Strategy For Optimal Design Of Culverts, Channel Transistions, Reservior And Irrigation Projects In Nigeria

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***Abstract*—Efficient reservoir irrigation systems can decisively contribute to the development of agriculture by draining marshy lands and allowing the conversion of short-root cultivations into more profitable long root cultivations especially a country like Nigeria with very fertile lands. A flow transition occurs when water moves from a reservoir to a channel, from a channel to a culvert, or from one channel geometry to the other. Information and field data required to properly design a culvert. Generalized explicit codes and standards have been used for the optimal design of culverts, channel transition and irrigation reservoirs.**

Keywords—Efficient, Irrigation, systems, reservoir, culvert, transition

1.0 INTRODUCTION

Nigeria is a developing country which entails that various infrastructures are being built all over the country such infrastructure includes highways and buildings. In the aspect of highways the construction of culverts and channel transitions cannot be avoided. The basic functions of highway drainage structures are:

- As hydraulic facilities to safely convey floods across highways under all but severe flooding conditions, and
- As portions of the highway to move highway traffic freely over stream channels.

There are two general types of drainage structures: bridges and culverts. The design of highway drainage structures involves both hydraulic design and structural design. Hydraulic design of a highway drainage structure consists of analyses of the hydraulic performance of the structure in conveying flood water across the roadway and determinations of the most economical design alternative. The investment cost is dependent on the environmental conditions such as the location of the structure, geomorphic conditions, the soil type at the structure site, type and price of construction material, hydraulic conditions such as slope of the stream bottom, and flow conditions, recovery factor of the capital investment, labor and transportation costs. In reality, the investment cost also involves various uncertainties. However, the consideration of the uncertainties in the investment cost is beyond the scope of this paper.

This paper therefore provides the most efficient strategy for the optimal design of these hydraulic structures. A careful approach to hydraulic structures design is very key and essential, both in new land development and retrofit situations, because culverts and channel transitions often significantly influence upstream and downstream flood risks, floodplain management and public safety Culverts can be designed to provide beneficial upstream conditions and to avoid negative visual impact.

1.1 Reservoir and Irrigation Systems

A Reservoir is an enlarged natural or artificial lake, storage pond or impoundment created using a dam or lock to store water. Reservoirs can be created by controlling a stream that drains an existing body of water. They can also be constructed in river valleys using a dam. Alternately, a reservoir can be built by excavating flat ground and/or constructing retaining walls and levees.

Reservoir design is an important element in water resources planning and management. It consists of several parameters like inflow, storage, evaporation and demands that define the operation strategies for giving a sequence of releases to meet a large number of demands from stake-holders with different objectives, such as irrigation.

A well design reservoir irrigation system should be able to emulate the following;

i. Store water to provide a reliable irrigation water supply or regulate available irrigation flows.
ii. Improve Water Use Efficiency on irrigated land.
iii. Provide storage for tail water recovery and reuse.
iv. Provide irrigation runoff retention time to increase breakdown of chemical contaminants.
v. Reduce energy use.
vi. Develop renewable energy systems (i.e., hydropower).

The design of drainage basins and storage reservoirs involves both hydraulic and earthwork considerations. The geometry of the basin and the outlet structures need to be determined for hydraulics. The geometry of the basin is often dictated by the optimization of earthwork. To design a basin, prospective sites are analyzed before selection. The desired storage of the new basin and the outflow capacity need to be determined .

2.0 LITERATURE REVIEW

2.1 Culverts

The function of a culvert is to convey surface water across a highway, railroad, or other embankment. In addition to the hydraulic function, the culvert must carry construction, highway, railroad, or other traffic and earth loads. Therefore, culvert design involves both hydraulic and structural design considerations.

Culverts are available in a variety of sizes, shapes, and materials. These factors, along with several others, affect their capacity and overall performance. Sizes and shapes may vary from small circular pipes to extremely large arch sections that are sometimes used in place of bridges. A simple culvert is shown in figure 1.

Fig 1: A simple culvert

The material selected for a culvert is dependent upon various factors, such as durability, structural strength, roughness, bedding condition, abrasion and corrosion resistance, and water tightness. The more common culvert materials used are concrete and steel (smooth and corrugated).

