A Case Study of the Impact of Wind and Wave Action on Floating Dock Anchorage Systems on Lake Brownwood, Texas

David C. Jones, B.S., P.E., M.ASCE[1]
Marco A. DeLeon, M.E., P.E., M.ASCE[2]
Matthew L. Breidenthal, M.S., P.E., S.E., M.ASCE[3]
Kurt W. Cady, M.E., P.E., S.E.[4]

[1] Branch Director, Nelson Architectural Engineers, Inc., 5901 Peachtree Dunwoody Road N.E., Suite C-35, Atlanta, Georgia 30328; phone: 678-350-2378; email: djones@architecturalengineers.com

[2] Vice President of Research and Development, Nelson Architectural Engineers, Inc., 2740 Dallas Parkway, Suite 220, Plano, Texas 75093; phone: 469-429-9000; email: mdeleon@architecturalengineers.com

[3] Senior Project Director, Nelson Architectural Engineers, Inc., 5901 Peachtree Dunwoody Road N.E., Suite C-35, Atlanta, Georgia 30328; phone: 678-350-2378; email: mbreidenthal@architecturalengineers.com

[4] Project Director, Nelson Architectural Engineers, Inc., 5901 Peachtree Dunwoody Road N.E., Suite C-35, Atlanta, Georgia 30328; phone: 678-350-2378; email: kcady@architecturalengineers.com

ABSTRACT

Lake Brownwood is a 7,300-acre reservoir located in the center of Texas, created by a dam on the Pecan Bayou, a tributary of the Colorado River. The shoreline of the lake and its three islands consists of approximately 90 miles of recreational waterfront property with nearly 1,000 floating dock structures. The dock structures at Lake Brownwood are similar in construction to those found at many lakes throughout the United States.

This paper will discuss structural forensic investigations of twenty-two floating dock structures damaged by straight-line winds that occurred on May 8, 2009. Over half of the recreational dock structures on Lake Brownwood were damaged during this severe weather event. The primary focus of the case study will be the anchorage systems employed by the dock structures and an evaluation of their effectiveness in resisting dynamic wind and wave conditions associated with open-water exposure of large lakes.

This paper will address common deficiencies of the observed anchorage systems, propose reinforcement of existing systems, and present a new paradigm for anchorage systems to improve the performance of future floating dock structures.

INTRODUCTION

Weather event on May 8, 2009

On May 8, 2009, between 7:15pm and 8:55pm, strong to severe thunderstorms moved through the Lake Brownwood area, producing hail up to 1.75 in in diameter, approximately 2.5 in of rain, and wind gusts up to 69 mph (CompuWeather, 2009). The thunderstorms caused extensive damage, including destroyed docks, sunken boats, and downed trees. The lake was closed to recreational use for two weeks in order to accommodate cleanup of storm-related debris (Emison, 2009).

During the storm event, Brownwood Regional Airport (KBWD), located approximately 5 to 10 miles southeast of the investigated docks, recorded wind speed and directionality data as indicated in **Figure 1**. A substantial change in wind direction – from 150° (SSE) to 70° (ENE) to 130° (SE) – occurred from 7:35pm to 8:55pm. A maximum wind gust speed of 69 mph, from the east-northeast, was recorded at 8:18pm (Weather Underground, 2009).

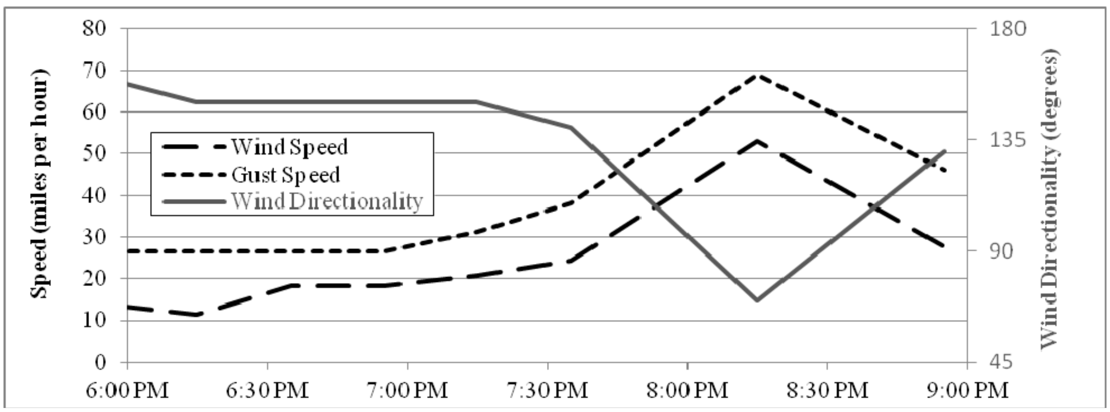


Figure 1. Wind speed and directionality at KBWD airport, evening of May 8, 2009 (Weather Underground, 2009).

