STRUCTURAL CONDITION ASSESSMENT

RODNEY RESERVOIR

8TH AND RODNEY STREETS
WILMINGTON, DELAWARE

DEPARTMENT OF PUBLIC WORKS
City of Wilmington

WILMINGTON, DELAWARE

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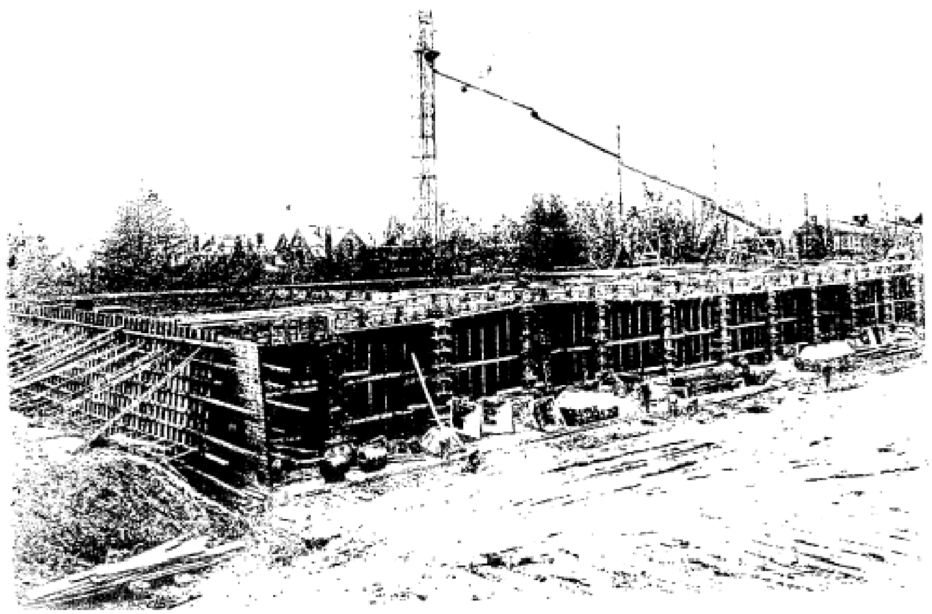
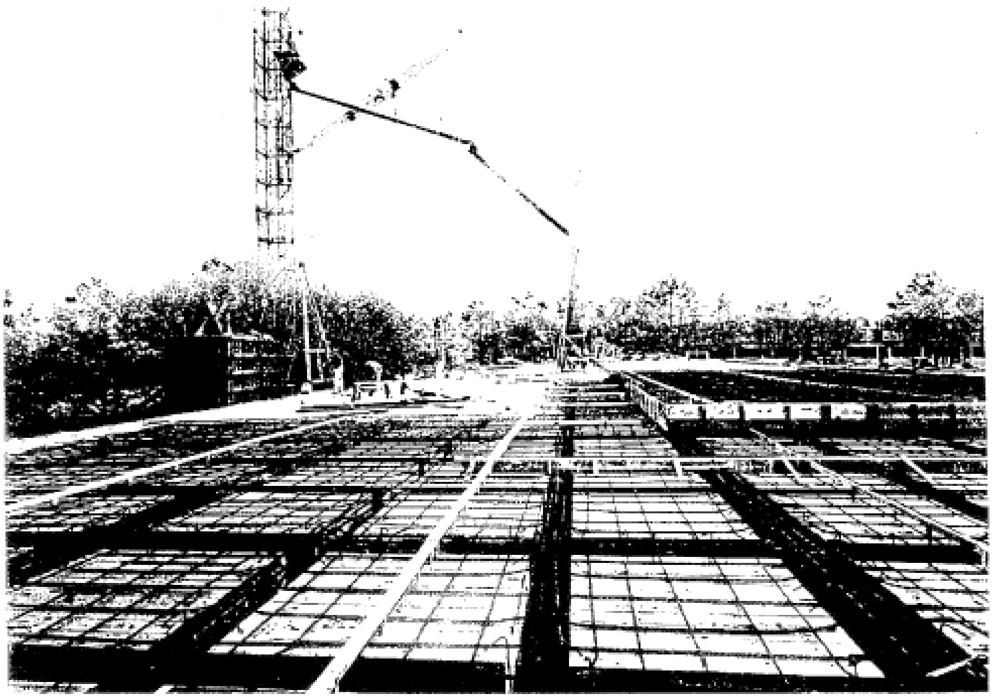
Rodney Reservoir is a large reinforced concrete structure with a plan form which covers a city block. The structure was built for the purpose of storing domestic water for the City of Wilmington; however, for the past two decades has been left empty and unused. Realizing the need for additional water storage; especially, when such storage can be provided in an existing structure that is closed and relatively secure, the City is now planning to reactivate the near century old reservoir. Concerns regarding the structural integrity of the reservoir were prompted when attempts were made to fill the reservoir were unsuccessful, perhaps due to a leak in the floor or walls of the structure. Concerns about the condition of the roof were also expressed. As a result of the concerns, the City requested that our firm provide an assessment of the structural condition of the reservoir. The reservoir was under construction in 1917 as witnessed by this photograph which appeared in the Forty-Eighth, Annual Report of the Board of the Water Commissioners, dated September 1, 1917. Available construction documentation obtained from the City is dated April 1917. For orientation purposes, we have assumed that the existing brick masonry mechanical building is located on the north end of the reservoir which fronts on 9th Street.



