THE HYDRAULIC PERFORMANCE OF 900MM DIAMETER PIPE CULVERT USING WENCHI – SAMPA ROAD AS CASE STUDY

by

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DECLARATION

I hereby declare that this submission is my own work towards the M.Sc. and that to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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ABSTRACT

Inadequate drainage of surface and subsurface water can have significant impact on road pavement behaviour and long-term maintenance costs. Interception of water before it infiltrates into the pavement foundation is essential unless the soils are truly free draining. Most pipe culverts are not seen by the travelling public and become noticeable only when a problem arises, such as flooding or settlement in the roadway. Occasionally there is an accident because an unexpected hydraulic failure of pipe culvert causes flood to overtop the roadway. In the past, the 450mm, 600mm, 1200mm and 1800mm diameter pipe culverts were used as cross drainage structures. Due to the hydraulic inefficiencies of the 450mm and 600mm diameter pipe culverts, the Ghana Highway Authority and the Department of Urban Roads decided in the 1980s to make the 900mm diameter pipe culvert (or its equivalent box culvert) the minimum cross drainage structure for their roads, as a regulatory measure. However, the hydraulic inefficiencies associated with the 450mm and 600mm diameter pipes were still found with the 900mm diameter pipes. This therefore necessitated the study into its hydraulic performance using the reconstructed 30km section of the Wenchi - Sampa Road in the Brong Ahafo Region of Ghana, as case study. Forty-five 900mm diameter concrete pipe culverts were covered in the study. The prevailing conditions at their locations were assessed. Generally, about half the number of the 900mm diameter pipe culverts were silted and few had their inlets and outlets scoured. The Regional Office of the Ghana Highway Authority was surveyed by administering a questionnaire to find from them their inspection and maintenance programmes for the 900mm diameter pipe culverts on the project road. Much of the information presented has been taken from the Field Survey Results. Information from the literature has also been incorporated and adapted where necessary, to fit highway needs. Appropriate recommendations were made based on the findings.

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CHAPTER 1

1. INTRODUCTION

1.1 Background of the Project

One of the most important aspects of the design of a road is the provision made for protecting the road from surface water or groundwater. The road pavement will fail if water is allowed to ingress into it. This means a good road drainage system should be provided to take the water away from the roadway. This road drainage system consists of roadside drains, subsurface drains and cross drains. The cross drains carry water from one side of a road to the other and this could be bridges, box culverts, pipe culverts, drifts and vented fords. The selection of any of them depends on the location of the structure, the hydrologic characteristics of the watershed through which the road passes, the flow of water passing under the road, the level of traffic and the cost involved.

The principal function of culverts is to convey water through the road embankment while at the same time supporting the weight of overlying fill and traffic; it can be box or pipe. There are various sizes of pipe culverts available in the country and in the past sizes of 450mm, 600mm, 900mm. 1200mm and 1800mm diameters were used as cross drainage structures depending on the amount of runoff that was to be conveyed across the road. However, in the 1980s, due to the rapid hydraulic failure of the 450mm and the 600mm diameter pipe culverts and the difficulty of maintaining them, the Ghana Highway Authority and the Department of Urban Roads decided to use the 900mm, 1200mm and 1800mm diameter pipes depending on the flow of water, thus instituting a regulatory measure of using the 900mm diameter concrete pipe culvert (or its equivalent box culvert) as the minimum cross-drainage structure for their roads. Easy entry into the culvert for maintenance (where and when required) was the main criteria for the regulatory measure. The 600mm diameter pipes were recommended for use as access culverts and it has been the practice up to today.

The single 900mm diameter pipe culvert therefore became the minimum cross drainage structure for roads managed by the two agencies throughout the country. All estimated runoffs crossing a road that could be contained by 450mm and 600mm diameter pipes were sized using 900mm diameter pipes because of the regulatory measure.

In Ghana, the most commonly used culverts are the circular concrete pipes. This shape is preferred due to the available structural options for various fill heights. Various standard lengths of circular pipe in standard strengths and classes are usually available from local suppliers at a reasonable cost. Pipe culverts are also used because of the small volume of excavation required for their installation and the ease of construction.

1.2 Problem Definition and Justification

The 900mm diameter pipe culvert is now the minimum size used as cross drainage structure; it requires that small volume of excavation be done during its construction. This pipe culvert is found, in singles and multiples, on all the roads in the country. Although it is relatively easier to maintain than the 450mm and 600mm diameter pipe culverts, it is still susceptible to many types of problems found with the 600mm and 450mm diameter pipe culverts. The more serious problems are the following:

- debris blockage,

- overtopping and washing out of embankments,
- aggradation of river beds requiring frequent cleanout,
- undermining due to artificial deepening of channel especially at the outlet end,
- erosion of fill at the inlets and
- outlet erosion

These hydraulic problems of the culvert are evident on most of the roads in the country. Thus, the problems which plagued the 450mm and 600mm diameter pipes have not been solved by the regulatory measure. The result is that there is reduction in its performance and the service life. This, therefore, calls for research into its hydraulic performance so as to improve its working efficiency. This study is the first of its kind in Ghana.

The reconstructed section of the Wenchi – Sampa road has 82% of its cross drainage structures being 900mm diameter pipe culverts. The road has, therefore, been chosen for a case study into the hydraulic performance shortfalls of this pipe culvert.

1.3 Objectives

The objectives of the study are the following:

- To assess the prevailing conditions at the 900mm diameter pipe culvert locations on the road.
- To investigate the hydraulic performance of this culvert on the road.

- To determine the construction and maintenance interventions which will help promote the hydraulic performance of this culvert.

