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Analysis and Design of a 10 M Elevated Reinforced Concrete Water Reservoir of 80 M³ Capacity

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Abstract

Reliable water storage is an essential component of water-supply infrastructure, particularly where continuity of supply is required during periods of peak demand or intermittent production. This paper presents the structural analysis and design of an 80 m³ elevated reinforced concrete water reservoir with a nominal staging height of 10 m. The proposed tank is rectangular in plan, measuring 6.7 m × 4.0 m, with a 3.0 m water depth and a 0.5 m freeboard, giving an overall tank height of 3.5 m. The structural assessment considers hydrostatic pressure, self-weight, gravity loads, wind action and the effects of these actions on the tank walls, base slab, roof slab, beams, columns, bracing members and foundations. The design approach follows the limit-state philosophy of the Eurocodes, with EN 1992-3 used for the liquid-retaining components and EN 1992-1-1 used for the supporting reinforced-concrete staging and other structural members. Particular attention is given to serviceability, crack control, deflection, durability and reinforcement detailing because an elevated water tank must satisfy both structural strength and liquid-tightness requirements. The design indicates 300 mm tank walls, a 350 mm base slab, 200 mm roof slab, reinforced concrete beams and 400 mm-class columns, with a 2.0 m × 2.0 m isolated footing adopted for the critical support. The results indicate that the proposed structural system can satisfy the stated design objectives under the assumptions adopted. However, the final construction design should be verified against project-specific geotechnical data, wind parameters, seismic requirements, material certificates and the approved structural drawings.

Keywords: Elevated water reservoir; reinforced concrete; hydrostatic pressure; Eurocode 2; liquid-retaining structures; ultimate limit state; serviceability limit state; crack control.

1. Introduction

Water storage infrastructure provides an important buffer between water production and water consumption. Adequate storage improves the reliability of supply by allowing water to be retained for use during periods of high demand, temporary interruption of production and other operational constraints. Elevated reservoirs have the additional advantage of providing hydraulic head through gravity, thereby reducing dependence on continuous pumping for distribution.

From a structural-engineering perspective, elevated reservoirs are more demanding than ordinary reinforced concrete buildings because the structure must simultaneously carry substantial permanent and liquid loads while remaining stable under environmental actions. The tank walls are directly subjected to hydrostatic pressure, whereas the supporting staging transfers the combined tank, water and environmental actions to the foundation. For liquid-retaining structures, serviceability is especially important because excessive cracking can compromise water tightness and durability even when the ultimate strength of the member is adequate. EN 1992-3 therefore provides additional rules for elements directly supporting stored liquids, while supporting members such as the tower are designed using the general provisions of EN 1992-1-1.

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The dynamic behaviour of elevated water tanks is also important where earthquake action is relevant. Housner (1963) demonstrated that the liquid response should be considered together with the response of the supporting tank structure because the free surface of the water can produce convective or sloshing effects. Subsequent work on elevated tank staging has similarly emphasized the importance of the flexibility and dynamic response of the support system (Jain & Sameer, 1990).
The present study develops and documents the structural design of an 80 m³ rectangular elevated reinforced concrete reservoir proposed for Ụmụnneochi L.G.A., Abia State, Nigeria..

2. Design Methodology

The design follows a limit-state approach. The structural system is first idealized into its principal components and the relevant permanent, variable and environmental actions are identified. The tank is then checked under ultimate and serviceability limit states. For the water-retaining components, the assessment places particular emphasis on crack limitation and durability in addition to flexural and shear resistance.

2.1 Design Standards and References

The principal standards adopted in the source design are:

• EN 1991 (Eurocode 1): Actions on structures, including general imposed actions and wind actions.

• EN 1992-1-1 (Eurocode 2): General rules and rules for buildings for reinforced concrete design.

• EN 1992-3 (Eurocode 2): Additional provisions for liquid-retaining and containment structures.

• EN 206: Concrete specification, performance, production and conformity.

• ACI 371R-16 is also relevant as supplementary guidance for the analysis and design of elevated concrete water-storage structures.

