A NEW THEORY FOR THE DESIGN OF REINFORCED CONCRETE RESERVOIRS.*

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In circular water receptacles the water pressure at the base per square foot equals the product of the weight of water per cubic feet by the depth in feet. The tension in the wall per foot in height equals the product of the water pressure per square foot by the radius. For example, in the Manchester reservoir (50 ft. diam., 72 ft. high) the water pressure per square foot at the base equals 62½ by 72 = 4,500 lbs. per sq. ft. The tension in the wall for the first foot in height equals 62½ by 71½ by 25, equal to 113,300 lbs. It has generally been assumed that this tension should be taken up entirely by steel reinforcement in the shape of horizontal steel rods bent to the radius of the reservoir and sufficiently lapped or mechanically attached to each other to develop the tensile strength when enveloped in concrete. It has been further assumed that a thickness of concrete sufficient to encase the steel reinforcement and to transmit the stress from one tension rod to another should be used. Empirical rules have been used for determining this thickness, relating only to obtaining the necessary bonding strength and a thickness of concrete supposedly enough to prevent seepage of water through the walls. No assumptions, to the writer's knowledge, have heretofore been made with the idea of utilizing the tensile strength of concrete prior to the construction of the reservoir at Rockland. The mixture of concrete that has generally been used in the past is one part of cement, two parts sand and four parts gravel or crushed stone with the addition of hydrated lime or special compounds for densifiers, if I may use that term. As it is almost impossible to so thoroughly mix a 1:2:4 concrete either by hand or machine so as to make it entirely impermeable to water, the walls and floor have been usually coated with a cement mortar or with some other waterproofing compound.

As there is a tendency for the diameter of a reservoir to increase after it is filled with water due to the elasticity of the steel in tension, and as the base of the reservoir is practically rigid, due to its intimate contact with the foundation upon which it rests, it has been deemed necessary to install some reinforcing material extending from the base up into the walls to take care of the bending moment and shear at the base. The writer does not know, nor has he been able to find any exact method of obtaining, the amount of steel required here, but he thinks that in most cases heretofore it has been underestimated.

As the several operations of building up forms, placing steel and concrete preclude making the concrete work continuous, it is advisable to make as short intervals as possible between successive layers of concrete, and where these joints occurred to bond together the successive layers in the best possible manner. These instructions as outlined were followed out in the construction of the reservoirs at Waltham, Manchester and Lisbon Falls, except that the two latter reservoirs were made with a 1:1½:3 mixture of concrete plus 5 per cent. hydrated lime. For the Manchester reservoir the thickness of the wall at the base is 20 ins., and at the top 12 ins. The steel is designed for a unit working stress of 12,000 lbs. per sq. in. when the reservoir is full of water. At the base are installed rods which are embedded in the floor and turned up into the walls. These rods are 1 in. in diameter and are laid 12 ins. on centers and extend into the wall about 4 ft. 6 ins. The floor was finished with 1 in. granolithic, and the walls were plastered with two coats, making about 1 in. thickness of 1:1 cement mortar. But after the filling of the reservoir various features were observed which showed that some improvement might be made in the design of future work.

There developed at several of the horizontal joints—and especially at the three lower joints—between each day's work, some seepage of water, which in three places increased to positive leaks. The seepage, however, at the upper joints gradually stopped, presumably due to the filling of the pores by hydrated lime. We at first saw no reason why any leakage should develop. We had supposed that the concrete was rich enough, that the inside coating of 1:1 plaster, put on in such a manner as to make a double lap over the joints, and that the care taken in grooving and grouting the joints between each day's work, was sufficient to make the reservoir absolutely tight, and when we found that a little leakage did occur after taking all these precautions, we naturally began an investigation to determine the reasons therefore and to obtain for future work some protection against it. Upon examination of the reservoir after it was emptied, we found that there were horizontal cracks at the joints mentioned, about 30 ft. long, and extending through the wall, also that there were vertical cracks in the plastering extending upward for 20 ft. or so, and furthermore, that there were checks in the plastering from which the water oozed back into the reservoir after it was emptied.

From these observations we made the following deductions: that there was not enough vertical steel properly distributed to fully distribute the bending moment and shearing stress between the rigid base and the walls, and that the lack of this probably was the cause of the horizontal cracks. Second, that the ultimate strength of the concrete was probably exceeded when the reservoir was filled with water, thus producing the vertical cracks, and that these vertical cracks allowed the water to permeate into the walls and through them to the lines of least resistance, which would be the horizontal joints. Third, that the addition of a rich plaster coat with a more or less permeable concrete back of it was useless, as the usual crazing and the vertical cracking which would occur due to the tension would also allow the percolation of water through it.

This second deduction is the basis of this paper. From tests which have been made on concrete beams, it has been found that microscopic cracks have developed in the concrete on the tension side when the steel reinforcement was stressed to 4,000 or 5,000 lbs. per sq. in., or perhaps less; that these cracks gradually widened until they were finally visible. It is presumable that these cracks began when the ultimate strength of the concrete in tension was reached, and at a time that the unit stress in the steel was approximately ten times that in the concrete. These microscopic cracks were made visible by the application of water, and water lines following them could be seen. If these cracks developed in beams when the stress in the steel was only 5,000 lbs. or thereabouts, sufficient to admit water, why should they not develop in reservoir walls when the steel was stressed to the same point? And furthermore, if the walls were made so thin that they took little of the tensile stress, it being all thrown in the steel, at 12,000 or 16,000 lbs. per sq. in. or at any intermediate working value between these, why would no vertical cracks show in the walls, and permit water to seep into the walls?

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