It is worth noting that culverts can also be assessed on such aspects as their structural performance, environmental impact, etc. The main emphasis in the study is the hydraulic performance.

1.4 Scope

The study was limited to the first 30km of the reconstructed Wenchi-Sampa road as shown in Fig.1.1. This covered all the 900mm diameter pipe culverts (singles and multiples). The hydraulic performance of the bigger sizes, which are 1200mm and 1800mm diameter pipe culverts, were also investigated and the results compared to those of the 900mm diameter pipe culverts..

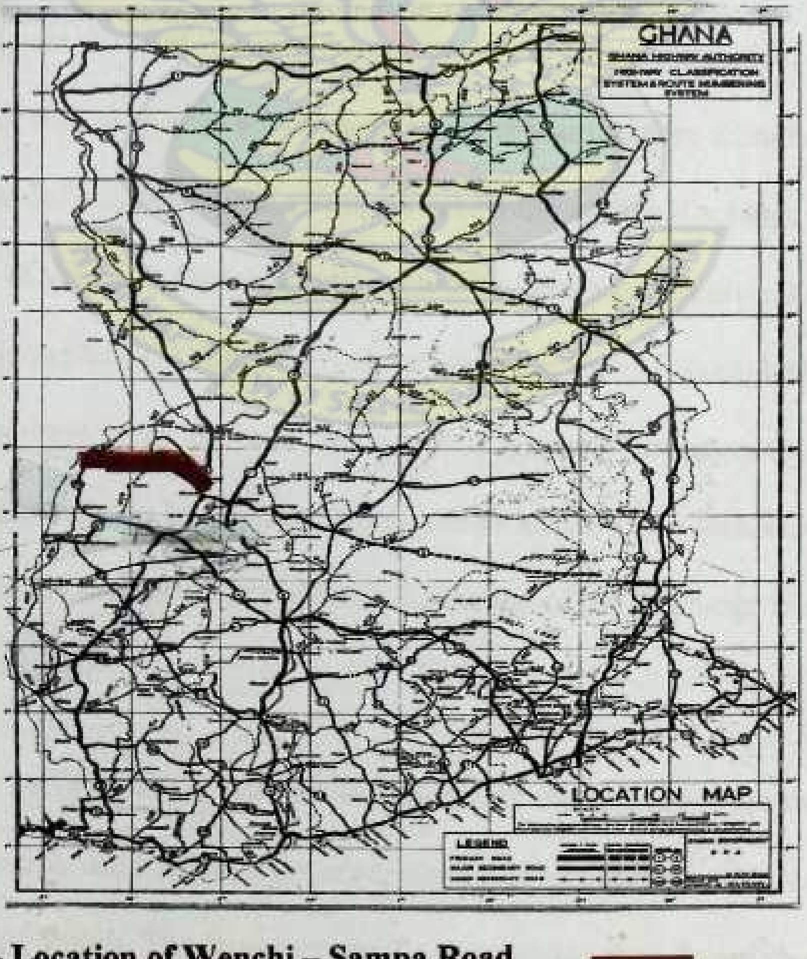


Figure 1.1 – Location of Wenchi – Sampa Road

CHAPTER 2

2. LITERATURE REVIEW

The most comprehensive publications available in the literature dealing with culvert design are the AASHTO Highway Drainage Guidelines and the Ontario Ministry of Transportation and Communication (MTC) Drainage Manual. These publications feature sections on design considerations, conventional culvert design, culvert end treatment and design, list of figures, design charts, performance curves, tables and forms.

Both AASHTO Drainage Guidelines and Ontario MTC Drainage Manual define culvert hydraulics design in terms of inlet and outlet control depending on the variables that influence the head required to push the flow through the barrel. Inlet control occurs for steep culverts flowing with free surface where flow goes through critical depth near the inlet. Flow in the culvert barrel below the critical depth section is supercritical flow that does not propagate downstream surface disturbances upstream. The only variables that affect the headwater are the discharge intensity and the geometry of the inlet. Outlet control occurs for gentle slope culverts where free surface flow is sub-critical and for any slope when the barrel is completely submerged. In these cases, the tailwater, which is typically known, is the control, and the headwater is affected by tailwater depth, outlet loss, friction loss, elevation difference, and the entrance loss (which is a function of the discharge intensity and the inlet geometry).

The hydraulic performance and backwater at various stream stages are the first measures generally used to judge the acceptability of an alternative highway stream crossing system design. The introduction of a constriction in a stream channel with supercritical flow conditions, such as highway crossing, will not cause backwater above the constriction. Constriction results in the conversion of potential energy to kinetic energy and, therefore there is rise to the water surface elevation upstream of the introduced constriction as far as the constriction is minor and does not cause a hydraulic jump to occur at the outlet.

A highway facility, like the pipe culvert (Fig. 2.1), which constricts a stream with sub-critical flow conditions will cause higher water surface elevations upstream of the crossing than prevailed during floods prior to construction of the facility. The higher water surface elevations represent the amount of kinetic energy converted to potential energy to overcome losses comprised principally of contraction and expansion losses. Other losses include those from friction from longer paths and if submerged. Friction losses can be significant if the flood plain constriction is relatively severe and the resistance to flow in the flood plain is high, as in forest areas.

The increase in water surface elevation upstream of the culvert is referred to as backwater. It is measured upstream of the waterway opening above the theoretical water surface elevation prior to construction of the culvert. Backwater above a culvert will cause incremental depth and duration of flooding, and increased area of inundation for a given flood magnitude. The incremental flooding associated with various flood magnitudes should be considered in evaluating the risks associated with alternative designs of the culvert. The effects on the velocities, flow distribution, stream environment, scour, construction cost, and risk costs are highly responsive to the total design of the culvert.