2.2 Design Data

Parameter	Adopted value
Location	Ụmụnneochi L.G.A., Abia State, Nigeria
Structure	Rectangular elevated reinforced concrete water reservoir
Storage capacity	80 m³
Staging height	10 m
Tank length	6.7 m
Tank breadth	4.0 m
Water depth	3.0 m
Freeboard	0.5 m
Overall tank height	3.5 m
Concrete	C30 in the source design; recommendation stated as C30/37
Reinforcement	High-yield reinforcement, f_{yk} = 410 N/mm²
Exposure class	XC3, as stated in the source document
Assumed soil bearing capacity	150 kN/m²
Basic wind speed used in source design	10 m/s

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2.3 Tank Geometry and Storage Capacity

The required storage volume is obtained from V = L × B × H. Adopting a water depth of 3.0 m gives a required plan area of approximately 26.7 m². The source design adopts a length of 6.7 m and a breadth of 4.0 m, giving a nominal storage volume of approximately 80.4 m³ at the 3.0 m water level. A 0.5 m freeboard is then provided, resulting in an overall tank height of 3.5 m. The freeboard provides space above the normal operating water level and helps reduce the likelihood of overtopping.

3. Structural Loading and Analysis

3.1 Hydrostatic Pressure

The governing liquid pressure on the tank wall occurs when the reservoir is full. For water, the hydrostatic pressure varies approximately linearly with depth and may be expressed as $p = \gamma w\ h$, where γw is the unit weight of water and h is the depth below the free surface. Using $\gamma w \approx 9.81$ kN/m³, the pressure at 3.0 m water depth is approximately 29.4 kN/m².

For a 1 m wide vertical strip of wall, the resultant hydrostatic force is triangularly distributed and acts at one-third of the water depth above the base. This produces the principal bending action in the lower portion of the wall.

3.2 Self-Weight and Gravity Actions

Permanent actions include the self-weight of the tank walls, base slab, roof slab, beams, columns and other permanent components. The design calculations use a nominal reinforced-concrete unit weight of 24 kN/m³. Water weight is also included in the vertical load transferred to the supporting system. Finishes and other permanent loads are included where applicable.

3.3 Wind Action

Wind action is assessed with reference to EN 1991-1-4. The design adopts a basic wind speed of 10 m/s and concludes that the direct wind pressure on the tank is comparatively small for the assumed condition, although wind action is relevant to the elevated staging because of its exposed height and lateral flexibility. In a final project design, the basic wind velocity, terrain category, orography, directional factors and pressure coefficients should be established from the actual site and the applicable National Annex.

3.4 Ultimate and Serviceability Limit States

The ULS assessment is used to establish the required flexural and shear resistance of the structural members, while the SLS assessment considers deflection and crack control. For water-retaining structures, SLS is not a secondary check: crack width and reinforcement arrangement are directly related to liquid tightness and durability. The design therefore increases reinforcement in the tank wall where the initial serviceability assessment is unsatisfactory and adopts relatively close bar spacing.

4. Design of Tank Components

4.1 Tank Walls

The source design initially investigates the required wall thickness using the liquid-retaining provisions of EN 1992-3 and subsequently adopts a 300 mm wall thickness. This provides a substantial concrete section for durability, reinforcement arrangement and crack control. The wall is designed for hydrostatic pressure and the resulting bending moment.

The design calculations indicate that Y16 reinforcement at 200 mm centres was initially considered at the ULS. The SLS assessment led to a closer spacing, and the final arrangement reported in the source document is Y16 at 150 mm centres on both the near and far faces. Transverse reinforcement is reported as Y12 at 150 mm centres. This arrangement provides approximately 1,340 mm²/m of Y16 reinforcement per face in the principal direction.

4.2 Base Slab

The base slab receives the hydrostatic load transmitted through the water and tank walls and must transfer the resulting actions safely to the supporting beams or staging. The source design adopts a 350 mm thick base slab. The design considers the wall load, roof load, water load, slab self-weight and finishes. The critical bending regions include support and span zones, with reinforcement provided to address both hogging and sagging actions.