Forensic investigation of 22 floating dock structures

The authors conducted investigations of 22 dock failures that were purportedly caused by the weather event of May 8, 2009. The evaluated dock structures were disbursed around Lake Brownwood, with directional exposures varying from north-northwest (335°) to east (90°) to south-southwest (200°). Most dock locations were exposed to an easterly wind, resulting in westward lateral displacements. Many of the dock locations were exposed to fetch distances located east of the structures.

LAKE BROWNWOOD TYPICAL DOCK CONSTRUCTION

Docks constructed around Lake Brownwood typically consisted of four major elements: a free-floating dock, an anchorage system that secured the floating dock, a gangway that allowed access to the floating dock, and a land-based pier or fixed landing that supported and provided access to the gangway. These common elements are represented diagrammatically in **Figure 2**.

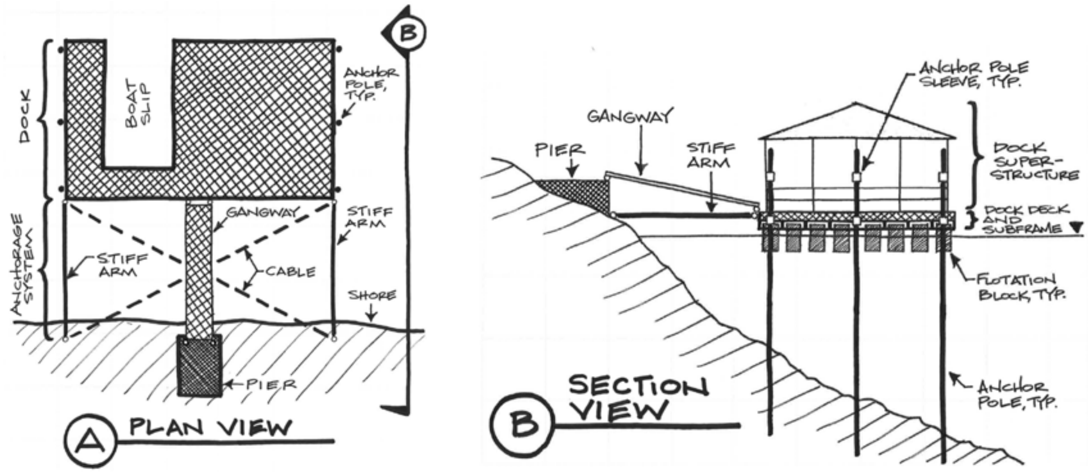


Figure 2. Typical dock components. *Note: not all of these components are present for each anchorage system type.*

For the purposes of discussion and comparison, the 22 docks were divided into five categories based on their anchorage systems. The five categories are presented below, with the number per group and associated percentage in parentheses, and in **Table 1**:

A. Laterally-fixed gangway (1; 4.5%)
B. Laterally-fixed gangway with one laterally-fixed stiff-arm (7; 32%)
C. Laterally-fixed gangway with two or three laterally-fixed stiff-arms (8; 36%)
D. Embedded anchor poles (5; 23%)
E. Cables with two stiff-arms (1; 4.5%)

The stiff-arms and gangways for docks in groups A, B, C, and E typically spanned 20 ft to 40 ft between the dock and their onshore anchorage.

<u>Floating Docks</u>
The floating dock structures reviewed on Lake Brownwood generally consisted of a plank deck constructed over a rigid, steel sub-frame supported by either exposed or encapsulated flotation blocks. The deck area of the docks ranged from 276 ft^2 to 3,464 ft^2, with a majority of the docks (16) in the range of 500 to 1,500 ft^2. All 22 docks had a full or partial one-level superstructure supporting a roof and/or an upper deck. One dock had a two-story superstructure and roof. Most of the docks (14) included at least one enclosed room, ranging from a small storage closet to larger recreational or dining rooms, typically comprising up to 25% of the floor area of the dock footprint.