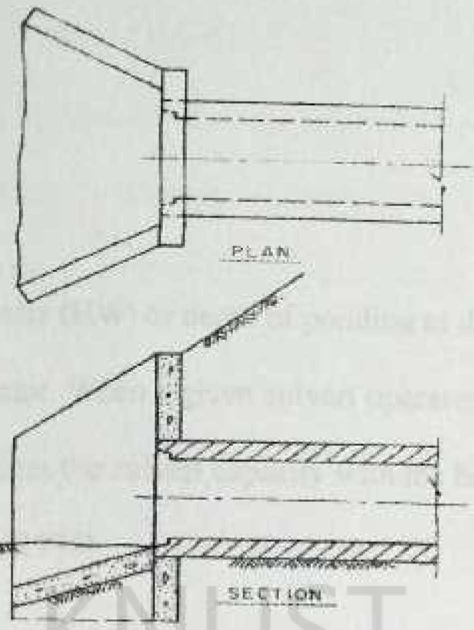


Figure 2.1 – Inlet of pipe culvert with headwall and wingwall [Drainage Criteria Manual (Kelly, 2001)]

2.1 Culvert Hydraulics

The culvert size and type can be selected after the determination of the design discharge, culvert location, tailwater and controlling design headwater. The location at which a unique relationship exists between the flow rate and the depth of flow upstream from the culvert is the control section (Garber and Hoel, 1992). The control section of the culvert is used to classify different culvert flows.

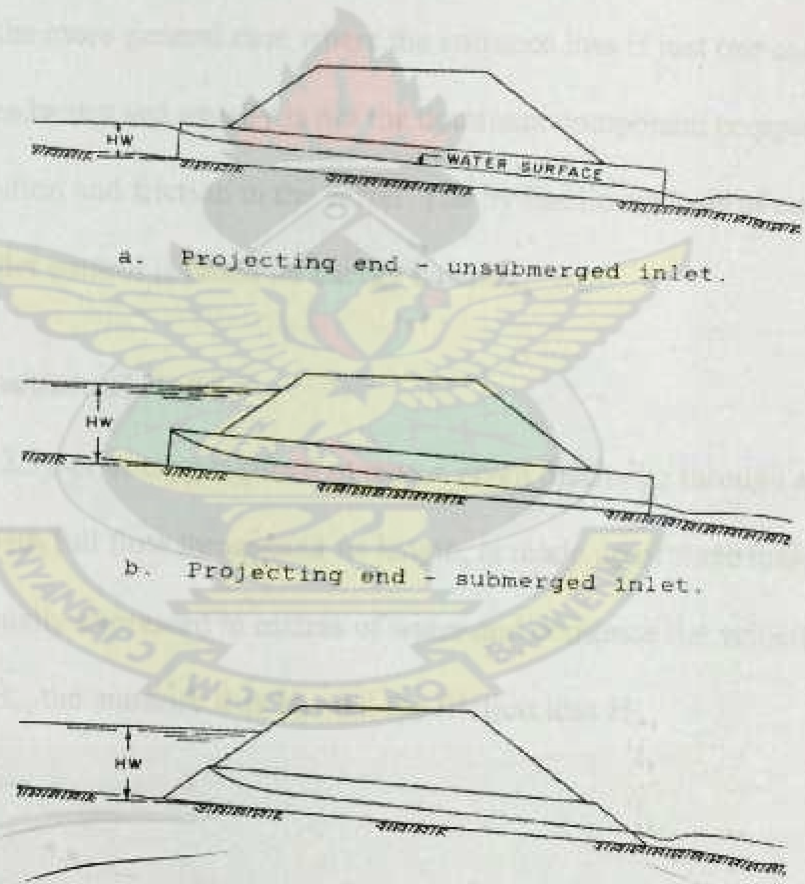
2.1.1 Culverts flowing in Inlet Control

Most culverts operate under inlet control which occurs when the culvert barrel is capable of carrying more flow than the inlet will accept. The flow in culverts operating under inlet control conditions is supercritical within the culvert barrel with high velocities and low depths (www.dot.ca.gov/hq/oppd/hdm/pdf/english/chp 0820.pdf). As discussed earlier, factors that affect the hydraulic performance of a culvert under inlet conditions are:

- the headwater depth,

- the inlet area,
- the inlet shape, and
- the inlet edge

In all culvert design, headwater (HW) or depth of ponding at the entrance to a culvert (Fig. 2.2) is an important factor. When a given culvert operates under inlet control, the headwater depth determines the culvert capacity with the barrel usually flowing only partially full (Jacobsen, 1995).



a. Projecting end - unsubmerged inlet.

b. Projecting end - submerged inlet.

c. Mitered end - submerged inlet.

Figure 2.2 – Flow Profiles for culvert in Inlet Control
[Ontario MTC Drainage Manual (Harris, 1985)]

2.1.2 Culverts flowing in Outlet Control

A culvert flows under the outlet control when the barrel is incapable of transporting as much flow as the inlet opening will receive (Garber and Hoel, 1992). Factors that affect the hydraulic performance of culverts under outlet control include that of the inlet control and

- tailwater depth and
- certain culvert characteristics, which include the roughness, area, shape and length.

Outlet control is the more general case where the entrance loss is just one component that affects the headwater and usually is not the dominant component compared to the tailwater elevation and friction in the barrel. The hydraulic analysis of culverts flowing under outlet control is based on energy balance..

2.1.3 Determination of Head

The head H (Fig. 2.3), or energy required to pass a given discharge through a culvert in outlet control with full flow throughout its length, is made up of three major parts. These parts are usually expressed in metres of water and comprise the velocity head within the barrel H_v, the entrance loss H_e, and the friction loss H_f.