The source design reports Y16 reinforcement at 200 mm centres in the principal negative-moment region and a closer spacing of Y16 at 100 mm centres following the serviceability assessment. Y12 at 150 mm centres is reported as transverse reinforcement. These values should be checked against the final support arrangement and actual load distribution before construction.

4.3 Roof Slab

The roof slab is not directly subjected to hydrostatic pressure, but it carries its own weight, finishes and access or maintenance actions. The source design considers two-way spanning behaviour and adopts a 200 mm slab thickness. Y16 reinforcement at 200 mm centres is reported as the principal reinforcement. Because the roof is not a liquid-retaining surface, its crack-control requirements differ from those of the tank walls and base.

5. Design of Supporting Beams

The tank support system comprises beams that collect and transfer the tank loads to the columns. The source design considers the self-weight of the beams, loads transferred from the two-way slabs and reactions from adjacent members. The critical beam sections are checked for flexure, shear and deflection.

Member	Section	Reported reinforcement
Beam 1	300 × 600 mm	5Y20 reported for principal tension reinforcement; 2Y16 support reinforcement; 2-leg Y10 links @ 250 mm
Beam 2	300 × 500 mm	2Y20 principal reinforcement; 2Y20 support reinforcement; 2-leg Y10 links @ 250 mm
Bracing beam	300 × 350 mm	2Y16 longitudinal reinforcement; Y10 links @ 250 mm
Ground beam	300 × 450 mm	3Y16 support reinforcement; 2Y16 span reinforcement; Y10 links @ 250 mm

One important result from the deflection calculation is the deflection check for Beam 1. The original 300 × 500 mm trial section produced an actual span-to-effective-depth ratio of approximately 8.3, which was greater than the reported allowable value. The beam depth was therefore increased to 600 mm. With the revised effective depth, the reported actual ratio reduced to approximately 6.7, which satisfied the stated deflection criterion. This illustrates the importance of serviceability checks in selecting member dimensions rather than relying solely on ultimate flexural strength.

6. Column Design and Stability

The elevated staging columns transfer the reactions from the tank-supporting beams to the foundation. The source analysis accumulates beam reactions and column self-weight through successive storeys or levels. The reported design axial forces increase toward the foundation, with values of approximately 346 kN, 392 kN and 444 kN for successive column segments.

The design calculation checks column slenderness and treats the investigated columns as short columns under the stated assumptions, thereby concluding that second-order effects are not governing. The reported longitudinal reinforcement is 4Y20, with Y10 links at 150 mm centres. The final detailing should nevertheless comply with the minimum longitudinal reinforcement, transverse

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reinforcement, cover, anchorage and confinement provisions of the adopted Eurocode and its National Annex.

7. Foundation Design

The foundation transfers the accumulated column action to the supporting soil. An allowable or assumed soil bearing capacity of 150 kN/m² is used in the source design. The critical support reaction is taken as approximately 460 kN, and a 2.0 m × 2.0 m isolated footing with a trial thickness of 600 mm is adopted. Flexural resistance is checked at the column face, while one-way shear and punching shear are assessed at the relevant critical perimeters.

The reported reinforcement is Y12 at 150 mm centres. The source design concludes that the calculated shear and punching-shear resistances exceed the corresponding design actions. These conclusions are conditional on the assumed soil bearing capacity; a geotechnical investigation is essential before the foundation dimensions are finalized.

8. Crack Control, Durability and Water Tightness

The most important distinction between a water reservoir and a conventional reinforced concrete frame is the requirement to maintain liquid tightness throughout the service life. EN 1992-3 supplements the general concrete design rules with provisions specifically directed toward structures containing liquids. Crack-control design is therefore influenced by reinforcement ratio, bar diameter, bar spacing, restraint, concrete properties and the specified tightness requirements.

