Journal of the National Academy of Forensic Engineers®

http://www.nafe.org
ISSN: 2379-3252

Vol. 38 No. 1 June 2021

Forensic Engineering Analysis of a Commercial Dry Storage Marina Reinforced Concrete Runway Slab

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Abstract

An important element of a commercial marina is the landside site work behind the bulkhead. At many dry storage marinas, boats are launched, retrieved, and handled by large forklifts with axle loads up to 100 tons. In this case, the owner of a commercial marina sued the general contractor, alleging numerous design and construction defects in the reinforced concrete "runway" between the dry storage buildings and the bulkhead. This auger cast pile supported structure served as a relieving platform carrying vertical loads below the depth of the adjacent bulkhead. Some of the observed deficiencies were random cracking, joint damage, excessive edge settlement, and readily visible live load deflections. This paper presents the methods used to investigate the design and construction of this specialized structure. A finite element model (FEM) was used to review the original design intent and help establish the cost to cure. The original design of the runway and pile foundations was found to be inadequate.

Keywords

Reinforced concrete pavement, heavy wheel loads, marina, relieving platform, auger cast piles, subgrade support, finite element model

Introduction

Ports and marinas facilitate a transition from land to water forms of transportation. Many require the use of specialized structures to create a flat area suitable for wheeled vehicles adjacent to water with adequate depth for vessel access.

The subject of this paper is a commercial "dry storage" marina constructed in 2004 to 2006. A site plan is shown in **Figure 1**. Dry storage means that boats are lifted from the water and stored on racks in a nearby enclosed building. In this case, the boat storage building is a two bay, pre-engineered steel building supported on piles. The boat storage racks are also pile supported. The floor of the building is a reinforced concrete pavement supported on a compacted subgrade.

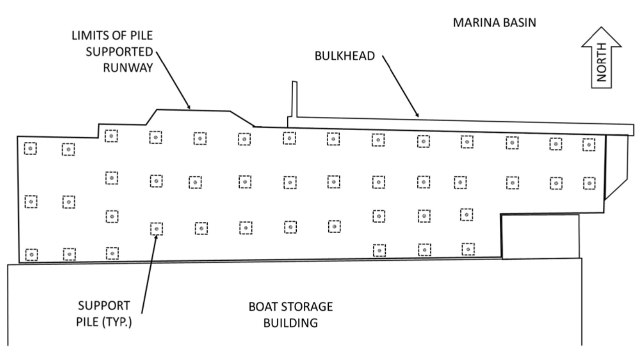

Figure 1
Site plan.

The pavement between the storage building and the marina bulkhead, referred to as the "runway," is a heavily reinforced concrete slab supported on isolated concrete piles that were cast in augered holes (hereafter "auger cast piles"). The runway slab serves as a "relieving platform," which is a structural system is used to reduce the soil pressure acting on the marina bulkhead.

The runway is used by two specialized forklifts to carry boats from the marina slips to the storage building. Each forklift has a total loaded weight of approximately 247,000 lb (123.5 tons). A section through the runway and the adjacent structures is shown in **Figure 2**. As the marina forklifts carry boats from dry storage to the marina, they cross from the slab-on-grade floor to a pile-supported grade

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DOI: 10.51501/jotnafe.v38i1.68

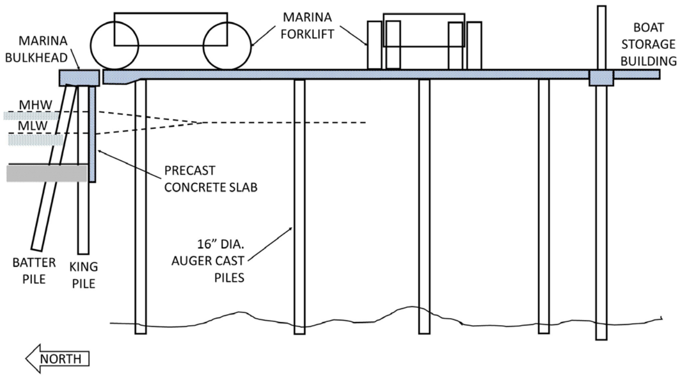

Figure 2
Section through the runway and adjacent structures.

beam to the pile-supported runway to the cap of the marina bulkhead. A smooth riding surface at these transitions is important for safe and efficient operation of the facility.

In the first eight years of use, the marina owner experienced performance issues with the concrete runway, including cracking and differential settlement of the slab. The owner claimed design and construction defects resulted in the need for substantial repairs or demolition and reconstruction of the runway. The author was retained to conduct a forensic investigation to determine the cause(s) and extent of the claimed defects.

Investigation

The investigation began with a site visit and a review of project design documents, construction plans, geotechnical studies, prior engineering studies, and other case documents obtained during discovery. This information revealed that:

- The marina bulkhead, runway, and boat storage building were each designed by a different structural engineer.
- While the runway and storage building were built by the same general contractor, the bulkhead was constructed prior to the subject work. It was shown as an existing improvement in the construction plans for the runway.
- The runway design considered the subgrade support in addition to that provided by the auger cast piles.