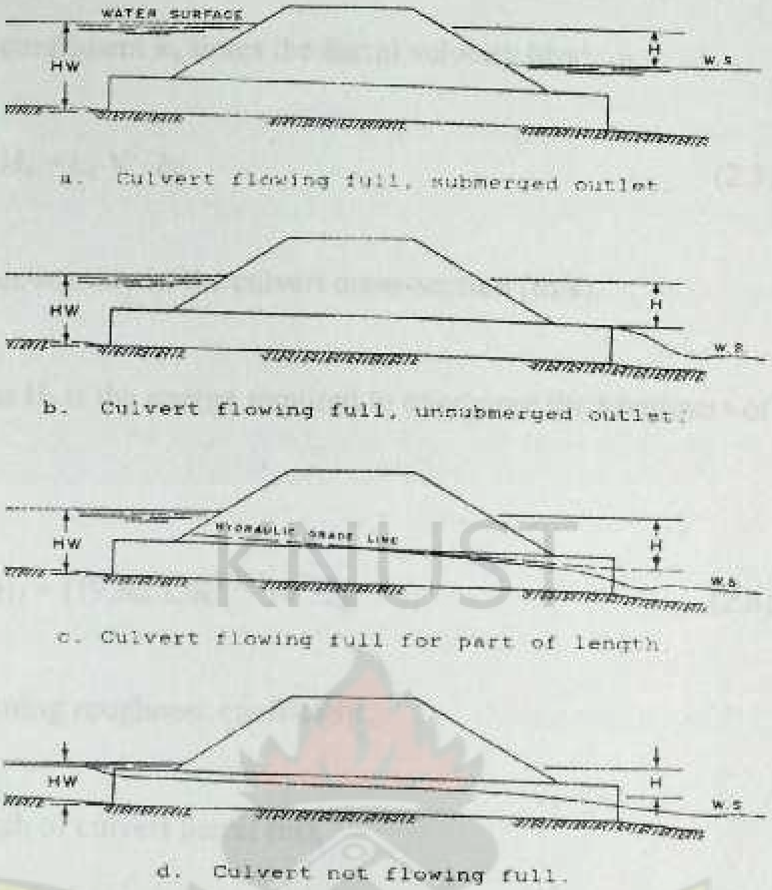


Figure 2.3 – Flow Profiles for culvert in Outlet Control [Ontario MTC Drainage Manual (Harris, 1985)]

The energy is derived from ponding of water at the entrance and from the velocity head in the entrance pond, and can be expressed in equation form:

$$H = H_v + H_e + H_f \qquad (2.1)$$

The velocity head H_v is given by

$$H_v = V^2/2g \qquad (2.2)$$

where V is the mean velocity in the culvert barrel (m/s) and g is the acceleration due to gravity (9.81 m/s^2). The mean velocity is the discharge Q, in m^3/s, divided by the cross-sectional area A, in m^2, of the barrel.

The entrance loss H_e depends upon the geometry of the inlet edge. This loss is expressed as a coefficient k_e times the barrel velocity head, or

$$H_e = k_e V^2/2g \tag{2.3}$$

where V = mean velocity in the culvert cross-section (m/s).

The friction loss H_f is the energy required to overcome the roughness of the culvert barrel;

$$H_f = [19.6n^2L/R^{1.333})V^2/2g \tag{2.4}$$

where n = Manning roughness coefficient,

L = length of culvert barrel (m),

V = mean velocity of flow in culvert barrel (m/s),

g = acceleration due to gravity (9.81 m/s^2),

R = hydraulic radius = A/P (m),

A = cross-sectional area of flow (m^2),

p = wetted perimeter (m).

Substituting in equation 2.1 and simplifying, we get for full flow:

$$H = [1 + k_e + 19.6n^2L/R^{1.333}] V^2/2g \tag{2.5}$$

2.1.4 Outlet Velocity

The outlet velocity of culverts is the velocity measured at the downstream end of the culvert and it is usually higher than the maximum natural stream velocity (Highway Drainage Guidelines, 1992). In erodible soils this may result in a scour hole immediately downstream. The outlet velocity should be calculated at sites where erosion may be harmful, to ascertain whether erosion control measures or modifications to the culvert design are required. The slope and roughness of the culvert barrel are the principal factors affecting outlet velocity.

Outlet velocities for culverts flowing in inlet control may be assumed equal to the mean velocity of flow in the culvert. This may be determined based on Manning's equation:

$$V = (R^{0.667}S^{0.5})/n \qquad (2.6)$$

where V = mean velocity of flow (m/s),

R = hydraulic radius (m),

S = culvert bed slope and

n = Manning's roughness coefficient

In outlet control, the culvert velocity is the discharge divided by the cross-sectional area of flows at the outlet. This flow area is measured up to the critical depth or tailwater depth, whichever is higher, but cannot exceed the full area of the culvert (Harris, 1985).

2.1.5 Inlet Efficiency

The capacity of a culvert operating in inlet control can be significantly increased by providing an efficient inlet, which reduces the flow contraction at the entrance and increases the flow depth in the barrel. Inlets of skewed culverts should preferably be oriented normal to the stream flow, for both hydraulic and structural reasons. This is especially important for multi-barrel culverts, since inlets parallel to the highway may cause unequal flow and sedimentation. In outlet control, the entrance losses, and major inlet improvements are not justified (Harris, 1985).

2.2 Hydraulic Design of Culverts

The ultimate objective in determining the hydraulic requirements for any drainage structure is to provide a suitable structure size that will economically and efficiently dispose of the expected runoff. Certain hydraulic requirements should also be met to avoid erosion and/or sedimentation in the system. Drainage structures should be sized such that the headwater elevation resulting from the design discharge is somewhat lower than the road shoulder break point at the low point in the road. This difference in level is referred to as the freeboard. The freeboard will vary according to the importance of the road but is usually set at 250mm for major roads and 100mm for minor roads (Harris, 1985).