Rodney Street Reservoir, form work for the east section
Forty-Eighth Report Board of Water Commissioners, 1 September 1917

Rectangular in plan form, the reservoir measures 268’ north-south by 251’ east-west. The structure is comprised of two symmetrical chambers located east and west of a central wall which runs north-south. The structure rises 20’ on thick (3’at the base to 2’ at the top) reinforced concrete walls and reinforced concrete interior columns (1’-9” square section) positioned at 18’ centers. The floor of the reservoir is constructed of 10” thick reinforced concrete with walls and column footings bearing on the top surface of the floor mat. The roof is framed with concrete girders, beams and deck -girders 18” wide by 30” deep span between the columns; beams 12” wide by 20” deep are on 6’ centers and span both directions between the girders and the deck is a 6” thick, two way slab of reinforced concrete spanning beam to beam. A copy of a sheet of the original construction drawings is provided by Figure 1 showing the structural section of the reservoir as described above



Pouring the concrete roof with girders, beams and slabs
Note: raised section to right is future paved area
Forty-Eighth Report Board of Water Commissioners, 1 September 1917

Field review consisted of visual observations and selective probing of the underside of the roof with an electric chipping hammer. Access was provided by staging erected on the floor of the reservoir. In addition, a total of seven (7) cores were extracted from the concrete deck at selected locations shown on a copy of the original roof deck plan provided on Figure 2. As can be seen from Figure 2 and the photograph on page 6, cores 3 (not shown) and 4, taken along the east and west sides of the reservoir, represent the only cores where the concrete slab remained intact for the testing. Four cores were taken from above the west chamber and three from the eastern half of the reservoir. Laboratory testing was performed on cores designated numbers 3, 4 and 5B. Enclosed is the report prepared by Construction Materials Consultants, Inc, dated October 13, 2006, which states the results of the laboratory testing. As input for our evaluation, copies of available portions of the original construction documents for this structure were provided by the City of Wilmington.

Description	**Sheet number**
Foundation plans	3
Roof framing sections	4
Roof girder details	10
Roof details	27
Roof plan	36

As can be seen from the 1917 photograph of the reservoir under construction, the elevation of the roof varies. However, in general, the roof slopes in all directions away from the central grassed area. The portions of the site outside the exterior walls have been backfilled with earth, forming a berm with increasing height and width as the natural grade of the site slopes downward proceeding from south to north. Earth backfill for the grassed areas follows the lines of the concrete roof providing positive surface drainage on the surface of the site. An estimate of the average depth of earth over the concrete roof is approximately 2'. Approximately 40% of the projected area of the reservoir is finished with hot-laid bituminous pavement approximately 1 ½" thick; the remaining 60% is earth fill and planted with grass.

A visual survey of the underside of the roof reveals that concrete deterioration has advanced throughout the roof section that supports the paved areas - cracking is pervasive. The roof section is saturated with moisture with droplets of water forming over the entire surface of the bottom of the elevated deck. Evidence of the migration of moisture through the cracks in the concrete deck is witnessed by efflorescent staining and exudations that have formed stalactites, some 4' in length, hanging from the underside of the deck and originating in the cracks. Directly below the stalactites are hard, knobby stalagmite formations which rise several inches above the concrete floor level. These calcium carbonate deposits are the result of the dissolution of cement hydration products by water migrating through the concrete. Once the water reaches the bottom surface, the drops of moisture evaporate, leaving the lime deposit.