As stated by Bachner in *Recommended Practices for Design Professionals Engaged as Experts in the Resolution of Construction Industry Disputes*, "the expert should evaluate reasonable explanations of cause and effects"[1]. In this case, that meant looking at the structural design, construction materials and workmanship, and the owner's operation and maintenance of the marina. Critical assumptions that would need to be verified were: a) use of the runway as a relieving platform to prevent vehicle loads from impacting the marina bulkhead; and b) whether the runway slab was rigid enough to carry forklift loads to the piles.

Review of As-Constructed Conditions

The investigation began approximately eight years after construction with a general overview of the improvements. The as-constructed conditions were compared with the construction plans for significant deviations.

The plans described the runway as an "auger-cast piling supported slab." The piles consist of isolated, 16-inch diameter auger cast piles laid out in a nominal 20 ft × 20 ft rectangular grid (**Figure 1**). The actual spacing between piles varies between approximately 15 to 24 ft. Each pile was topped with a 5 ft round or 5 ft square cast-in-place concrete capital. The structural plans and details did not specify the subgrade preparation.

The runway typical section consists of a 12-inch-thick concrete slab, reinforced with two layers of $^{7}/_{8}$-inch diameter (#7) deformed steel bars. Each layer has an orthogonal grid of bars spaced at 9 inches. The bottom grid is protected from ground contact by 3 inches of concrete "cover." The top grid is protected from the salty marine environment by a cover of 4 inches. These cover dimensions reduce the effective depth of the concrete section. The concrete compressive strength was specified to be 6,000 psi.

The north perimeter of the runway is adjacent to the marina bulkhead, which was designed and built shortly before the runway but as part of the same development project. The bulkhead consists of a precast concrete "king pile-and-slab" system (**Figure 3**). The vertical concrete king piles, spaced approximately 14 ft apart, support precast concrete wall panels or slabs. There is an inclined batter pile in front of the king pile to increase the lateral load capacity of the bulkhead. The precast piles and panels are locked together with a cast-in-place reinforced concrete cap. This type of construction is also known as a "soldier-beam" retaining wall[2].

The runway is separated from the bulkhead cap by an isolation joint. The only support for the north edge of the runway is a line of individual piles spaced at 17 to 20

Figure 3
Marina bulkhead king pile and slab system.

feet. The runway edge cantilevers 4 ft 8 inches beyond the nearest pile centerline.

The south perimeter of the runway is adjacent to the boat storage building. The slab is pinned to the building foundation grade beam with a concrete key and steel dowels. The nearest piles are 5 ft to 14 ft 10 in. from the runway edge.

The east and west perimeters cantilever 9 ft 6 in. and 5 ft 8 in., respectively, beyond the nearest pile centerline. The east edge of the slab is separated from the adjacent slab-on-grade by an isolation joint. The west perimeter is pinned to the adjacent slab-on-grade with steel dowels.

The installation of the auger cast piles was observed by an independent testing lab. Due to a communication error, 10 piles at the east end of the runway were not observed by the testing lab. The geotechnical engineer determined that the 16-inch diameter piles should yield an allowable downward bearing capacity of 55 tons each, with a safety factor between 2 and 3.

As part of the investigation, the wheelbase and tire dimensions of one of the marina forklifts were measured and compared against the manufacturer's published data[3]. **Figure 4** shows a side view of the forklift equipment working on this site.

Observation and Testing of the Runway Surface

Additional site visits were made to make more detailed observations and coordinate material testing. The concrete runway was examined to locate the visible deficiencies described in the complaint, including differential settlement, uncontrolled cracking, and surface spalls. The general locations of these defects are shown in **Figure 5**. Where the concrete surface was spalled, no exposed reinforcing steel was observed. **Figure 6** is a representative

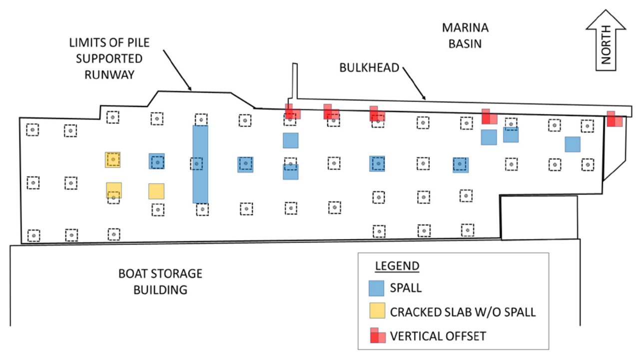

Figure 5
General location of runway deficiencies.

Figure 4
Marina forklift approaching the bulkhead.

Figure 6
Runway surface spalls and cracks.

photograph of some of the surface deficiencies. Some areas of the runway had been repaired prior to the author's first site visit. Throughout the investigation, the marina remained open, and the runway was in use.

During the original construction of the runway slab, 13 sets of concrete cylinder specimens were taken. Two specimens from each set were tested at an age of 28 days and the average reported as the compressive strength. The average strength of all tests was 7,512 psi. No test fell below the specified strength of 6,000 psi.