2.2.1 Hydrologic Consideration for Culverts

In order to determine requirements for culvert as cross drainage structures, information must be collected and predictions made about the level of traffic and the likely flow of water passing under the road. This enables decisions to be made about the size of the structure and the number required. In order to determine the maximum likely flow of water to be accommodated by the chosen structure, information may be needed on the following:

- water catchment area
- rainfall characteristics
- topography
- vegetation and soils
- catchment shape
- available storage upstream and
- urban development (if any)

The peak flow rate can be obtained from many rainfall-runoff models such as the unit hydrograph at the culvert site or by using the Rational formula,

$$Q = 0.278\ C.\ I.\ A, \qquad (2.7)$$

where Q is the peak flow rate (m^3/s), C is the runoff coefficient, I is the rainfall intensity (mm/hr) and A the catchment area (km^2). The return period is selected such that construction and maintenance costs balance the probable cost of damage to adjacent properties if the storm should occur (Garber and Hoel, 1992).

2.2.2 Headwater Elevation

Any culvert which constricts the natural stream flow will cause a rise in the upstream water surface to some extent. The total flow depth in the stream measured from the culvert inlet invert is termed headwater. Design headwater elevations and selection of design floods should be based on these risk considerations:

- damage to adjacent property,

- damage to the culvert and the roadway,
- traffic interruption,
- hazard to human life, and
- damage to stream and floodplain environment (Highway Drainage Manual, 1992).

The headwater elevation for the design discharge should be at least 0.5m below the edge of shoulder elevation. A ratio between headwater depth and height of culvert opening (HW/D) equal to 1.2 is recommended in cases where insufficient data are available to predict flooding effect from high headwater. Headwater depth is a function of the discharge, the culvert size and the inlet configuration (Jacobsen, 1995).

2.2.3 Tailwater

Tailwater is the flow depth in the downstream channel measured from the invert at the culvert outlet. It is an important factor in culvert hydraulic design because a submerged outlet may cause the culvert to flow full rather than partially full (Highway Drainage Guidelines, 1992). High tailwater elevations may occur due to the hydraulic resistance of the channel or during flood events if the flow downstream is obstructed (Garber and Hoel, 1992).

A field inspection of the downstream channel should be made to determine whether there are conditions that facilitate high tailwater elevations. These conditions include

- channel constrictions,
- intersections with other water courses,
- downstream impoundments,

- channel obstructions and
- tidal effects

If these conditions do not exist, then the tailwater elevation is based on the elevation of the water surface in the natural channel (Garber and Hoel, 1992).

2.2.4 Upstream Storage

The ability of the channel to store large quantities of water upstream from the culvert may have some effect on the design of the culvert capacity. The detention of flood flows in lakes and wetlands can greatly reduce peak rates of runoff. The storage capacity upstream should therefore be checked using large-scale contour maps, from which topographic information is obtained (Garber and Hoel, 1992).

2.3 Culvert Location

The most appropriate location of a culvert is in the existing channel bed (Fig. 2.4), with the centreline and slope of the culvert coinciding with that of the channel. At this location the minimum cost associated with earth and channel work is achieved and stream flow disturbance is minimized. The basic principle used in locating culverts is that abrupt changes at the inlet and outlet of the culvert should be avoided (Garber and Hoel, 1992).

Culvert locations normal to the roadway centreline are not recommended where severe or abrupt changes in channel alignment are required upstream or downstream of the culvert (Fig. 2.5). Abrupt changes in channel alignment downstream of culverts may cause erosion on adjacent properties. Short radius bends are subject to erosion on the concave bank and deposition on the inside of the bend.. Abrupt changes to a flatter grade in the culvert or in the channel adjacent to the culvert will induce deposition. In flat terrains drainage is often provided by excavated channels (Highway Drainage Guidelines, 1992)