The design demonstrates this principle by modifying reinforcement spacing after an SLS crack-width assessment. The wall reinforcement was changed from Y16 at 200 mm centres to Y16 at 150 mm centres after the reported initial crack-width assessment was judged unsatisfactory. This is a sound design philosophy: when liquid tightness governs, the designer should not rely on minimum reinforcement alone but should proportion and distribute reinforcement so that cracking is controlled.

Durability also depends on adequate concrete quality, cover, compaction, curing and detailing at construction joints. ACI 371R-16 recognizes that elevated water-storage tanks have structural and construction considerations that differ from ordinary structures. For components in contact with stored water, liquid-retaining design principles should be followed consistently rather than treating the tank as an ordinary building slab or wall.

9. Summary of Principal Design Results

Design item	Result / adopted provision
Tank plan dimensions	6.7 m × 4.0 m
Water depth	3.0 m
Freeboard	0.5 m
Overall tank height	3.5 m
Nominal storage capacity	80 m³
Tank wall	300 mm thick
Wall main reinforcement	Y16 @ 150 mm c/c each face, as reported
Wall transverse reinforcement	Y12 @ 150 mm c/c
Base slab	350 mm thick
Base slab principal reinforcement	Y16 @ 100–200 mm c/c in reported critical regions
Roof slab	200 mm thick; Y16 @ 200 mm c/c reported
Beam 1	300 × 600 mm; 5Y20 reported
Beam 2	300 × 500 mm; 2Y20 reported
Bracing beam	300 × 350 mm; 2Y16 reported
Columns	4Y20 longitudinal reinforcement reported; Y10 @ 150 mm links
Critical footing	2.0 m × 2.0 m × 0.6 m trial footing

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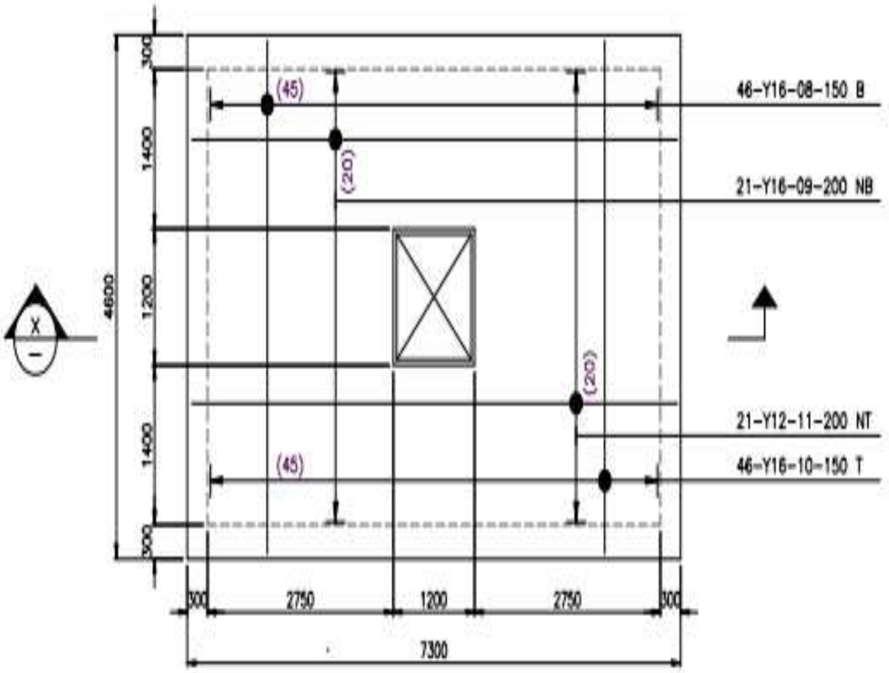
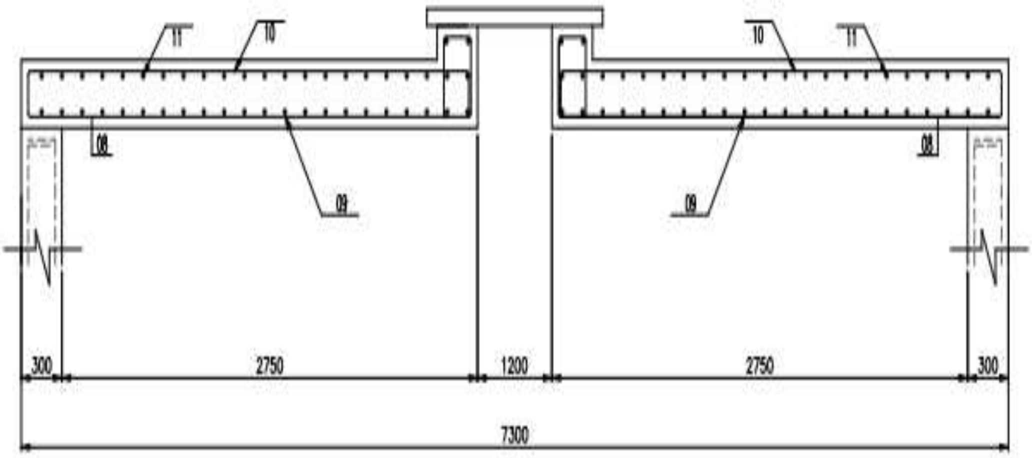