To further investigate the quality of the concrete, rebound hammer readings were taken at 12 locations near the observed surface defects. This is a common practice at waterfront facilities to assess the near surface uniformity of the concrete and to look for areas of poor quality or with a deteriorated condition[2]. This non-destructive test was selected because it did not require restricting the owner's use of the site. The tests were performed in accordance with the Standard Test Method for Rebound Number of Hardened Concrete (ASTM C805)[4]. The hammer readings all ranged from 43 to 51, which indicates a concrete compressive strength greater than the 6,000-psi design strength.

Visual Examination of Concrete Cores

The owner, as a remediation effort, had thirty-two 3.5-inch steel pipe micropiles installed to support the runway slab. The micropiles were installed after 24-inch-diameter access openings were cut, and the concrete "cores" were removed from the runway slab. The process disturbed the subgrade so the presence or lack of a void space below the slab could not be determined. Each pile was preloaded with a hydraulic jack to transfer a portion of the concrete slab dead load to the pile. The contractor did not measure the slab elevation before or after jacking the slab.

The oversized cores produced during installation of the micropiles were marked and stored on-site. They provided an opportunity to observe the as-constructed cross-section of the slab. Eighteen cores taken from the runway slab were measured and visually examined for mix uniformity, concrete consolidation, cracks, aggregate segregation, corrosion of the steel reinforcement, and the cover thickness to the top and bottom surfaces. See **Figure 7** for core locations and identification numbers.

Excessive flexural cracking was noted that penetrated well beyond the reinforcing steel layer. In seven of the 18 cores examined, cracks that originated at the bottom surface extended more than 6 inches up into the slab. The

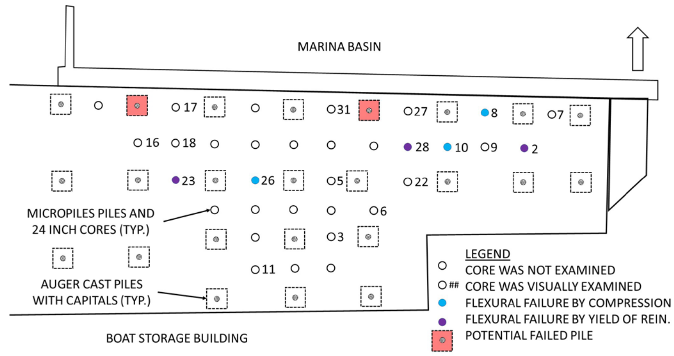

Figure 7
Select core and failure locations.

cracks in several cores (#2, #23 and #28) went further and penetrated beyond the neutral axis for balanced design. This indicates these locations failed in flexure by plastic deformation (yielding) of the steel reinforcement in tension. Core #23, shown in **Figure 8**, was taken midspan between two auger cast piles (see **Figure 7** for location). This is an area of high positive moment (i.e., tension on the bottom side of the slab). Multiple flexural cracks begin at the bottom and extend up 7.5 to 8.4 inches.

Three of the cores (#8, #10 and #26) examined had horizontal cracks at the elevation of the top reinforcing steel (**Figure 9**). This caused a delamination (spall) of the concrete cover above the top steel that indicates the concrete section failed in compression.

North Edge Deformations

Irregular settlements occurred along the north edge of the runway adjacent to the marina bulkhead cap. As forklifts cross this joint, additional live load deflections were readily visible. The owner installed steel cover plates at some

Figure 8
Concrete core with excessive flexural cracking.

Figure 9
Concrete core with horizontal cracking.

locations to ramp from the runway to the cap (**Figure 6**).

Precast concrete marina bulkheads and relieving platforms are among the types of structures commonly associated with loss of supporting soil through the retaining structure. A routine inspection of the marina bulkhead would normally include an observation of the fill behind the wall[2]. In this case, the reinforced concrete runway prevents direct observation of the fill.

As part of the investigation, vertical offsets between the north edge of the runway slab and the south edge of the bulkhead cap were measured using a straight edge and steel rule. Measurement locations were referenced to the northeast corner of the runway slab. The north edge should have been constructed flush with the top of the cap within the tolerances of the Specifications for Tolerances for Concrete Construction and Materials and Commentary (ACI 117)[5]. The measured offset is compared with the ACI 117 tolerance of 0.25 +/- inches in **Figure 10**.

Approximately 27 percent of the north edge is within 0.25 inches of the top of cap. Another 25 percent is between 0.25 and 0.5 inches. Approximately 15 percent is between 0.5 and 1.0 inches. The remaining 33 percent has deformations (settlement plus dead load deflection) between 1.0 and 2.8 inches.

Marina Forklift Design Loads

The wheel loads from the forklifts used at this marina substantially exceed those from highway trucks and general-purpose forklifts. The load from one set of dual tires on the forklift drive axle is approximately 109.4 kips (54.7 tons) based on the equipment manufacturer's data sheet used in the runway design. This is approximately equal to the 55-ton design capacity of each auger cast pile.