<u>Anchorage System Components</u>
An anchorage system is intended to resist lateral translation of a dock due to forces from wind and waves while allowing free vertical movement of the dock resulting from fluctuating water levels and wave action. The anchorage systems at the investigated docks consisted of the following components:

Anchor Pole: a long metal pole embedded into the lake bed and extending up through vertical metal pipe sleeves attached to the dock sub-frame and/or superstructure. The sleeves allow the dock to "slide" vertically relative to the pole while the bending stiffness of the pole resists lateral movement. Anchor poles are typically installed at the corners of the dock substructure.

Stiff-arm: a horizontal axial component connecting the dock to a land-based anchorage or to a structural system such as a wet truss. A stiff-arm is "pinned" at both end connections to accommodate vertical and horizontal translation of the dock. The axial stiffness of the stiff-arm provides lateral restraint parallel to the stiff-arm (perpendicular to the shoreline).

Cable: a tension component, typically angled from a fixed anchorage to the opposing corner of the floating dock. The cable acts in tension to resist lateral translation of the dock parallel to the shore and away from the shore. Other anchorage system components (such as stiff-arms or a gangway) resist translation of the dock toward the shore.

Wet Truss: an intermediate structural system that acts to supplement or replace the land-based anchorage system where the span from dry land to the dock is excessive. A wet truss is typically anchored into the lake bed near the water's edge at the typical shoreline elevation.

Gangway: a bridge-type walkway that spans between a land-based access structure (pier) and a floating dock structure. For anchor pole lateral systems, the gangway typically rests on rollers on the dock surface to allow free vertical and lateral translation between the gangway and floating dock. For stiff-arm bracing systems, the gangway is typically attached via a hinge at both ends to accommodate vertical translation of the dock, allowing the gangway to act as both a walkway and a lateral restraint.

Dock Design Challenges at Lake Brownwood

Lake Brownwood presents two challenges that impact the design of its docks: 1) a shoreline and lake bed consisting mostly of exposed bedrock, and 2) a water elevation that historically fluctuates up to 15 ft. The combination of these two parameters generally precludes the effective use of embedded anchor poles and leads to land-based anchorage systems with long spans to the floating dock structure. The rocky and steep shoreline of much of the lake complicates the construction of the land-based portion of the anchorage system. For these reasons, the typical anchorage consists of a combination of vertically-hinged and laterally-fixed stiff-arms and gangways, occasionally supplemented with diagonal cabling.

Many of the dock and anchorage structures were constructed of retired drilling pipe field-welded into dock frames, columns, roof beams, stiff-arm struts, gangway frames, and wet trusses.

IMPACTS OF WIND AND WAVE ACTION

While the flotation system supports the weight of the dock, lifted boats, equipment, and occupants, the anchorage system resists the lateral translation of the dock resulting primarily from wind and waves acting on the vertically projected surfaces of the dock structure.

Wind Effects on Dock Structures

Wind induces lateral forces on the exposed vertical surfaces of the deck framing, non-submerged flotation system, and the wall and roof surfaces of a superstructure supported by the dock structure. During severe windstorms, wind pressures acting on these surface projections can produce significant forces. Wind pressures are proportional to the square of the associated wind speed: the amount of force induced by 60 mph winds is approximately nine times greater than the force induced by 20 mph winds. The anchorage system must resist the summation of the wind forces acting on all exposed surfaces of the dock structure. Although adjacent terrain may shield a dock from wind to some degree, wind forces can come from any direction and are especially strong when approaching over open water.

Wave Effects on Dock Structures

Waves on a lake are typically generated by breaking thrust from marine transports (boat wake) or by wind. Wind-generated waves are the result of winds blowing over the water surface; the energy of the wind is transferred by friction to the water. The largest boat wake forces on a dock occur when the boat is travelling parallel to shore and the wake approaches the structure perpendicular to shore.

The propagation and characteristics of wind-generated waves are determined by wind direction, wind velocity, the duration of the wind event, water depth along the path of the wind, and the distance (fetch) of open water over which the wind directly affects the water surface. For a restricted body of water, such as Lake Brownwood, the size of wave propagation is limited by water depth and the available fetch. The restricted fetch limits the distance over which the wind can act upon the water surface before the wind runs out of fetch and the wave breaks upon the shoreline. Even for wind events with extreme wind velocities, the distance over which the wind transfers energy to the lake surface is too brief to allow wave growth substantially greater than that experienced during normal conditions. This is especially the case for high wind events such as the one that occurred on May 8, 2009, where the change in wind directionality during the highest winds restricted the wind's contribution to previous wind-wave propagation and limited the capacity of those high winds to contribute to new wind-wave propagation (Anthoni, 2000).