TOP SLAB (COVER) DETAILING

SCALE 1:100



SECTION X–X

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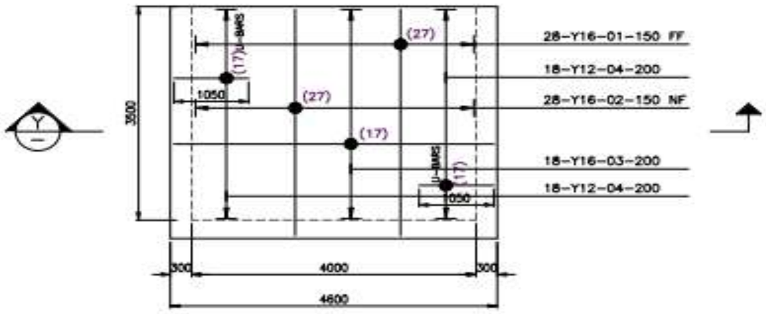

SIDE WALL DETAILING
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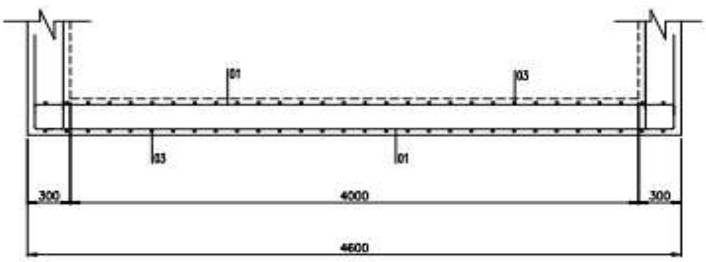

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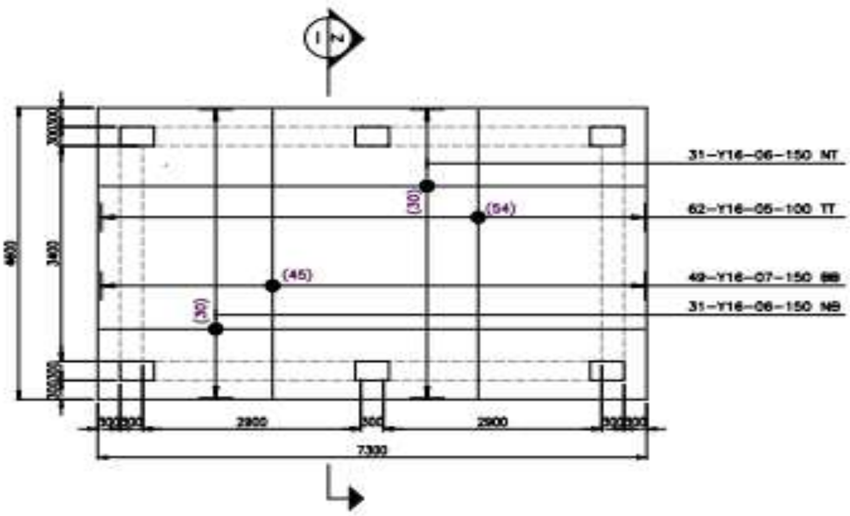