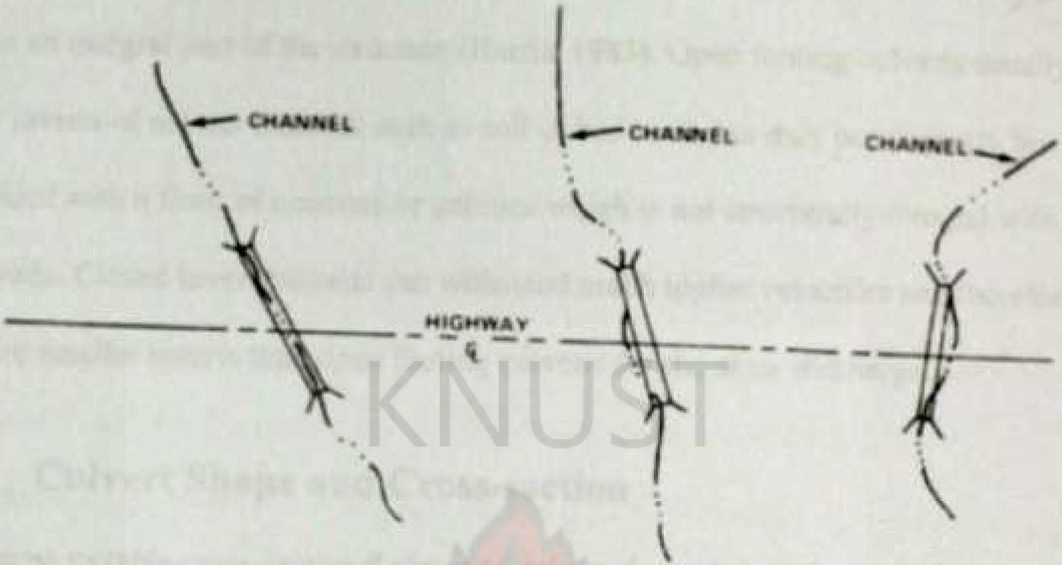


Figure 2.4 – Culvert Located in Natural Channel

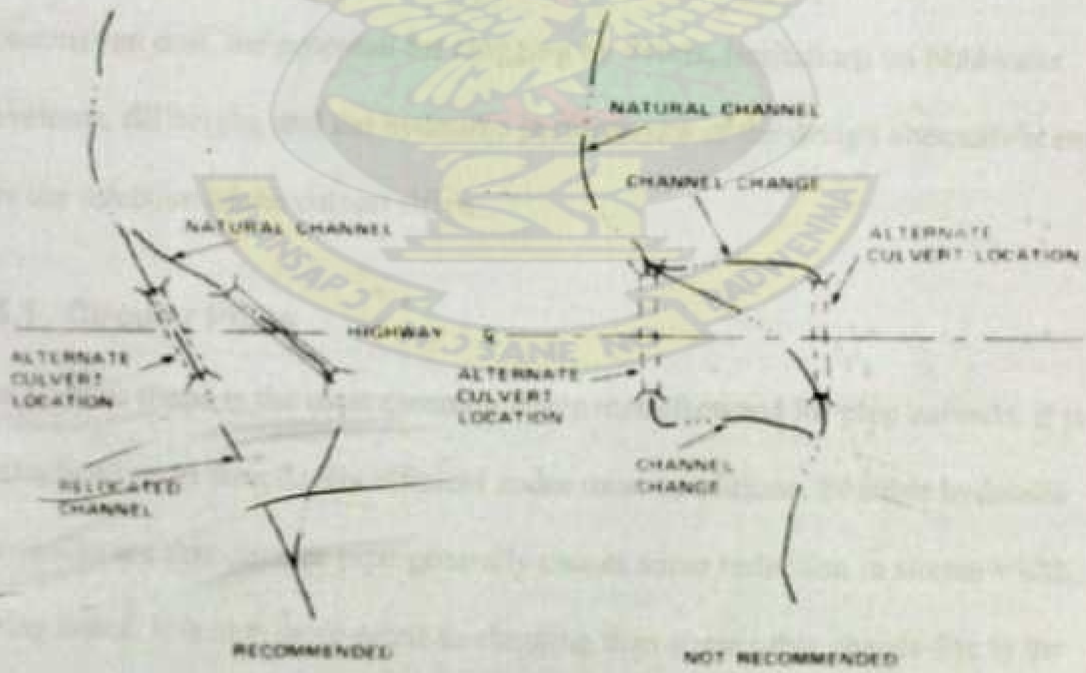


Figure 2.5 Methods of Culvert Locations
[Highway Drainage Guidelines (1992)]

2.4 Culvert Classes

Culverts may be divided into two broad classes, the closed invert type and the open footing type. The closed invert type such as pipe or box culverts, have invert which forms an integral part of the structure (Harris, 1985). Open footing culverts usually have inverts of natural material such as soil or bed-rock, but may occasionally be provided with a floor of concrete or gabions which is not structurally integral with the walls. Closed invert culverts can withstand much higher velocities and therefore require smaller barrels than open footing culverts for the same discharge.

2.5 Culvert Shape and Cross-section

The most suitable cross-sectional shape of culvert depends largely on the height of fill and depth of flow (Harris, 1985). Circular, rectangular or arch shapes of equal hydraulic capacity are generally satisfactory. However, it is often necessary for the culvert to have a low profile because of the terrain or limited fill heights. Construction cost, the potential for clogging by debris, limitations on headwater elevations, fill height, and the hydraulic performance of the design alternatives enter into the selection of the culvert shape.

2.5.1 Circular Pipes

The circular shape is the most common shape manufactured for pipe culverts. It is hydraulically and structurally efficient under most conditions. Possible hydraulic drawbacks are that circular pipe generally causes some reduction in stream width during flows. It is also more prone to clogging than some other shapes due to the diminishing free surface as the pipe fills beyond the midpoint (www.ct.gov/dot/cwp/view.asp?a=3200 260116) .

2.5.2 Multi-Barrel Culverts

Culverts having more than one barrel or cell may be necessary for wide streams having relatively low depths of flow, and for shallow fills. Multi-barrel culverts suffer the disadvantage that on debris-carrying streams they are more susceptible to blockage, and on curved stream alignments, the inner barrel is more prone to silt deposition (Harris, 1985). The practice of altering the channel geometry to accommodate a wide culvert will generally result in deposition in the widened channel and in the culvert (Highway Drainage Manual, 1992). To avoid widening of the natural channel, provide overflow (flood) relief, support environmental preservation, and to reduce sedimentation and debris problems, it is good practice to install one barrel of the multiple-barrel culverts of the flow line of the stream while the other barrels are set at slightly higher invert elevation (Highway Drainage Guidelines, 1992).

2.6 Culvert Size

Some of the standard sizes of pipe culverts are 450mm diameter, 600mm diameter, 900mm diameter, 1200mm diameter and 1800mm diameter. Connecticut Department of Transport Drainage Manual recommends that 600mm diameter should be the minimum size for circular shapes as cross drainage to avoid maintenance problems and clogging. In New Zealand, the recommended minimum diameter is 300mm and the reason is that small culverts are easily blocked by only a small amount of debris (www.mfe.govt.nz/publications/land/culvert-bridge-Oct04/html/page2.html). The Transport and Road Research Laboratory (TRRL) recommends in Overseas Road Note 5 (1988) that pipes of less than 1000mm should not be used because they are difficult to maintain. In Ghana, the recommended minimum size of pipe for cross drainage is 900mm diameter.

