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THE DESIGN OF AN UNDERGROUND STORAGE SYSTEM FOR RAINWATER HARVESTING IN IBADAN METROPOLIS, NIGERIA

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Abstract

With vastly increasing population concentration in urban areas of Nigeria, water availability has already caused an intractable problem, whose solution has to involve harnessing and storing water from all sources for continual use. This work is on designing a rainwater storage system for use in individual homes in Ibadan, Oyo State, Nigeria.

Inputs to the design are rainfall data for 1980 to 2003 from which the theoretical rainwater quantity harvestable each month was calculated. Water demand per household of eight persons was computed for use in the design. Plotting the graphs of the cumulative mean monthly rainfall and of uniform monthly water demand, the minimum capacity of water storage tank to meet the demand was obtained.

The size of the storage tank and various forces acting on it were found to depend on the roof type and roof plan area.

Introduction

Rainwater is not always available when needed, rainfall being seasonal. Even during rainy seasons, rain does not come everyday. This necessitates the need for storage facilities. A DTU (2002) Report, lists five different types of storage tanks of varying sizes that have been designed and put to use. These could be underground or aboveground. They are:

- ***Precast Concrete Tanks:*** These are popular in developed countries such as Germany and Australia. They were found to be too expensive for use in developing countries (Szilassy, 1999; Lee and Visscher, 1990).
- ***Steel Tanks:*** They are common storage means in use worldwide. However, corrosion problems have limited its usage, especially in the hot, humid developing countries.
- ***Plastic Tanks:*** They are gaining popularity. Poor access for cleaning the inside of the tank is a problem. Tanks of black colour tend to overheat as it absorbs radiant heat when exposed to the sun. This could be an advantage as heat help in killing some germs in the water.
- ***Ferrocement Tanks:*** They are regarded as a technology of choice for many rainwater harvesting programmes. The tanks are relatively inexpensive and require only little maintenance. They last almost indefinitely. The technique for its fabrication was developed in France (Morgan, 1994), and has spread to parts of Africa (Nissen-Peterson and Lee, 1990).
- ***Brick Tanks:*** These are not good for water tanks (DTU, 2002). They are weak in tension, and relatively porous.

A good water storage tank should be strong and be water-tight. There is the need for its foundation to be able to withstand outpouring of excess water. Being opaque to sunlight is desirable, in order to prevent algae and larval growth. Adequate ventilation is also essential in order to prevent anaerobic decomposition of washed-in matters (DTU, 2002).

Storage size, alongside with water demand and rainfall pattern, is responsible for the reliability or otherwise of rainwater harvesting system as a mean of water supply, especially in homes. In a study of 24 years' rainfall data of Ibadan, Lucas *et al.*, (2006) found that, for rainfall level that is less than or equal to 1316mm, the probabilities of exceedence are high (above 50%) and thus a low return period of less than or equal to 1.9 years is required in order to ensure the reliability of the rainfall pattern of Ibadan (with annual average amount of 1310mm) for rainwater harvesting system. The theoretical size of the storage tank required is determined by multiplying the daily water needs by the number of expected dry days (about 150 days); the requirement being projected for future expansion.

Underground storage tanks are cost-saving as the foundation problems are eliminated since the tanks are immersed in the supporting soil. Large tanks, such as of 90m^3 capacity developed in

Kenya by Nissen-Peterson and Lee (1990), could be so constructed. Such tanks have been found to be "popular for schools and public buildings" (DTU, 2002). Stable soils, such as obtains in Ibadan, have the property of reliably taking the force of the water and thus cement mortar is needed as sealant. Thomas and McGeever (1997) made such tank in Western Uganda with 25mm layer of mortar applied directly to the soil with few reported problem after 5 years' service. Although, underground tanks may have some problems such as difficulty in locating and repairing leaks, good design and construction will overcome such problems and underground storage would in this wise be advantageous as it does not occupy ground level space and it is of low cost.

Methodology

Rainfall data for Ibadan covering the period 1980 to 2003 inclusive, were collected from the International Institute of Tropical Agriculture (IITA) Ibadan. These were used to calculate the mean monthly rainfall over the period. The cumulative of the mean monthly rainfall (from January) was calculated. These are contained in Table 1. The theoretical quantity of rainwater, Q_h, that could be harvested each month as a direct function of roof plan area (A_r) and roof type (C_r) was calculated, using the formula Abegunrin, 2004)

$$Q_h = HCR \,.\, A_r \,.\, C_r$$

where HCR is the highest cumulative rainfall; A_r is the roof plan area and C_r is the coefficient of runoff, which is roof type specific. The uniform monthly water demand was (also) calculated using the formula $Q_m = Q_h/12$, where Q_m is the uniform monthly water demand.