Regardless of the runway flexural strength, or the

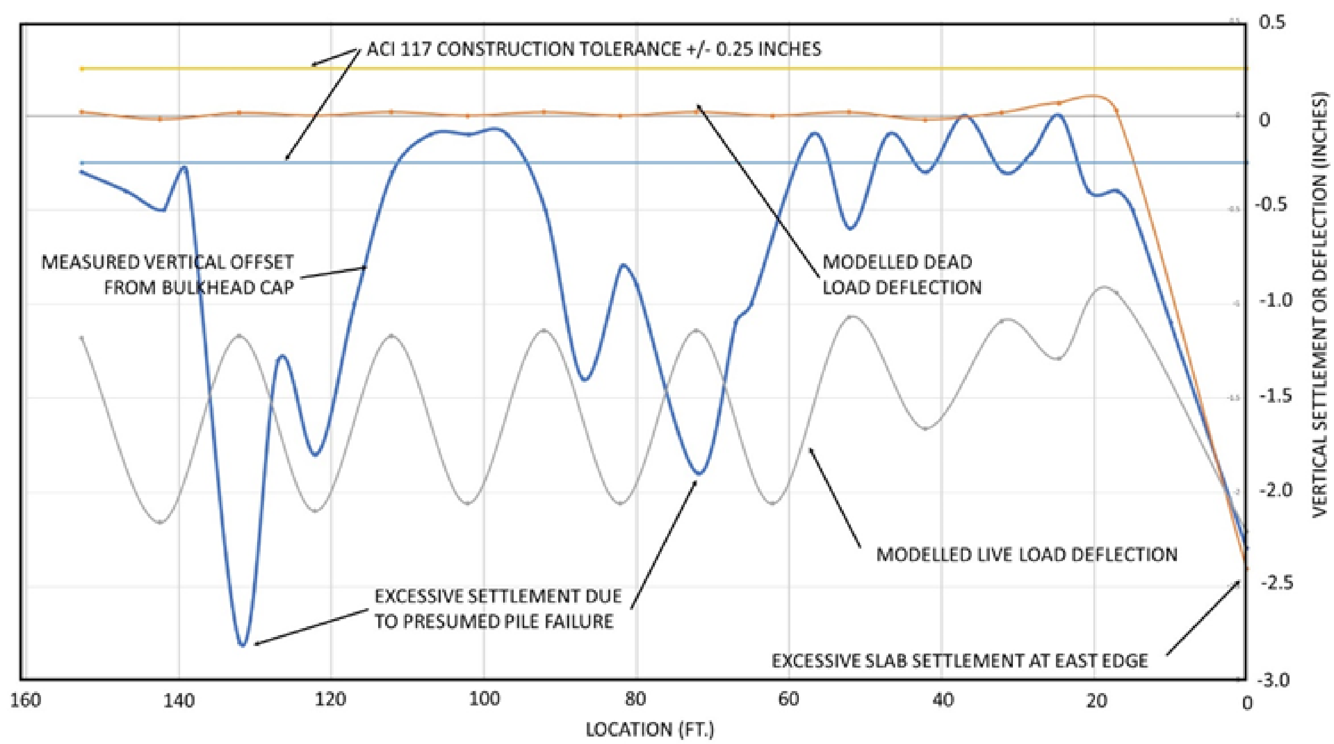

Figure 10
Measured and predicted deflections along the runway north edge.

presence of subgrade support, the auger cast piles will receive some dead load from the runway slab and the pile capital (**Figure 11**). At a minimum, each pile will support a tributary area approximately 6 ft square via shear and direct bearing. This minimum dead load is about 4.5 tons. The specified piles have a design capacity of 55 tons with a safety factor between two and three. Adding the minimum dead load of 4.5 tons to the 54.7-ton live load from one dual set of marina forklift tires yields a minimum pile load of 59.2 tons (DL + LL). This reduces the safety factor of the design, but is unlikely to trigger a pile failure.

In the worst case, with no subgrade support and a runway with adequate flexural strength, a runway area of