Another factor that significantly affects the performance of a culvert is its inlet configuration. The culvert inlet may consist of a culvert barrel projecting from the roadway fill or mitered to the embankment slope. Other inlets have headwalls, wing walls, and apron slabs or standard end sections of concrete or metal.

2.2 CHANNEL TRANSISTION

A transition is an open-channel flow structure whose purpose is to change the shape or cross-sectional area of the flow. The design objective is to avoid excessive energy losses and to minimize surface waves and other turbulence. When the transition is designed to keep the streamlines smooth and parallel, the theory of gradually varied flow is applicable. In practice, the design of channel transitions is based on the principles of energy and momentum conservation.

The form or shape of a transition may vary from as simple as straight-line headwalls normal to the flow to very elaborate streamlined warped structures. Straight-line headwalls are often satisfactory for small canal structures or where there is plenty of available hydraulic. Other simplifications may be applied as long as they do not cause excessive wave action or turbulence. A simple channel is indicated in figure 2.

Fig. 2 A simple channel transition

2.3 CULVERTS

Required Design Information

The hydraulic design of a culvert essentially consists of an analysis of the required performance of the culvert to convey flow from one side of the roadway (or other kind of embankment, such as a railroad) to the other. The designer must select a design flood frequency, estimate the design discharge for that frequency, and set an allowable headwater elevation based on the selected design flood and headwater considerations. These criteria are typically dictated by local requirements although state and federal standards will apply to relevant highway projects. The culvert size and type can be selected after the design discharge, controlling design headwater, slope, tail water, and allowable outlet velocity have been determined.

The design of a culvert includes a determination of the following:

• Impacts of various culvert sizes and dimensions on upstream and downstream flood risks, including the implications of embankment overtopping.

• How will the proposed culvert/embankment fit into the relevant major drainage way master plan, and are there multipurpose objectives that should be satisfied?

• Alignment, grade, and length of culvert.

• Size, type, end treatment, headwater, and outlet velocity.

• Amount and type of cover.

• Public safety issues, including the key question of whether or not to include a safety/debris rack

• Pipe material.

• Type of coating (if required).

• Need for fish passage measures, in specialized cases.

• Need for protective measures against abrasion and corrosion.

2.4 Hydraulic Design Consideration

The discharge used in culvert design is usually estimated on the basis of a preselected storm recurrence interval, and the culvert is designed to operate within acceptable limits of risk at that flow rate.

3.0 Field Data

Information and field data required to properly design a culvert includes a description of the ground cover of the drainage area, a soil description of the stream bed at the proposed site, a topographic map showing contours and the outlining of the drainage area and for major culverts, a profile of the stream bed extending 150 metres upstream to 150 metres downstream from the proposed site with cross sections. The width of each cross section should extend beyond the limits of the flood plain on each side. Field surveys will be necessary where inadequate or no mapping exists. The proposed roadway alignment and culvert location must be shown. A detailed map to a scale not larger than 1:10 000 should be provided showing the roadway alignment and culvert location.

3.1 Channel Transition

This section covers the evaluation of the capacity and stability of natural drainage channels, and Design of constructed drainage channels, swales, and roadside ditches.

3.2 General Design Considerations

Except for roadside ditches and swales, open channels are nearly always a component of the Major (emergency) drainage system. There are a number of factors which must be considered in determining whether to specify an open drainage way as opposed to an underground storm drain: Material and installation cost, maintenance costs and problems, acceptability to the developer or home buyer, public safety, appearance, etc.

Basins are included in a hydrologic model used to estimate the peak flow rate and provided the

Detention basins are located in permanent drainage easements.

The design storm frequency shall be as follows:

Total drainage area less than one (1) square mile: 25-year (4% AEP) storm

Total drainage area one (1) square mile or more: 100-year (1% AEP) storm

Maximum Depth

Unless otherwise approved due to unavoidable physical or right-of-way constraints, the Maximum depth for the 25-year storm shall be three feet (3') in constructed channels.