The inflow mass curve, which is the graph of cumulative of mean monthly rainfall against time (months) was plotted. The graph of uniform monthly water demand; a straight line through the origin was also plotted on the same axis. The curves are presented in figure 1. The minimum storage capacity of the tank required to meet the water demand is obtained from the curves.

Result Analysis and Discussions

The quantity of rainwater that could be harvested per year is given as (Abegunrin, 2004)

$Q_h = 1373.83A_rC_r$

The uniform monthly demand is given as (Abegunrin, 2004)

$Q_m = (1373.83A_rC_r) / 12$

$Q_m = 114.49A_rC_r$

In Figure 1, X_1 is the lowest point on the inflow curve. X_2 represents the minimum initial storage required to cater for the deficit during *0* to X_1. Between points *A* and *B*, demand is approximately equal to the inflow. From B to X_3, the gradient of the mass inflow curve is greater than that of the demand, meaning that water level in the tank is increasing. X_3 represents the maximum storage tank level.

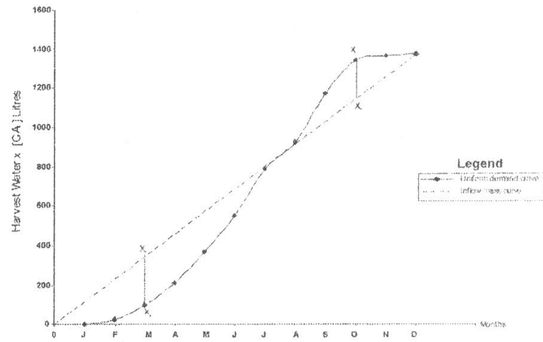

Fig. 1, Mass Curve of Mean Monthly Rainfall of Ibadan between 1980 and 2003

The minimum storage capacity, S_c, of the tank required to meet the demand is given as:

$S_c = [X_2 - X_1] + [X_3 - X_4]$

$= [337.5\text{-}100] + [13337.5\text{-}1137.5]\, A_rC_r$

$= 437.5A_rC_r$ litres

where

S_c = Minimum storage capacity

A_r = Roof plan area

C_r = Coefficient of runoff

In this work, a cylindrical tank was considered because the absence of sharp edges reduces the incidences of stress concentration. For a household of 8 persons, with a roof plan area 20m^2 of iron sheet ($Cr = 0.9$), requiring 20litres of water per person per day, a typical underground cylindrical tank is shown in Figure 2.

The tank should serve the household for 150 dry days in the year (Abegunrin, 2004).

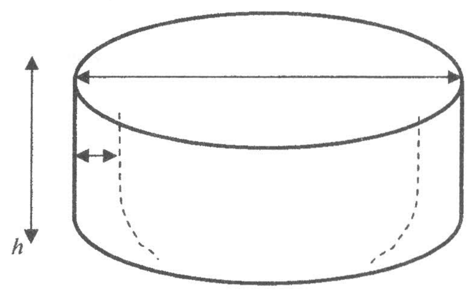

Figure 2: Sketch of a typical concrete mortar underground water tank.

d = *diameter (m), say 5.53m*

h = *height (m), say 4.26m*

t = *thickness (mm), say 25mm*

Table 1: *Cumulative mean monthly rainfall for Ibadan between 1980 and 2003*

Month	Mean Rainfall (mm)	Cumulative of Mean Rainfall (mm)	Quantity of Harvested Water* (Litres)
January	2.35	2.35	2.35
February	22.75	25.10	25.10
March	74.23	99.33	99.33
April	112.95	212.28	212.28
May	156.46	368.74	368.74
June	183.45	552.19	552.19
July	235.64	787.83	787.83
August	136.8	924.63	924.63
September	244.7	1169.33	1169.33
October	172.4	1341.73	1341.73
November	22.88	1364.61	1364.61
December	9.22	1373.83	1373.83

* Quantity of harvest rainwater = Cumulative of Mean Rainfall x $[A_r C_r]$

The pressure in a liquid is directly proportional to both the depth and specific weight of the liquid.

$$p = h\rho g$$

p = pressure (N/m^2)
ρ = density (kg/m^3)
g = acceleration due to gravity (m/s^2)

The water pressure is maximum at the bottom and zero at the surface. Thus where space is available, a cylindrical tank in which the diameter is greater than the height is advantageous as the water pressure will be minimum.