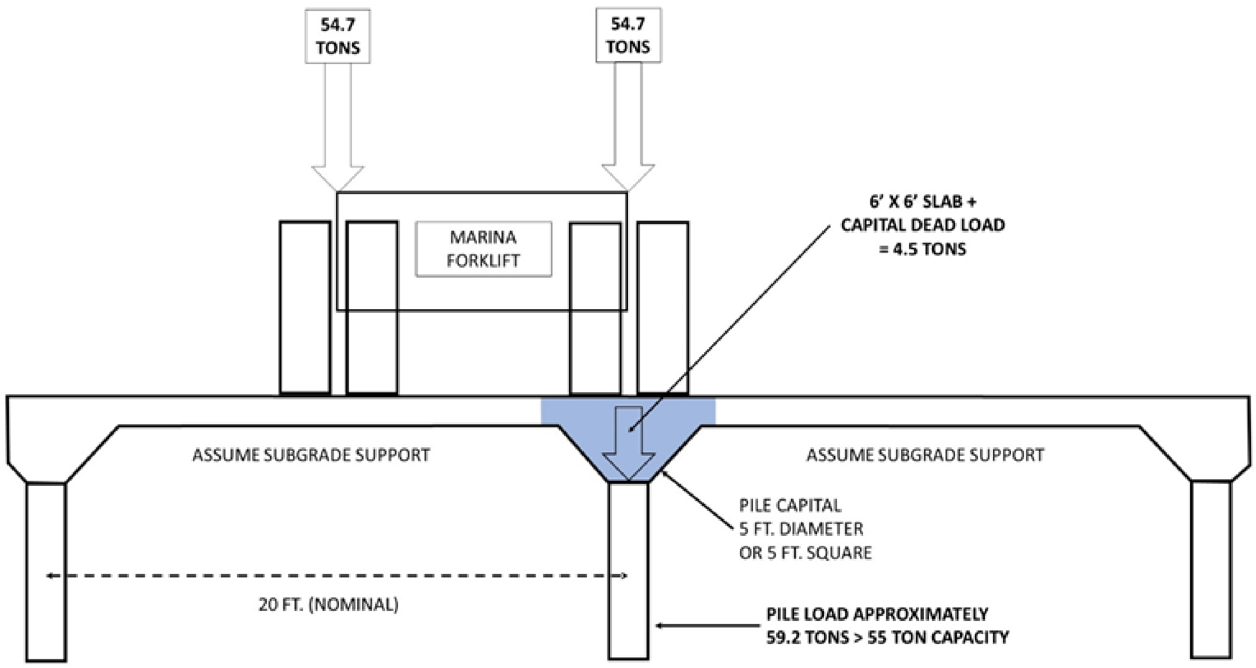

Figure 11
Minimum load on interior pile.

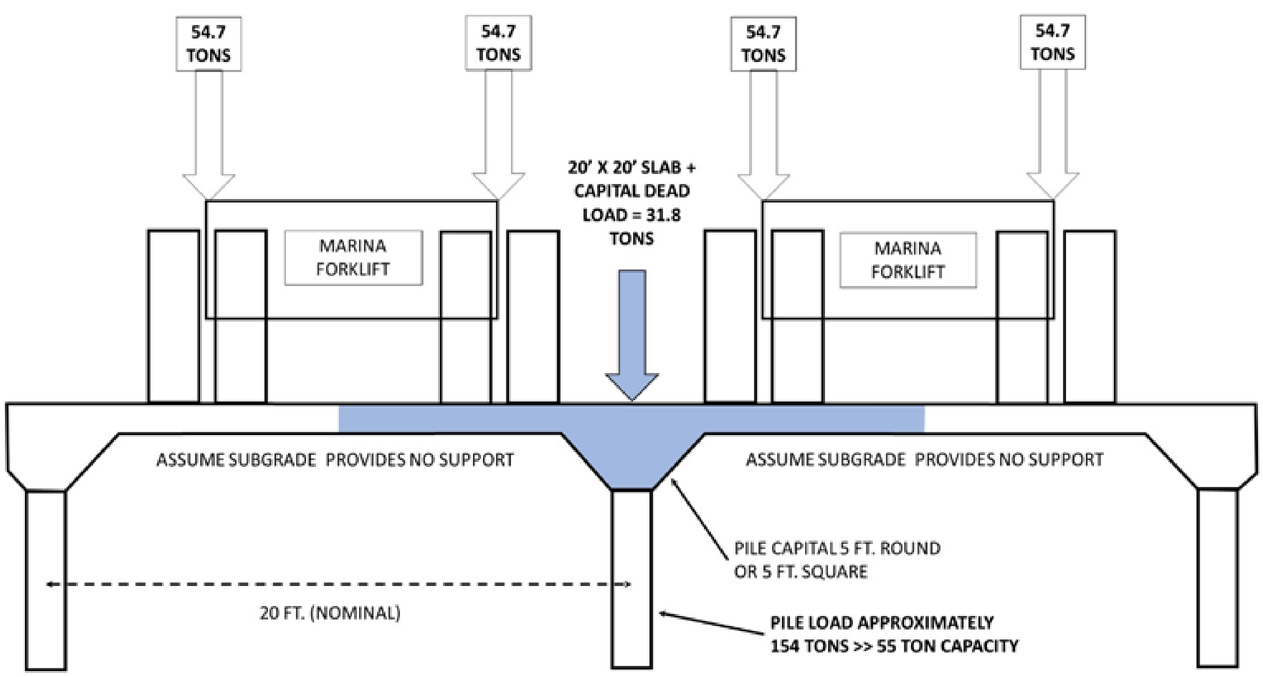

Figure 12
Maximum load on interior pile.

about 20 ft square would be tributary to the pile (**Figure 12**). This maximum dead load is about 31.8 tons. This leaves only 23.2 tons to support the forklift wheel loads.

Review of Design Intent

At the subject marina, the pile supported, reinforced concrete runway serves several primary functions. First, the supporting piles are much stiffer than a soil subgrade and should do a better job of limiting live load deflections. This is important where the runway meets and matches the elevation of other riding surfaces, such as the bulkhead cap and the floor of the storage building.

Second, the auger cast piles are founded on a deeper and stronger soil stratum. They will control the long-term settlement of the runway.

Third, the runway slab serves as a "relieving platform." This type of structural system is used to reduce the lateral pressure acting on the marina bulkhead. In essence, the heavy equipment live load and the runway slab dead load are carried as vertical loads to a deep level where they do not affect the bulkhead[6]. Without the relieving platform, the forklift wheel loads, when close to the bulkhead, would substantially increase the vertical soil pressure and thus the lateral soil pressure acting against the wall. The assumption of soil support of the runway is inconsistent with the purpose of a relieving platform.