Deterioration of roof slab below paved areas in the west section
Gredell & Associates, 13 July 2006

The visual surveys revealed areas of reinforcing steel corrosion as witnessed by the brown coloration of the stalactites and the spalling of the concrete. The spalling is caused by the corrosion of the reinforcing bar – the volume of the byproducts of corrosion are approximately double that of the original section. As a result of the expansion, tensile cracking occurs in the surrounding concrete. The cracking weakens the section to the extent that it fails; exposing the corroded reinforcement steel. Working with an electric powered chipping hammer, probes were made in the concrete to expose sections of the underlying reinforcing steel. Typically, the positive (bottom) reinforcing steel in the girders and the beams showed only mild signs of corrosion; however, the reinforcing steel in the 6" deck slabs is actively corroding. Accordingly, it is reasonable to assume that that the negative (top) steel in the girders and the beams has been adversely affected by the moisture in the slab section.

During the course of our review, we observed the condition of the walls, columns and floor. We found these elements to be in good condition with no signs of deterioration. Based on the observed good condition of these structural components, the focus of this study and report is the deteriorated roof slab.

In order to diagnose the condition and recommend a repair procedure, an understanding of the cause of the problems is required. The primary ingredients of concrete are cement, coarse and fine aggregates and water. The cement is composed of calcium silicates, calcium carbonates and gypsum which react with water (and each other) to form the cement paste. The extremely complicated process by which concrete hardens to form a structural entity is called hydration. Hydration produces calcium hydroxide in solution that fills all the capillary cavities, gel pores which envelope the reinforcing steel. The hardened concrete is extremely alkaline in nature with a pH of 13 or larger. The relatively high pH is a key factor in the prevention of the corrosion of the steel reinforcement in concrete construction.

Probing the concrete girder with electric chipping tool to observe reinforcing steel
Note: probe being made at construction joint
Gredell & Associates, 31 August 2006

Water enters the pores of the hardened concrete. The amount and size of the pores is basically a function of the water-cement ratio in the concrete when cast- the more the amount of water in the mix, the greater the volume of pore space in the concrete. The source of the water in the voids is precipitation. The paved areas on the roof of the reservoir are surrounded by concrete curbing cast monolithically with the roof slab. Water passes through the deteriorated asphalt pavement to the concrete roof structure. Catch basins are flush with the pavement so water trapped in the deteriorated pavement enters the concrete slab. Evaporation is impeded by the bituminous pavement. Water that enters the slab is subject to freezing. Porous concrete, with virtually no air-entrainment, not only holds more water but because the pores are larger, the temperature for freezing is 32 degrees F. Lower temperatures are required to freeze the pore water in air–entrained concrete. As water freezes in the pore spaces of the concrete, expansion occurs causing internal stressing and micro-cracking. Cycles of freeze-thaw "open" the concrete to receive more water. Eventually cracks extend into the bottom of the slab. The lime or calcium hydroxide (pH 13) that once provided a thin layer of protection to the reinforcing steel is reduced to calcium carbonate (pH 9). At this level, the bar is no longer protected and provided there is oxygen and an electrolyte, corrosion will occur.

Corrosion of the reinforcing steel is the result of the formation of a galvanic cell in the concrete. The electrolyte is the water that has entered the concrete along with substances dissolved from the concrete. An anode forms where the protective film is weak (low pH). These are the cracked sections where the presence of relatively low pH calcium carbonated is witnessed by the efflorescent stains and stalactite formations. The cathode is the area where there remains good protection (higher pH, calcium hydroxide) on the bar surfaces. Corrosion occurs at the anode. We observed an entire 6' by 6' section of the bottom of the slab fully delaminated with practically no section of steel reinforcement bar remaining. The rate of corrosion increases with higher temperatures and humidity. High temperature and humidity characterize the interior of the reservoir; especially, during the summer months and at the underside of the roof.

