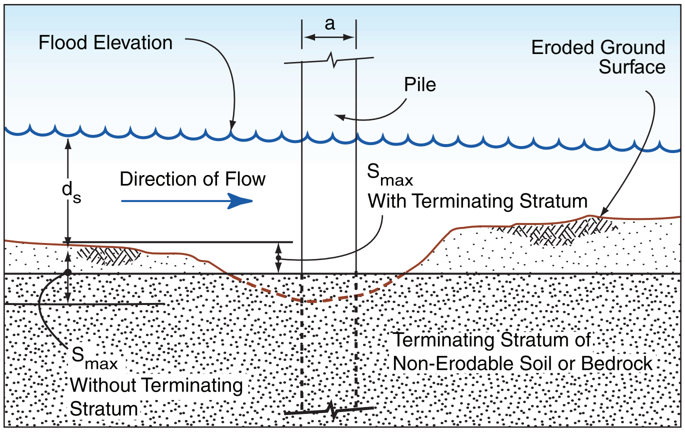

Figure 11. CCM Figure 11-12 illustrating scour estimate around a single pile – Hurricane Ike showed this method may underestimate local scour.

Existing Homes: Are the Pile Foundations Adequate?

The owner of an existing home may wonder whether the pile foundation is adequate to withstand erosion and scour during a design event. The builder or building official may have permit records, building plans, or foundation design information for the house, or may be able to provide information about typical design requirements, construction practices, and probable pile embedment depths for houses of the same age. A licensed engineer can perform an inspection of the foundation, provide information about non-destructive testing methods to determine pile embedment depth, review available foundation data, and analyze the foundation.

References

ASCE. 2005. *Minimum Design Loads for Buildings and Other Structures*. ASCE/SEI 7-05.

FEMA. 2000. *Coastal Construction Manual*, 3rd ed. FEMA 55.

FEMA. 2005. *Home Builder's Guide to Coastal Construction*. FEMA 499. See http://www.fema.gov/library/viewRecord.do?id=1570

ICC 2006. International Building Code.

ICC 2006. International Residential Code with 2007 Supplement.

ICC 2008. *Standard for Residential Construction in High Wind Areas*. ICC 600.

Louisiana Department of Natural Resources. 2008. Coastal Restoration and Management data and reports. See http://dnr.louisiana.gov/crm/

NOAA. 2008. Post-Ike aerial photographs. See http://ngs.woc.noaa.gov/ike/index.html

Texas Bureau of Economic Geology. 2008. Coastal Studies Program data and reports. See http://www.beg.utexas.edu/coastal/coastal01.htm

USGS. 2008. Post-Ike aerial photographs and data. See http://coastal.er.usgs.gov/hurricanes/ike/