Figure 13 illustrates the effect a relieving platform has on reducing the design loads on the bulkhead. In this example calculation, the backfill load is based on a dry unit weight of 122 lb per cu ft, an angle of internal friction of 34 degrees, and a depth to water table of 6 ft. The equipment loads on top of the backfill or "surcharge" is based on a single pair of forklift drive wheels. The normal stress was estimated from Giroud 1970 using Tables 3.14 to 3.18 as presented by Poulos and David 1974[7]. Because the bulkhead is rigidly supported by batter piles, the at-rest coefficient of earth pressure of 0.44 was used to calculate lateral pressures[8].

In this example calculation, for a condition with backfill only, the maximum lateral soil pressure is approximately 869 psf. For the backfill plus surcharge condition, the maximum lateral soil pressure is approximately 2,300 psf. Integrating over the height of the wall results in total design loads of 4,090 lb per ft of wall and 12,800 lb per ft of wall for backfill only and backfill plus surcharge, respectively. This represents an increase of more than 300% in design pressure.

To avoid this increase in design load on the bulkhead, the runway slab must be rigid enough to carry the forklift loads to the piles, and the piles must be capable of carrying the weight of the slab plus the forklifts.

During construction, the runway slab was cast against and supported by a soil subgrade. During the few weeks it took for the concrete to cure and reach design strength, the subgrade continued to carry the slab dead load. After eight years of use, the condition of the subgrade and its contribution to supporting the runway is difficult to determine.

The assumption that the subgrade would support the slab dead load throughout the service life of the structure is not well founded. The stability of the subgrade, particularly near the marina bulkhead, cannot be guaranteed. Some soil will be lost from behind the bulkhead by tide action piping through joints in the concrete panels (**Figure 14**). Additional soil can be lost from beneath the panels due to localized scour from prop wash near the bulkhead. These losses are a common occurrence for bulkheads of similar construction[2]. The previously discussed vertical deformations along the north edge of the runway are the

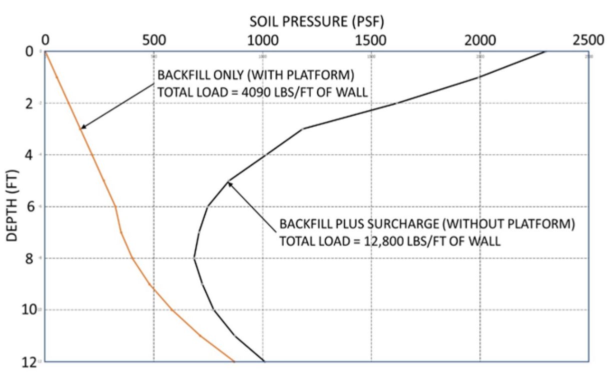

Figure 13
Effect of runway acting as a relieving platform to reduce bulkhead design load.

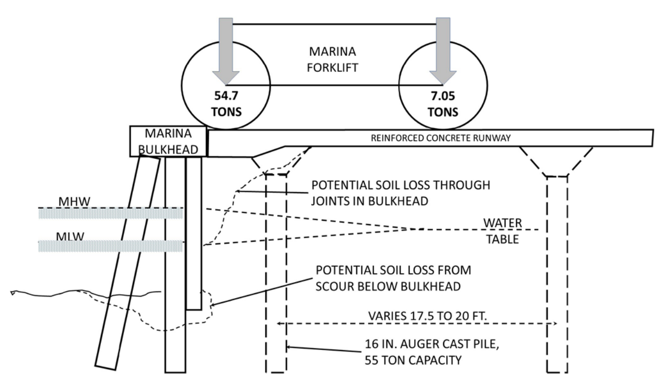

Figure 14
Runway section at marina bulkhead.

best indication that subgrade support is no longer uniform.

Finite Element Model (FEM)

Several finite element models (FEM) were created using a software application commonly used for the design of reinforced concrete slabs. An FEM permits the analysis of continuous framed concrete structures that do not meet the limitations of prescribed designs or simplified solutions. The FEM considers the elastic properties of materials and can include the elastic properties of supports. The runway slab and pile foundation were modeled as a two-way slab system. It considered the self-weight dead load of all structural elements and the live loads of two forklifts moving about the runway.

Models A and B

Multiple models were created to represent different support conditions. Model A was developed based on the runway design dimensions and typical slab section. The original design support conditions were modeled by representing the 45 ft deep auger cast piles as concrete columns and the subgrade support as a grid of spring supports. An alternate, Model B, was built using the same dimensions as Model A, but assumes no subgrade support, which is consistent with the design of a relieving platform. **Figure 15** shows the pile layout for Models A and B and the assumed edge conditions.

The wheel loads were input as area loads derived by dividing the loaded weight wheel load (109,400 lb) by the recommended tire pressure of 145 psi. The wheel loads were distributed over 755 sq. inches for each front tire, and 97 sq. inches for each rear tire. No other live loads (uniform, area, or concentrated loads) were considered in addition to the forklift loading.