Spalled concrete exposing corrosion of the reinforcing steel
Note: construction joint provides path for water / anode formation
Gredell & Associates, 21 September 2006

In order to determine the condition of the interior of the slab, a total of 7-3 inch diameter cores were extracted by using a core drill. The cores were located in such a manner as to determine conditions where visually the concrete appeared sound and alternatively those areas where conditions were poor - good below grassed areas and poor below the bituminous pavement. The locations of the cores are shown on Figure 2.
Cores 3, 4 and 5 B with core diameter 2 ¾" and lengths, 6 3/4 , 6 and 4 inches, respectively, were sent to the laboratory of Construction Material Consultants, Inc.

Cores 4 and 5B were sent to the laboratory for testing
Note: freeze-thaw delamination and bituminous pavement for all cores except #4
Gredell & Associates, 31 August 2006

Representatives of the laboratory were instructed to determine the composition and quality of the concrete; the compressive strength, cloride ion content, and depth of carbonation. Of the seven cores taken from the reservoir roof only cores 3 and 4 taken from the grass area had structural integrity with 4 somewhat better than number 3. All others were extracted from the paved area. Examination of the core samples reveals extensive moisture activity in the concrete as witnessed by fibrous, secondary ettringite, calcium carbonation, and layered silica reaction gel. Because the concrete contains no appreciable air- entrainment and the material is saturated with moisture, surface parallel cracking due to cycles of freeze- thaw have caused severe deterioration of the concrete. Contributing to the deterioration of the steel reinforcing bars is the advance of carbonation into the concrete towards the reinforcing steel. The action of carbon dioxide gas in the atmosphere on the free line in the cement paste converts the highly alkaline lime (calcium hydroxide) to only slightly alkaline calcium carbonate. Accordingly, the oxide film on the reinforcing steel ordinarily passive at pH 12 becomes active at pH 9. Carbonation is normally a problem only in older structures with an average rate of advance of 0.01 inches per year. Striping the cores with phenolthalein indicator revealed that carbonation has reached depths of ¾” in the cores which were submitted for testing. Shallow concrete cover on much of the reinforcing steel in the roof slabs results in the steel being located in the carbonation layer where little or no protection is provided.

Petrographic Examination

Petrographic examination of the samples of the concrete roof slab seen in core 5B, and to a certain extent 3, are representative of five of the cores extracted from the concrete that lies below the paved areas. The laboratory examination reveals the following:

- Large aggregate siliceous gravel, having a maximum size of ¾” contains quartzite, chert, granite, sandstone and schist

- Fine aggregate siliceous sand , with a maximum aggregate size of ¼”, containing quartz, quartzite, chert, granite, schist, ferruginous rocks and mafic materials

- Portland cement contents of 5 to 5 ½ bags of cement per cubic yard of concrete

- Cement paste having a water / cement ratio of from 0.50 to 0.55

- An air content of less than 1%, mostly large circular and irregular shaped voids

The cores, both 3 and 5B, contain extensive visual cracking. The cracks transect and circumscribe the aggregate particles and are oriented parallel to the surface. The cracking extends through the full depth of the core. The cracking has been caused by cyclical freeze-thaw of water that has saturated the concrete section and a lack of air- entrainment. Core 4 taken towards the west side of the reservoir below the grassed area contains no visible cracking. Core 3, although taken from below the grassed area, does show signs of cracking due to freeze-thaw action. A compression test performed on core 4 revealed that the non- deteriorated concrete is extremely strong with a breaking strength of 6186 PSI (ASTM C42). For the samples taken from below the paved areas there is clear evidence of extensive moisture migration as witnessed by the precipitation of secondary ettringite, calcium carbonate and alkali –silica gel deposits found in the cracks and voids of the samples reviewed under the microscope. The concrete is determined to be of poor quality.

Evaluation

The available construction documentation does not include the sheets presenting the magnitude of the live loadings upon which the structural design for the reservoir roof was based. Accordingly, based on the plans and sections provided by the City, a determination of the allowable live loading was provided in order to establish a safe loading for portions of the roof structure which are in good condition and to establish the structural requirements and sequencing for the proposed repair work. The evaluation is based on a concrete compressive strength of 3000 PSI and an allowable working stress in the reinforcing steel of 18 KSI. Based on our evaluation, we determined that the newly built structure was capable of supporting a live loading of approximately 300 PSF. Accordingly, assuming the 2' of earth cover over 60% of the area of the roof as dead loading, the allowable live loading of the grassed areas is approximately 100 PSF.