BOTTOM SLAB DETAILING
SCALE 1:100

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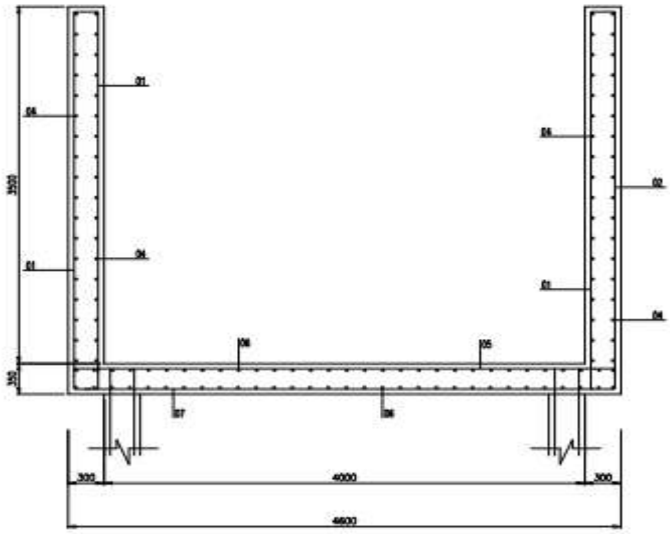

SECTION Z–Z
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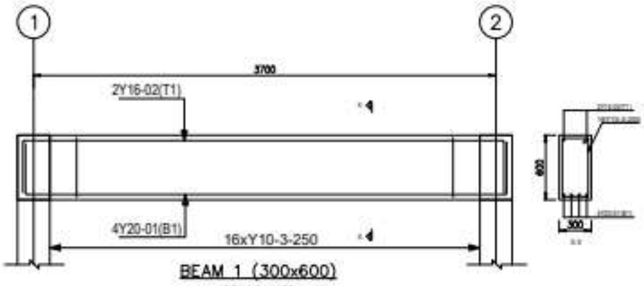
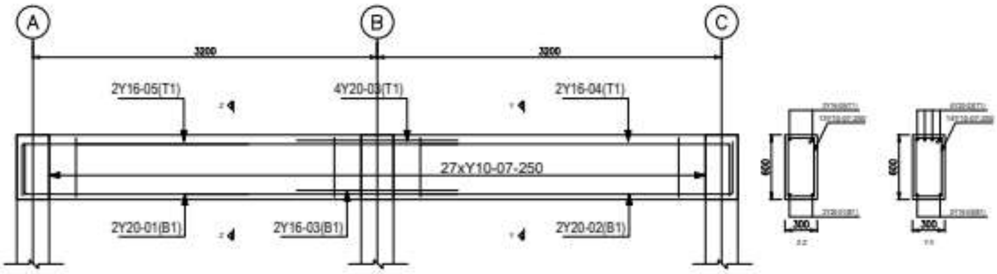


BEAM 1 (300x600)
SCALE 1:50



BEAM 2 (300x600)
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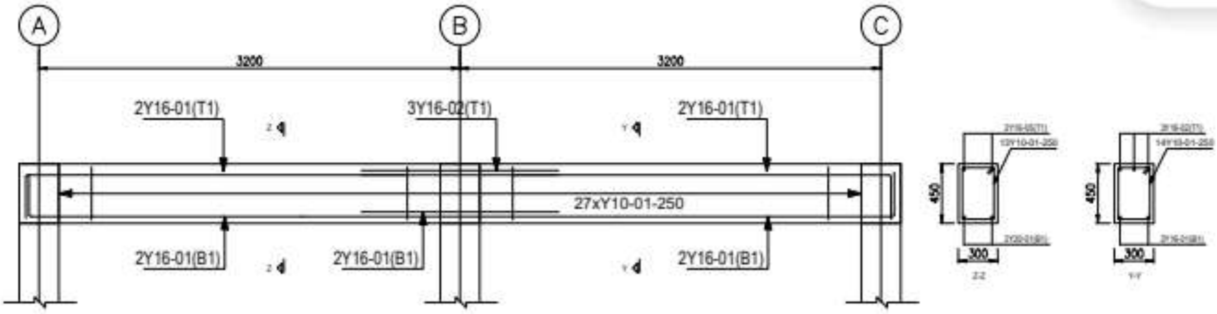