Forklift wheel loads were positioned at several locations to determine the critical stresses in the runway and maximum loading on the piles. Models A and B were analyzed under three load scenarios described below and illustrated in **Figure 16**.

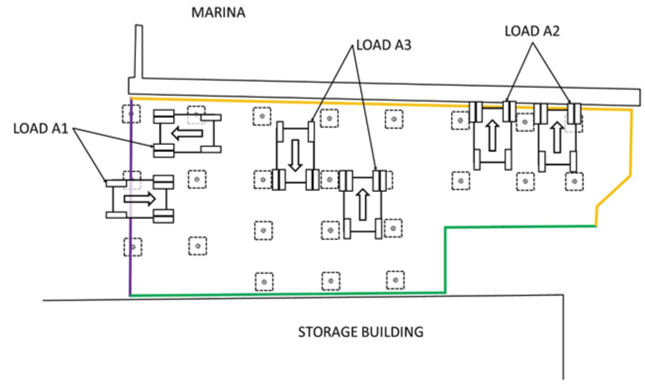

Figure 16
Partial site plan with load scenarios A1, A2, and A3.

Load A1 - Maximum positive moment: two forklifts side by side, spaced 5 feet apart, positioned with the drive (heavy) axle at the midspan between support piles.

Load A2 - Maximum negative moment over a pile: a forklift positioned with the drive axle near the north perimeter of the runway, with both wheels on the same span between two piles; and a second forklift with one drive wheel on the adjacent span.

Load A3 - Maximum pile load: two forklifts side by side, spaced 5 feet apart, positioned with the drive axles on an interior pile line, and centered on a pile.

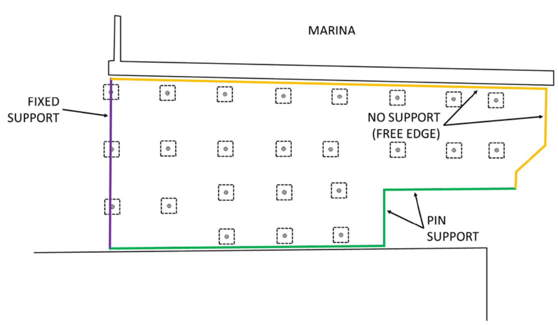

Figure 15
Models A and B pile layout and edge conditions.

Model C – Proposed Repair

To help estimate the cost to cure, a third finite element model, Model C, was created using a proposed reconstruction plan with closer pile spacings and a thicker slab section. It was assumed that subgrade did not contribute to the support of dead or live loads. This would result in a stiffer slab capable of distributing more load to adjacent piles. This plan was created by another party's expert but is considered by the author to be a practical (if not optimized) combination of the pile capacity, number of piles, and the slab thickness. It included a phasing plan that would have allowed partial use of the site during reconstruction.

Model C was analyzed under three load scenarios that differ slightly from Models A and B due to changes in the pile layout. They are described below and shown in **Figure 17**.

Load C1 - Maximum positive moment: two forklifts

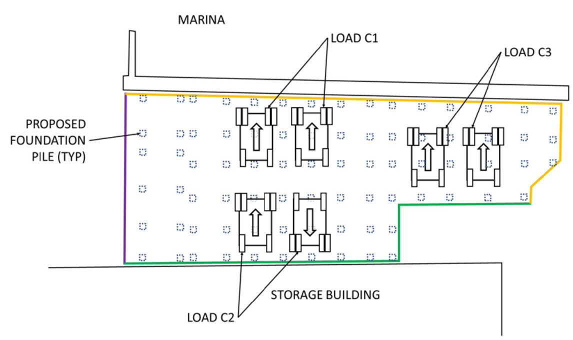

Figure 17
Proposed pile layout with load scenarios C1, C2, and C3.

side by side, spaced 5 feet apart, positioned with the drive (heavy) wheels near the midspan between support piles. The steering (light) wheels are on adjacent spans but not located near the midspan.

Load C2 - Maximum negative moment over a pile: two forklifts, side by side but facing in opposite directions, spaced 5 feet apart, positioned with the drive axle of one forklift and the steering axle of the second forklift centered on an interior pile.

Load C3 - Maximum pile load: two forklifts side by side, spaced 5 feet apart, positioned with the drive axles on an interior pile line, and over three individual piles.

FEM Results

A brief summary of the FEM results is shown in **Figure 18**. The maximum runway slab moments are presented as ultimate strength design (USD) moments based on 1.2 times dead load plus 1.6 times live load. The maximum moments for Models A and B are compared against the calculated capacity of the existing runway. Model C results are presented for information only. Since Model C is based on a proposed reconstruction plan, the capacity of the slab would be designed to meet the calculated design stresses.

The largest moments in both Model A and B are negative moments that create tension in the top of the slab over the piles. Compared with an existing capacity of (-)25.9 kip-ft per ft, Model A at (-)66.0 kip-ft per ft is under designed by a factor of 2.55. Model B at (-)90.6 kip-ft per ft is under designed by a factor of 3.50.