2.7 Culvert End Treatment

The term end treatment encompasses the shape of the culvert ends, end structures and erosion control measures for the adjoining fill and channel (Harris, 1985). Some of the typical culvert ends include

- headwalls and wingwalls,
- cutoff wall (toe wall),
- projecting ends,
- mitered ends, and
- pipe end sections

Headwalls and wingwalls, and cutoffs are the culvert end treatments found on the project road. Culvert end treatments may be required to perform one or more of the following functions:

- to prevent erosion of the fill,
- to improve culvert capacity,
- to inhibit seepage through the bedding and backfill,
- to retain the fill,
- to prevent the undermining of culvert ends,
- to improve aesthetics,
- to resist hydraulic uplift forces, and
- to meet traffic safety requirements.

2.7.1 Headwalls and Wingwalls

Headwalls and wingwalls are generally cast-in-place concrete structures commonly constructed on the ends of culvert barrels. Although headwalls are skewed to the culvert barrel to fit the embankment slope, an alignment normal to the direction of flow provides a more hydraulically efficient opening (Highway Drainage Manual, 1992). Headwalls should extend at least 0.3m above high water or flood level and should be long enough to keep the fill out of the waterway. If a concrete or gabion apron is provided to prevent undermining of wingwalls a cutoff should be included. Slope paving should be keyed into the slope at its ends to prevent undermining (Harris, 1985).

2.7.2 Cutoff walls

A cutoff (toe wall) is a vertical wall constructed below the end of a culvert, apron or other structure to prevent undermining or uplift. Concrete cutoffs shall extend at least 0.5m below the estimated limit of scour subject to the following minimum depth requirements in Table 2.1. The minimum depth requirements shall not apply if highly scour-resistant material is encountered at a higher elevation (Harris, 1985).

Table 2.1 - Minimum Depth Requirements

Span or diameter(m)	Maximum depth below culvert invert (m)
Up to 1.0	1.0
More than 1.0	1.2

[Ontario MTC Drainage Manual (Harris, 1985)]

2.8 Deposition in Pipe Culverts

Deposition occurs in culverts because the sediment transport capacity of flow within the culvert is often less than in the stream. The following factors contribute to deposition in culverts:

- at moderate flow rates, the culvert cross-section is larger than that of the stream, thus the flow depth and sediment transport capacity is reduced,
- point bars form on the inside of stream bends and culvert inlets placed at bends in the stream will be subjected to deposition in the same manner. This effect is most pronounced in multiple-barrel culverts with the barrel on the inside of the curve often becoming almost totally plugged with sediment deposition, and
- abrupt changes to a flatter grade in the culvert or in the channel adjacent to the culvert will induce deposition. Gravel and cobble deposits are common downstream from break in grade because of the reduced transport capacity in the flatter section (Highway Drainage Guidelines, 1992).

2.9 Erosion and Scour Protection of Pipe Culverts

2.9.1 Inlet

Unchecked erosion is the prime cause of culvert failure. At culvert inlets erosion may be caused by high inlet flow velocity. Where the flow enters the transition between the embankment and the wingwalls, high local velocities and flow disturbances are expected, justifying the slope protection to be extended a certain distance beyond the wingwalls upstream. In cases where it is impossible to locate the culvert in the same direction as that of the stream, for example, culverts carrying water below the road from one side ditch to the other, water may flow along the embankment before entering the culvert. As runoff begins, the water will flow along the embankment with a relatively small depth, but not necessary with a low velocity until reaching the culvert entrance. Care should therefore be taken to protect the embankment upstream of the culvert from erosion. If the flow velocities near the inlet indicate a possibility of scour threatening the stability wingwall footings, erosion protection should be provided. A concrete with cut off wall between wingwalls is the most satisfactory means of providing protection (Jacobsen, 1995).

2.9.2 Outlet

Erosion at culvert outlets is a common problem. Determination of flow condition, scour potential and channel erodibility at the outlet should be standard procedure in the design of all road culverts. A reasonable procedure is to provide at least minimum protection and then inspect the outlet channel after major rainfalls to determine if the protection must be increased or extended. Two types of scour can occur in the vicinity of culvert outlets – local scour and general channel degradation. Local scour is the results of high velocity flow at the culvert outlet, but its effect extends only a limited distance downstream. Natural channel velocities are almost universally less than culvert outlet velocities, because the channel cross-section including its flood plain is generally larger than the culvert flow area. Channel degradation may proceed in a fairly uniform manner over a long length, or may be evident in one or more abrupt drops progressing upstream with every runoff event. The latter type referred to as head cutting, can be detected by periodic maintenance inspections following construction. The highest velocities will be produced by long, smooth-barrel culverts on steep slopes. These cases will no doubt require protection of the culvert channel at most sites. However, protection is also often required for culverts on mild slopes (Jacobsen, 1995).

2.9.3 Scour Protection

To prevent scour at outlet, energy dissipators such as drop structures, riprap basin, stilling basin, etc. are the most far-reaching anti-erosion devices. Standard practice is often to use the same treatment at the culvert entrance and exit. It is important to recognize that the inlet is designed to improve culvert capacity or reduce head loss while the outlet structure should provide a smooth flow transition back to the natural channel (Jacobsen, 1995).