EFFECTIVENESS OF EXISTING ANCHORAGE SYSTEMS

The effectiveness of an anchorage system can vary significantly depending on the direction in which a lateral force is imposed onto the dock. Most land-based anchorage systems provide the greatest lateral resistance in a direction perpendicular to the shoreline since this is generally the orientation of the primary anchorage components. The most substantial wave and wind forces typically impact a dock in an onshore direction, especially for docks that are at least moderately shielded on their landward sides by topography and/or vegetation. Many anchorage systems are significantly weaker in the direction parallel to the shoreline. Therefore, the direction in which lateral forces are imposed on the structure during a severe windstorm can have a substantial impact on the performance of the anchorage system, ranging from minimal structural distress to total failure of the anchorage system and dock.

Stiff Arm and Gangway Systems

The most common anchorage systems observed at Lake Brownwood consisted of docks that were laterally restrained solely by stiff-arms and/or gangways that were installed perpendicular to the shoreline (categories A, B, and C). In these configurations, parallel-to-shore wind loads are resisted by the nominal flexural rigidity of the stiff-arm and gangway components and the nominal rotational fixity of their hinged end connections. The magnitude of stresses imposed on these components by parallel-to-shore wind forces is directly proportional to the length of the component, which varied between 20 ft and 40 ft. The resultant forces in the stiff-arm components are also magnified by the relatively close spacing of the resulting couple at their end connections. An evaluation of the wind forces and the resulting moments, couples, and stresses indicate significant stresses within the stiff-arm and gangway frames and especially at the "laterally-fixed" hinge connections at each end. Even wind forces acting at a slight angle from onshore can result in a transition from axial loads to excessive bending stresses in this anchorage configuration.

Anchor Pole System

The only reviewed anchorage system that has relatively consistent lateral capacity irrespective of the direction of lateral load or distance from shore was the anchor pole system (Category D). The magnitude of force that can be resisted by the anchor pole system is controlled by 1) the bending strength of the pole material, 2) the length of the cantilevered anchor pole from the embedment in the lake bed to the attachment of the anchor pole sleeve on the dock structure, and 3) the number of anchor poles used. Assuming that there is some uniformity of the pole layout relative to the surfaces being loaded by the wind, the dock will respond similarly under all wind directions.

Cabled System

The least commonly observed anchorage system was a cabled system with stiff-arms (Category E). This system consists of a combination of individual tension and compression components in which the tension components (cables) resist the dock's lateral translation away from shore while the compression components (stiff-arms) resist the dock's lateral translation toward shore. At least two of each type of component are incorporated into the anchorage system and one of the component types must be angled between the dock and the shoreline to resist any lateral forces directed along the shoreline. Typically, the cables are installed at an angle opposing each other while the stiff-arms are installed perpendicular to the shore to minimize their unsupported compression length. In this configuration, offshore wind forces are resisted by tension in the cables, assisted by tension in the stiff-arms, and onshore wind forces are resisted by compression in the stiff-arms only. Parallel-to-shore wind forces are resolved by the geometric configuration of the tension and compression components that creates a truss-like response to the applied forces.

Combined Anchorage Systems

Some anchorage systems can be effectively combined if the geometric relationships and anchorage mechanisms are similar. For example, cabled systems can be combined with hinged stiff-arm and/or hinged gangways if the anchorage elevations are similar for both systems. The combined system likely includes some redundancy, which is not necessarily detrimental to the overall anchorage of the dock.

At a few dock locations, anchorage systems were observed to be incorrectly combined. At one location, a cabling system was combined with an anchor pole system. At other locations, an anchor pole system was combined with a hinged stiff-arm and gangway system.

In the anchor pole anchorage system, the floating dock translates vertically without any intentional lateral translation. For this reason, the anchor pole system should not include any components with any form of connectivity at both ends, such as stiff-arms or hinged gangways. A gangway for this system is typically supported on wheels or rollers at one end to allow for shortening of the distance between dock and pier as the elevation of the dock varies with the water level. For a 25 ft gangway connected to a dock experiencing a 15 ft rise in the lake's water level, the dock would be forced up to 5 ft farther away from shore by a hinged gangway. This would induce significant bending into the vertically cantilevered poles of an anchor pole system. Instead, the gangway must be allowed to travel laterally along the deck of the floating structure as the dock translates directly upward/downward.