Freeboard

For channels designed for subcritical flow conditions, a minimum of one foot (1') of freeboard shall be provided between the design high water elevation and the top of the channel. Freeboard shall be increased on the outside of curves according to the following formula

$$h = \frac{[V^2 T]}{g r_c} \geq 0.5\,ft.$$

h = super elevation (feet)

V = average channel velocity (feet/second)

T = top width of flow (feet)

g = acceleration due to gravity (32.2 ft/s^2)

rc = centreline radius of channel (feet)

For channels designed for supercritical flow, additional freeboard may be required depending

Upon the risk of damage which could occur if flow were to become subcritical due to debris or

Other obstructions.

Horizontal Alignment

The centreline of constructed channels shall be aligned parallel with property lines unless otherwise approved. A radius shall be provided whenever the alignment of a constructed channel

Changes by ten (10) degrees or more. The minimum centreline radius shall be three (3) times the top width of the design flow

3.3 HYDRAULIC DESIGN

Uniform Flow

Open channels having a design flow rate less than five hundred (500) cfs may be designed Assuming uniform flow conditions in conjunction with computed headwater depths at culverts and other hydraulic structures or reservoir stages at detention and sediment basins. Water surface Profiles using techniques for gradually varied flow may be required for design flow rates less than five hundred (500) cfs where accurate determination flooding depths is necessary to ensure flood safety. Under steady state, uniform flow conditions channel capacity shall be computed using Manning's

Equation:

$$Q = \frac{1.49}{n} A\, R^{2/3} S^{1/2}$$

Where

Q = rate of flow, cubic feet per second

n = Manning's roughness coefficient

A = cross sectional area of flow, square feet

P = wetted perimeter, feet

R = hydraulic radius = A/P, feet

S = S f = friction slope

Definitions

Critical depth, dc - the depth of flow at which the specific energy is a minimum for a given flow

Rate and channel cross shape, and a unique relationship exists between depth and specific energy.

Normal depth, -the depth at which uniform flow occurs when the discharge rate is constant. Friction and gravity forces are in balance.

Subcritical flow - lower energy, lower velocity flow, which occurs when the normal depth is greater than the critical depth. Subcritical flow is controlled by downstream conditions.

Supercritical flow - high energy, high velocity flow, which occurs when the normal depth is less than the critical depth. Supercritical flow is controlled by upstream conditions.

Froude number, $F_r = \frac{V}{\sqrt{gD}}$

Where

D = hydraulic depth (feet) = A/T

A = cross sectional area of design flow (square feet)

For supercritical flow, Fr > 1

For subcritical flow, Fr < 1

For critical flow, Fr = 1

Specific energy, E, is the energy per unit weight of fluid

$$E = d + \frac{V^2}{2g}$$

DESIGN & CONSTRUCTION REQUIREMENTS

3.5 Composite Channels

Many different channel shapes and lining types are possible. Different shapes and lining types can be combined in a composite design. In determining the capacity and depth of flow in composite channels, they shall be analysed as an irregular section using representative "n" values for each segment of the channel cross-section.

Velocity limitations set forth above shall be adhered to for each lining type.

3.4 Concrete Channels

Where velocities or slopes cannot be limited to values required for natural, grass, or composite channels due to right-of-way or other constraints, concrete channels may be utilized. Concrete channel shapes will typically be trapezoidal or rectangular. Other shapes may be used, but are less efficient. Crushed rock bedding and pore pressure relief are required whenever the lining height exceeds twelve inches (12"). Whenever the concrete channel bottom is wide enough to accommodate construction or maintenance equipment (generally eight feet (8') wide or more), it shall be designed to carry an HS-20 leading and shall be reinforced. Welded wire mesh or steel reinforcing bars may be used. Concrete channels shall be designed for subcritical flow where possible. Where flow is supercritical, the conjugate depth must be checked and additional freeboard may be required. Where slopes must be decreased to provide stability or maintain subcritical flow, drop structures should be provided.

4.0 RESERVOIR AND IRRIGATION

In order to attain optimal design for irrigation reservoir various consideration need to be implemented in the design.