GROUND BEAM 1 (300x450)
SCALE 1:50

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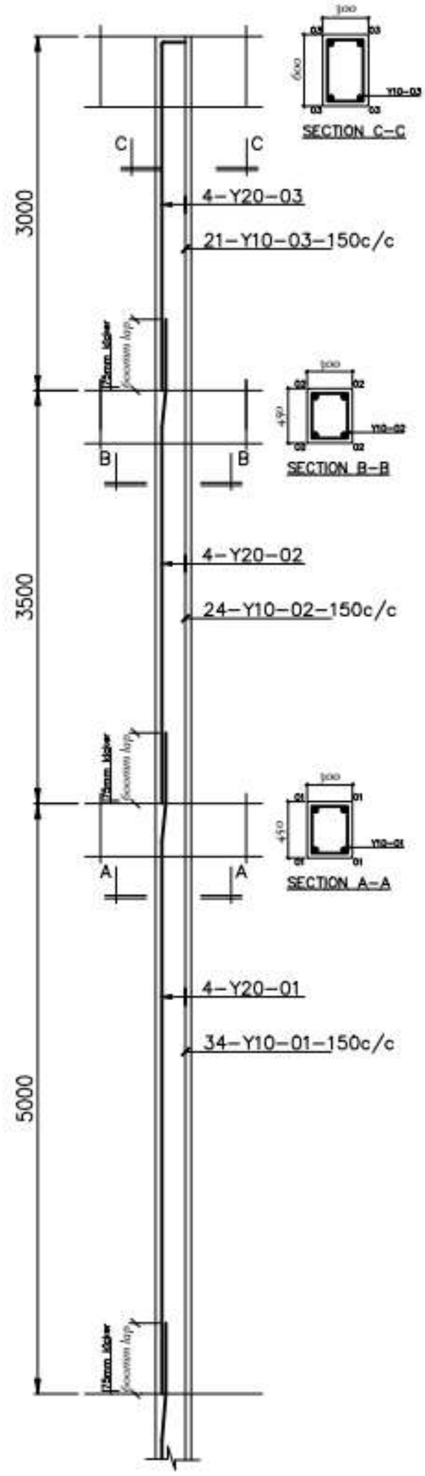
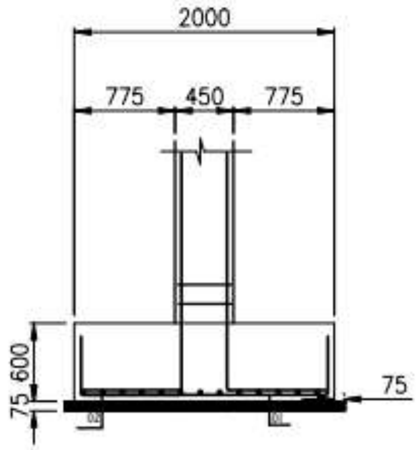
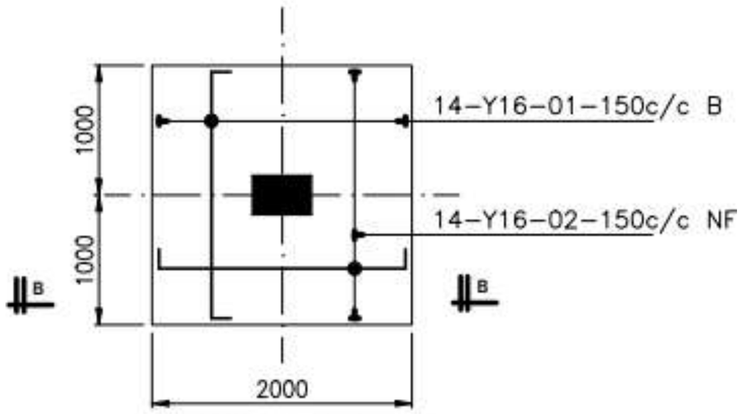