FORENSIC ANALYSIS OF DISTRESS MECHANISMS

Forensic evaluation of the 22 dock structures at Lake Brownwood indicated that, for most of the observed sites, the anchorage system ultimately was the origin of structural distress and, in some cases, was the only component that was damaged as a result of the storm event. Review of the reported storm conditions, Lake Brownwood attributes, dock characteristics, and anchorage geometry also indicated that wind forces acting on the projected surfaces of the dock structures were most likely the critical load condition that resulted in the observed distress. Central to this conclusion was the 80° change in the predominant wind direction from south-southeast to east-northeast at approximately the same time as the highest recorded wind speeds. Additional information regarding directional displacement and statements from eye witnesses corroborated these conclusions.

Investigation revealed nominal wind-related distress to the dock structures, with the exceptions of minor roof damage, flotation loss or damage, and impact damage from floating debris. The majority of distress to the floating docks was related to impact with the shore following failure of the anchorage systems and the resulting displacement of the docks.

COMMON DEFICIENCIES OF ANCHORAGE SYSTEMS

The most common deficiency of the observed anchorage systems was the deteriorated condition of the steel components from aging, corrosion, lack of a protective coating, modifications, and deferred maintenance. Many of the system anchors were composed of steel pipe with nominal protection from corrosion, embedded vertically in cast-in-place concrete foundations or the exposed bedrock of the shoreline, or driven into the lakebed, depending on the water level and shore profile. These conditions resulted in progressive failure of cored bedrock or foundations, embedded pipe anchors, steel pipe hinges, and stiff-arm connections. Very seldom was there any evidence of global buckling of compression struts or frames.

The second most common failure mechanism was the hinged connection at both ends of the stiff-arm and gangway elements. The development of large bending moments due to lateral wind forces acting at the end of relatively long moment arms resulted in failure of the hinge connector plates, the hinge pin, or the connection of the strut to the hinge. Subsequent loss of the lateral fixity of the strut element resulted in progressive failure of similar components and lateral translation of the dock.

Figure 3. Failed stiff-arm.

Figure 4. Failed anchor pole.

Displacement of the docks with anchor pole systems was typically the result of flexural overstress and yielding of the cantilevered anchor poles. Subsequent damages were related to deflection and twisting of the anchor pole sleeves and the structural framing directly connected to the sleeves.

Failure of the dock anchorage that utilized tension cables and stiff-arms occurred at the stiff-arm connection to the dock. Loss of the stiff-arm allowed lateral displacement of the dock toward shore in the direction of the failed stiff-arm.

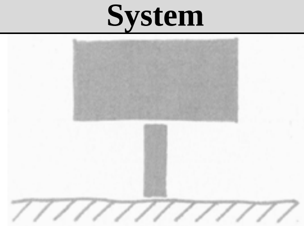
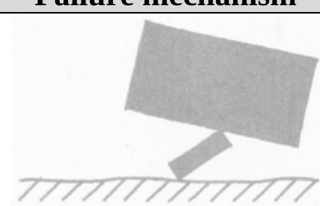
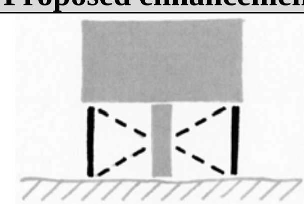
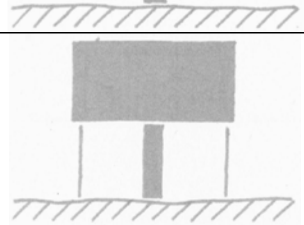
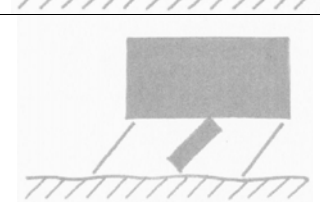
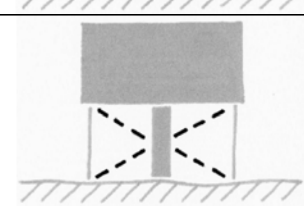
RECOMMENDATIONS FOR EXISTING ANCHORAGE SYSTEMS