There are a few different reasons for an irrigation reservoir to be utilized including frost Protection and irrigation flexibility. It must also be designed to state and local standards. Design considerations for irrigation storage reservoirs include site selection, permitting requirements, sizing, grading design, outlet design, and liner selection.

4.1 Frost Protection

A reservoir designed for freeze protection must supply enough water to operate for 3 or 4 nights in a row. Extreme weather data for the area must be evaluated in order to determine the exact amount of hours and nights that the sprinklers have to run. Generally a reservoir should be designed to account for 7-12 hours a night for 3 consecutive nights. The first step to designing a reservoir for frost protection is to figure out the time of operation. The most essential step in design is comparing the amount of water that goes into the reservoir versus what goes out. The water that goes into a reservoir is the wells flow rate times the amount of time the well is operating. The water that goes out of the reservoir is the time of operation times the flow rate out of the pond. The reservoir size is the water out minus the water in. Typically the reservoir is sized in acre-feet

The amount of water that the plants need for freeze protection is determined by a few factors. The size of the fields, type of crop, and the Distribution Uniformity of the system affect how much water needs to be applied. The net application rate can be determined from a relationship between Wind Speed and Temperature. The gross application rate can be determined by the

Equation:

*Gross (in/hr.) =Net/ (CCDU*GPMDU) (1)*

Where: CCDU= Catch Can Distribution Uniformity

GPM DU= Gallons per minute distribution Uniformity

The flow rate per sprinkler can then be determined by the formula (Burt, 2012):

*GPM out =Gross application rate * (Sprinkler Area/96.3) * #sprinkler/acre (2)*

The reservoir sizing must also take into account crop evapotranspiration requirements, evaporation, seepage, and leaching Irrigation Storage. To determine the capacity of a reservoir based on irrigation needs, one must decide how much flexibility they want. For example, a farmer's pumps may only be able to irrigate one block at a time. With a properly sized storage reservoir, more or all of the blocks could be irrigated at one time. It is most important for the storage reservoir to be able to provide the necessary irrigation application rates for a certain set time the application rate for a system can be determined by the equation:

Application Rate (in/hr.) = (Flow x 96.3)/Area (3)

Where: Q=Flow in GPM

A = Area in Square Feet

Once the application rate is determined, the total flow of the system can be calculated. This calculated flow along with a given set time can yield the volume required per acre per set. This number multiplied by the total farmed acreage will yield the required reservoir storage to irrigate all of the fields in one day.

4.2 Embankment Stability

All earth fill dams and reservoirs should be designed in order to be safe during the course of its life. According to the Department of Water Resources, these design considerations must be followed (DWR, 1993):

1. The slopes must be stable under all possible conditions. This includes rapid Reservoir drawdown.

2. Seepage must be controlled in the reservoir so that erosion does not occur in the interior of the embankments.

3. The embankments must be designed in order to not overtop.

4. The reservoir must be able to withstand earthquakes.

5. The embankment slopes must not be affected or damaged by rain.

Slope Bank Protection

Embankments need to be protected from erosion. Vegetation can be an effective means for erosion control if the vegetation has good coverage and can be sustained without irrigation. Structural protection such as rip rap can be used where vegetation is not possible. It is also very useful for the outlet or spillway of the reservoir to reduce the erosive energy (NRCS, 2005).

4.3 ANALYSIS OF RESULTS

A research on the strategy for optimal design of culverts, channel transition, irrigation and reservoir projects in the Nigeria was carried out through serious survey and study of previous published related research works which ended up providing a standard for engineers to follow in designing these mentioned hydraulic structures.

5.0 CONCLUSIONS

Generalized explicit codes and standards have been presented for the optimal design of culverts, channel transition and irrigation reservoirs. Using the optimal design consideration standards along with the various equations and tables, the optimal design of culverts, channel transition and irrigation reservoirs can be obtained to the fullest.

5.1 RECOMMENDATION

Designers of these hydraulic structures should be made aware of these generalized code and standards in the classroom for designing in order to achieve optimal designs in practical world. Latest development must be integrated into the design.

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