SECTION B-B



PAD FOOTING DETAILING
SCALE 1:100

COLUMN SECTIONAL DETAILING
SCALE 1:100

The design illustrates the interaction between strength and serviceability in elevated liquid-retaining structures. Although hydrostatic pressure is the dominant direct action on the tank walls, the total structural demand is distributed through the base slab, support beams, columns, bracing system and foundations. The elevated arrangement also makes the staging sensitive to lateral actions because the tank mass is located well above ground level.

The use of relatively thick tank walls and a substantial base slab provides practical advantages for reinforcement arrangement, durability and crack control, but it also increases permanent load. The

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design therefore requires a balanced approach in which member dimensions are sufficient for structural performance without unnecessarily increasing dead load. The beam redesign prompted by the deflection check is a useful example of this iterative process.

The source design treats wind as relatively small under the assumed basic wind speed, but this conclusion should not be generalized to every location. The lateral response of an elevated tank depends on tank geometry, exposed staging area, terrain, wind velocity and structural stiffness. Similarly, seismic action has not been fully developed in the source calculations. Housner's work shows why liquid-structure interaction and sloshing should be considered where earthquake loading is relevant.

The principal limitation of the study is that some numerical intermediate equations and graphical calculation sheets in the supplied document are not available as machine-readable text. Consequently, the present article preserves the reported design outputs and methodology rather than inventing missing intermediate values. Before construction, all calculations should be independently rechecked from the final structural model and drawings.

11. Conclusions

The study demonstrates the structural design process for an 80 m³ elevated reinforced concrete water reservoir supported approximately 10 m above ground. A rectangular tank measuring 6.7 m × 4.0 m with a 3.0 m water depth and 0.5 m freeboard was selected to satisfy the required storage volume.

The tank walls, base slab and roof slab were proportioned for their respective loading conditions, while the supporting beams, bracing members, columns and isolated foundations were designed to transfer the resulting actions safely to the ground. The reported design adopts a 300 mm wall, 350 mm base slab and 200 mm roof slab, with reinforcement arrangements selected from ULS and SLS considerations.

The serviceability assessment was particularly important. The source design demonstrates that increasing reinforcement density and reducing bar spacing can improve crack control, while increasing beam depth can be an effective response to excessive deflection. These measures are consistent with the fundamental requirements of liquid-retaining concrete structures, in which durability and water tightness are as important as ultimate strength.

Overall, the reported design provides a reasonable academic basis for the analysis of the proposed reservoir under the stated assumptions. Nevertheless, the design should not be regarded as construction-ready without verification of the final geometry, site-specific wind and seismic parameters, geotechnical investigation, concrete and reinforcement specifications, construction joints, water-tightness detailing and the applicable Nigerian regulatory requirements.

12. Recommendations

• Use the specified concrete strength and reinforcement grade only after confirming their availability and conformity through approved material testing.

• Carry out a site-specific geotechnical investigation before finalizing the foundation size and reinforcement.

• Reassess wind action using the actual site terrain, exposure, basic wind velocity and the applicable National Annex.

• Where seismic action is applicable, perform a dedicated seismic analysis that accounts for the dynamic interaction between the stored water, tank and staging.

• Maintain the crack-control philosophy throughout detailed design, especially at wall-base junctions, corners, construction joints and penetrations.

• Provide appropriate concrete cover, compaction, curing and joint-waterproofing details to improve durability and water tightness.

• Use structural-analysis software as an independent verification tool rather than as a substitute for engineering judgement and hand checks.

• Prepare final reinforcement drawings showing bar diameters, spacing, laps, anchorage, bends, cover and construction-joint details before construction.

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