If the slab is to be replaced below the paved areas, the top 6" of the girders and beams, which are integral with the slab, must also be removed as part of the demolition. The removal will adversely affect the strength of the members since the proposed demolition exposes the top steel of the girders and beams (located above the columns and girders, respectively), rendering the top reinforcing steel useless with regard to load carrying capacity. The removal transforms the structure of both girders and beams from "fixed' end to simple span members. The resultant configuration is incapable of safely supporting the weight of the wet concrete for the replacement deck. Therefore, shoring of the girders and beams will be required in order to successfully replace the deteriorated concrete roof deck.

Recommendations

Based on the findings of our field review and the results of the laboratory testing of the cores taken from the roof slab, we are of the opinion that 40 % of the roof deck is in poor condition and should therefore be replaced. Prior to performing any work on the deteriorated portions of the structure, temporary shoring of the girders and beams must be provided. Shoring towers would be placed at the mid-span of the girders and at the point of intersection of the beams. We recommend that portions of the 6" structural slab and the top 6" of the girders and beams that support the slab be removed by selective demolition and subsequently replaced with new concrete structure matching the original section. The area is all that underlies the paved section seen at grade- approximately 33, 700 square feet of concrete deck. We envision that the demolition will be accomplished by saw-cutting the 5 1/2'by 5 1/2' panels of deck from the surrounding beams and girders and picking the pieces with a lifting eye anchored to the slab with a through bolt. Lifting each 1 ½ ton section would be performed by a small crane positioned at the perimeter of the reservoir. With the slabs removed, install plywood formwork on temporary clips attached to the beams and girders. This will provide staging for demolition of the deteriorated tops of the beams and the girders. Careful removal would be provided by hand operated chipping hammers. With demolition complete, set the reinforcing steel and cast the new concrete deck. Once curing is complete remove the temporary clips, the plywood forms and the shoring towers. High strength concrete, low water/ cement ratios and air-entrainment will provide an extremely durable structure.

In order to extend the service live of the portions of the roof that underlie the grassed sections, we are recommending that the deck be covered with a waterproof membrane protected by protection board. Remove 2' of earth that covers the deck and install a membrane with protection board over the entire grassed surface – approximately 40, 800 square feet in area. Once the deck was covered with membrane, the earth fill would be replaced and the area seeded and mulched.

There appears to be no reason to maintain a parking area above the reservoir. Accordingly, the concrete curbs and catch basins would be demolished; and storm water piping from the catch basins would be removed from the interior of the reservoir. To enhance the service life of the replacement roof deck, a membrane would be applied to the concrete surface. The placement of grass covered earth fill in this central area of the reservoir would be graded in such a manner as to provide positive drainage in all directions. For purposes of cost estimating we have assumed the depth of fill in this central area to be approximately 1 foot.

Estimate of construction cost

The following engineer's estimate of probable construction cost is based on our experience with other projects of similar scope; conversations with contractors and cost information provided in Building Construction Cost Data as published by RS Means. The costs associated with the temporary shoring of the girders and beams amounts to over half the cost of the recommended repair effort. For portions of the structure below the grassed areas, 60% of the total roof area, the cost of temporarily removing the fill and waterproofing the deck is considered an important part of extending the service life of the structure; especially, since the remaining 40% of the roof deck will be replaced. Although this deck is considered to be in fair to good condition, observed cracks and deposits of calcium carbonate on the underside of the deck indicate moisture is entering the concrete and adversely affecting the service life of this portion of the structure.

Description of work	Unit	Quantity	Unit price	Amount
Mobilization	LS	1	$10,000	$10,000
staging / shoring	LS	33,700	$25	$842,500
Demolition of concrete	SF	33,700	$5	$168,500
Cast replacement slab	SF	33,700	$9	$303,300
Excavation and backfill	CY	3,100	$20	$62,000
Earth fill (above replacement slab)	CY	1,300	$10	$13,000
Membrane cover	SF	74,500	$4	$298,000
Seed and mulch	SY	8,400	$1	$8,400
Subtotal				$1,705,700
Contingencies 20%				$341,100
Engineering / administration 6 %				$122,800
Total				$2,169,600