The capacity of a cylindrical tank of height h and diameter d is given as

$$C = (\pi d^2 h)/4$$

where

C = capacity (m^3)
d = diameter (m)
h = height (m)

This capacity must be large enough to contain the minimum water requirement to meet the demand. That is;

$$C \geq S_c$$

$$(\pi d^2 h)/4 \geq 437.5 A_r C_r \times 10^{-3}$$

$$h \geq 0.557 A_r C_r d^{\ 2}$$

Given that the density of water = $1000 kgm^{-3}$ and acceleration due to gravity $9.81 ms^{-2}$, then the maximum pressure, p_{max}, at the bottom of the tank will be

$$p_{max} = 5.46\, A_r C_r\, d^2\ kNm^{-2}$$

This pressure acts vertically over the whole base and thus the maximum loading is $5.46\, A_r C_r\, d^{-2}\ kNm^{-2}$. The total force F_b on the base will then be

$$F_b = p_{max} \times base\ area \quad kN$$
$$= 4.29 C_r A_r \quad kN$$

This force F_b acts at the centre of the base. The total force on side per metre of perimeter, F_w, is given as

$$F_w = \frac{p_{max}\, h}{2}$$

$$F_w = 1.52 A_r^2 C_r^2\, d^{-4}\ kN$$

F_w will act at $^1/_3\ h$ above the base.

The burst strength of the concrete of thickness t for the underground tank must well exceed the pressure of water at the bottom of the tank.

The hoop or circumferential stress Φ_c on the cylinder, as a pressure vessel is given as

$$\Phi_c = (p_{max} . d)/2t \ (N/mm^2)$$

where

p_{max} = maximum pressure (N/mm^2)
d = diameter of the cylinder (mm)
t = thickness (mm)

$$\Phi_c = 2.73 \times 10^{-3} A_r C_r\, d^{-1} t^{-1}\ (N/mm^2)$$

The longitudinal stress, Φ_L, is given as

$$\Phi_L = \tfrac{1}{2}\, \Phi_c$$
$$= 1.37 \times 10^{-3}\, A_r C_r\, d^{-1}\, t^{-1}\ (N/mm^2)$$

These values were found to compare favourably with the absolute values.

Table 1 shows the quantity of rainwater that could be harvested in a year, for a given roof plan area and roof type. This quantity was divided by twelve to obtain the average monthly demand. Figure 1 shows that the initial water storage is $[X_2 - X_1]$ litres and the final storage as $[X_3 - X_4]$ litres. The storage capacity of the tank was obtained as a function of roof type and roof area. Thus the sizing of the tank is proportional to the roof area. This has a cost-saving advantage as the tank will not be unnecessarily big or small. The design is however based on the average rainfall records. In effect, there will be some dry years, when the tank will not come to filling, and there will also be good rainy years, when the water will exceed the evaluated capacity. It is therefore necessary to provide an overflowing opening in the design and an estimated value of about 20% should be allowed in the volume of the tank to cater for any excess in water inflow due to heavier rains.

The storage tank was designed to cope with maximum water pressure. Where space is not at premium, the tank should be as shallow and wide as practicable. The design gave the tank depth as a function of roof area, roof type and the tank diameter. The two conflicting parameters, depth and diameter, could thus be varied as a function of the available space. Concrete (mortar) to be used must be able to withstand the forces acting on the tank. These forces were found as functions of roof type and roof area, which affect the quantity of water that could be harvested and hence the size of the storage tank. This allows for different concrete (mortar) strengths for different tank sizes which has cost-saving advantage, unlike the common practice where the same strength was use for big or small tanks which invariably result in 'over' or 'under' strength; an economic waste! The hoop and longitudinal stresses were found as function of roof area, roof type, tank depth, diameter and concrete (mortar) thickness. These were found to be adequate.

Conclusions

The following conclusions are drawn from the findings of this work.

- The size of the storage tank depends on the roof plan areas and roof types. This has a cost-saving advantage.
- Where space is available, cylindrical tanks with relatively large diameters and heights of lower dimensions are preferred as this results in lower lever hydraulic pressure, requiring lower concrete strength for the tanks, and therefore being a cost-saving measure.
- The different forces acting on the tank depend on the roof plan areas, roof types, (water depth and concrete thickness). This has a cost saving advantage because smaller tanks will require lower cost and *vice versa* compare to the usual practice.

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