The pile loads shown in **Figure 18** are unfactored. The existing design capacity of 55 tons includes a safety factor of two to three. The Model A pile load of 67.5 tons is a factor of 1.23 above the capacity. Model B with a maximum load of 154 tons is a factor of 2.8 above the pile capacity.

Load Scenario	Description	Units	Existing Capacity	Model A	Model B	Model C
A1	Max positive moment	k-ft/ft	29.5	25.9	58.1	
A2	Max negative Moment	k-ft/ft	-25.9	-66.0	-90.6	
A3	Max pile load	ton	55	67.5	154	
C1	Max positive moment	k-ft/ft				50.3
C2	Max negative Moment	k-ft/ft				-11.7
C3	Max pile load	ton				68

Note:
Moments are USD based on 1.2 DL + 1.6 LL
Pile loads are unfactored
"k" = kip = 1000 lb

Figure 18
Finite element model results.

Figure 10 shows the live load deflections of the slab edge predicted by the FEM Model A. They generally oscillate between about 1.1 inches at the pile centerline and about 2.1 inches midspan between the piles.

Discussion

The runway slab appears to generally conform to the plans and specifications. The concrete compressive strength, quantity, and placement of the reinforcing steel (and overall slab thickness) were inspected and accepted during construction. Examination of concrete cores did not find aggregate segregation, cold joints, or critical deviations in the placement of the reinforcing steel. The observed surface damage, consisting of shallow spalls, chips and raveled joint lines (**Figure 6**), are not deep enough to affect the strength of the slab.

The differential settlements and dead load deflections along the north perimeter of the runway, measured as a deviation from the elevation of the bulkhead cap, are substantially larger than expected. The plans intended these surfaces to be flush. The construction tolerances of ACI 117 would allow up to 0.25 inches of deviation in the original construction[5]. There are two locations, coincident with pile centerlines, with dead load deflections approximately 1.9 and 2.8 inches below the cap. When compared with the calculated dead load deflections in **Figure 10**, these locations are shown to be deflecting too far to be within 5 ft of a pile. This indicates that two of the auger cast piles have failed in bearing or in axial compression (**Figure 7** for locations).

Ultimately, the original design of the runway slab and the supporting piles appears, based on the analysis performed as part of this investigation, inadequate for the forklifts being used at this marina. Even when considering the subgrade's potential contribution to support the slab dead load, the negative design moments determined by the FEM analysis are as much as 2.5 times the flexural capacity of the slab (-66.0 vs. -25.9 kip-ft/ft, respectively). This is due primarily to the thin slab section and the relatively wide spacing of the piles. If the subgrade contribution to support is omitted, as is typical in designing a relieving platform, the maximum negative design moment increases to -90.6 kip-ft/ft, which is 3.5 times the slab capacity. This results in excessive cracking of the slab and increased deflections.

The north perimeter, adjacent to the marina bulkhead, is the greatest concern. The wide pile spacing, the 4 ft 8 in. slab cantilever, and the thin slab section all contribute to large live load deflections. **Figure 10** also shows the calculated live load deflections along the north edge. Depending on the location, the slab could be expected to deflect from 1 to 2 inches each time a forklift approaches the bulkhead. This discontinuous edge of the runway could have been designed with an edge beam to prevent this deflection.

Regardless of the runway flexural strength or the presence of subgrade support, the auger cast piles will be called upon to carry a minimum dead load of about 4.5 tons from the pile capital and the runway slab directly above. In the worst case — with no subgrade support and a runway with adequate flexural strength — an area of about 20 ft square will be tributary to the pile. This maximum dead load is about 31.8 tons. Based on the forensic analytical model, when two fully loaded forklifts pass each other with a pile centered between them, the maximum pile load would be as high as 154 tons (DL + LL). This event would likely fail the pile in bearing or axial compression. The pile spacing and the thin section of the runway would prevent the effective transfer of load to adjacent piles. The runway slab would subside until it was supported by the subgrade.

Conclusions

The design of the runway slab was inadequate for the support conditions and the applied loads. The slab thickness and size/spacing of steel reinforcement did not have adequate flexural capacity. Flexural failures in both tension and compression have already occurred and were observed in concrete cores taken from the reinforced concrete slab. Large dead load deflections were measured relative to the adjacent marina bulkhead.

The design of the auger cast piles was inadequate in several respects. The overall spacing between piles was too large. It allowed multiple wheel loads to be tributary to an individual pile. The design vehicle live loads, regardless of subgrade support conditions or runway flexural strength, exceed the load capacity of the piles and reduce the design safety factor. Runway edge deflections indicate that two piles may already have failed.

In addition, the pile layout did not provide adequate support for the runway at the north and east perimeters. The 4 ft 8 in. cantilever and large pile spacing along the north perimeter produces live load deflections of up to 2.1 inches below the marina bulkhead. The 9 ft 6 in. cantilever along the east perimeter increases both the flexural stress in the slab and the load on the piles.

Because of the damage that has already occurred to the runway slab, correction will require demolition and removal of the slab and substantial additions to the pile foundation. With stronger piles and a reduced pile spacing, a slab thickness of 18 inches would be adequate to support the design loads.

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