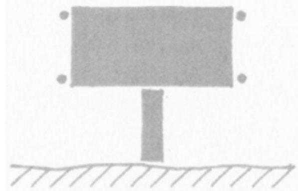
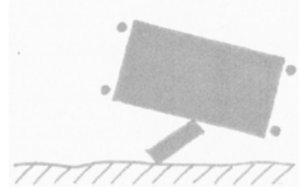
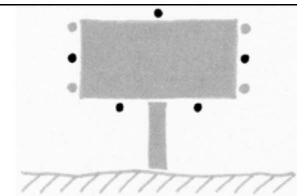
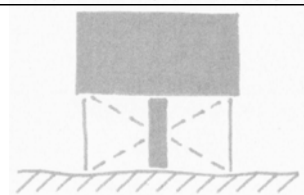
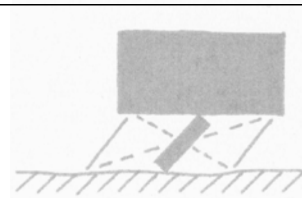
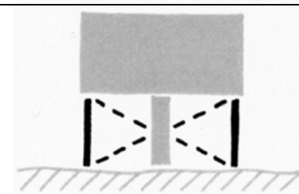
The vast majority of the anchorage systems observed at Lake Brownwood have likely exceeded their effective lifespan due to exposure to natural elements, deferred maintenance, and deficient design and construction. However, it is likely that the same or similar anchorage systems will continue to be used, repaired, and constructed at this and other similar lakes across the country. Contributing to the continued use of these deficient anchorage systems are the physical constraints of the exposed bedrock of the lake's shoreline, the large fluctuation of the lake's water level, and the abundance of similar replacement materials.

Considering the restraints of the existing anchorage systems, the authors have evaluated the general shortcomings of each system and have proposed enhancement of the existing systems to improve their performance for general use and during extreme storm events similar to that experienced on May 8, 2009, at Lake Brownwood. The proposed enhancements (see **Table 1**) are intended to address the primary deficiencies inherent in each anchorage system and the observed failure mechanisms by adding common components currently used at the subject site.

In the anchorage type that relies on a single, laterally-fixed gangway (Category A), the proposed enhancement is the addition of opposing diagonal tension cables and strut components. In anchorage systems that rely on the lateral fixity of multiple stiff-arms and gangways (Categories B and C), the proposed enhancement is the addition of opposing diagonal tension cables. For embedded anchor pole systems (Category D), the proposed enhancement is an increased number of anchor poles. Alternatively, the use of stronger/stiffer anchor poles and/or the use of more rigid connections to the dock would increase the strength of the system. For cable anchorage systems with stiff-arms (Category E), the proposed enhancement is an increased number of cables and/or installation of stronger/stiffer stiff-arms.

Table 1. Failure mechanisms of anchorage system types and proposed enhancements.

Type	System	Failure mechanism	Proposed enhancement
A			
B&C			

D			
E			

RECOMMENDATIONS FOR NEW DOCK ANCHORAGE

As evidenced by the deteriorated state of the existing anchorage systems, continued repairs of aged and deficient systems, and construction of new structures using the same or similar components, it is apparent that creative and innovative solutions are needed in the design and development of a modern dock anchorage system for use along the shoreline of Lake Brownwood and similar lakes.

Due to the steep inclination and inaccessibility of much of the shoreline of the lake and its islands, a marine-based anchorage installation would be most effective. Of the observed dock structures, the anchor pole systems exhibited the best performance. Their observed deficiencies included insufficient capacity of the system and corrosion of the anchor poles. The authors propose a more robust anchor pole system with greater lateral capacity constructed of a material that is more resistant to deterioration. One possibility is a system consisting of two or more precast concrete piles embedded into the lakebed. Concrete is much more durable than steel in a marine environment and the use of fewer, but stiffer/stronger, piles would provide the required strength while minimizing their impact on the functionality of the dock and on the amount of required coring of the lakebed.

REFERENCES

Anthoni, J. Floor. 2000. "Oceanography: Waves." Accessed March 5, 2012. www.seafriends.org.nz/oceano/waves.htm.

Emison, Celinda. 2009. Storm Damage Closes Lake Brownwood. *Abilene Reporter-News*. May13. www.reporternews.com/news/2009/may/13/lake-brownwood-closed-due-debris.

Weather Underground, Inc. "History for Brownwood, TX – Friday, May 8, 2009." Accessed March 5, 2012. http://www.wunderground.com/history/airport/KBWD/2009/5/8/DailyHistory.html.

CompuWeather. 2009. *Site Specific Weather Analysis: Brownwood Lake May 8, 2009.* CompuWeather, Inc.