2.10 Stream Channel Types

Streams are classified in two broad general categories, those with floodplains and those without. Floodplains are usually not a direct result of large flood flows but rather the result of lateral movement of the stream from one side of the plain to the other through geologic time. Streams are more specifically classified as straight, meandering or braided (Highway Drainage Guidelines, 1992). Figure 2.6 shows the different types of channel characteristics.

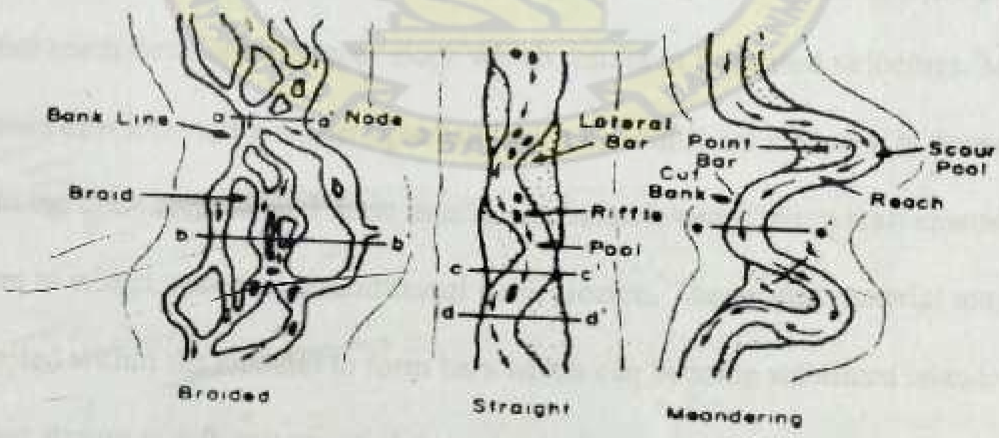


Figure 2.6 – Stream channel types

[Highway Drainage Guidelines (1992)]

2.10.1 Straight Stream Channel

Straight channels are sinuous to the extent that the thalweg (that is, path of deepest flow) usually oscillates transversely within the low flow channel and the current is deflected from one side to the other. The current oscillation usually results in the formation of pools on the outside of bends while lateral bars, resulting from deposition, form on the inside bends. Artificial straight channels in alluvium may be very unstable. Straightening of meandering channels results in steeper gradients and degradation and bank caving upstream are common as the stream attempts to establish equilibrium. The eroded material will be deposited downstream resulting in reduced stream slopes, reduced sediment transport capacity, and possible braiding (Highway Drainage Guidelines, 1992).

2.10.2 Braided Streams

A braided stream is one that consists of multiple and interlacing channels. Causes of braiding are bank caving and a large quantity of bed load which the stream is unable to transport. Deposition occurs when the supply of sediment exceeds the stream's transport capacity. As the stream bed aggrades from deposition, the downstream channel reach develops a steeper slope which results in increased velocities. Multiple channels develop on the milder upstream slope as additional sediment is deposited within the main channel and these interlaced channels cause the overall channel system to widen, resulting in additional bank erosion. The eroded material may be deposited within the channel to form bars which can become stabilized islands. A braided stream is difficult to stabilize in that it changes alignment rapidly, is subject to degradation and aggradation, is very wide and shallow even at flood stage and is, in general, unpredictable (Highway Drainage Guidelines, 1992).

2.10.3 Meandering Streams

A meandering stream consists of alternating bends of an S-shape. In alluvial streams, the channel is subject to both lateral and longitudinal movement through the formation and destruction of bends. Bends are formed by the process of erosion and sloughing of banks on the outside of bends and corresponding deposition of bed load on the inside of bends to form point bars. The point bar constricts the bend and causes erosion in the bend to continue, accounting for the lateral and longitudinal migration of the meandering stream. As a meandering stream moves along the path of least resistance, the bends will move at unequal rates because of differences in the erodibility of the banks and floodplain. Bulbs form which are ultimately cut off resulting in oxbox lakes. After a cutoff is formed, the stream gradient is steeper and the stream tends to adjust itself upstream and downstream.

Modification of an alluvial channel from its natural meandering tendency into a straight alignment usually requires confinement within the banks. A stream thus confined may become braided or degrade its bed due to the steeper gradient in the straight alignment. When an unprotected straight channel is constructed, the current will tend to oscillate transversely and initiate the formation of bends. Eventually, the straight channel reaches may be destroyed as a result of the natural migration of meanders upstream of the modified channel (Highway Drainage Guidelines, 1992).

2.11 Factors that affect Stream Channel Stability

Factors that affect stream stability and potentially culvert and highway stability at stream crossings, can be classified as geomorphic factors and hydraulic factors (www.ct.gov /dot/cwp/view.asp?a=3200 260116). Geomorphic factors include:

- stream size,

- valley setting,
- sinuosity,
- width variability,
- natural levees,
- bed material,
- flow habit,
- flood plains,
- channel boundaries,
- degree of braiding,
- tree cover on banks,
- bar development, and
- apparent incision

The hydraulic factors include

- magnitude, frequency and duration of floods,
- bed configuration,
- resistance to flow and
- water surface profiles

Rapid and unexpected changes may occur in the streams in response to man's activities in the watershed such as alteration of vegetative cover. Changes in imperviousness can alter the hydrology of a stream, sediment yield and channel geometry. Channelization, stream channel straightening, stream levees and dikes, culverts and bridges, reservoirs and changes in the land use can have major effects on stream flow, sediment transport and channel geometry and location (www.ct.gov

/dot/cwp/view.asp?a=3200 260116). Natural disturbances such as floods, drought, earthquake, landslides and forest fires can also cause large changes in sediment load and thus major changes in the stream channel.

2.12 Hydraulic-Related Maintenance Considerations

A comprehensive programme of channel maintenance should include periodic inspections and routine repair of these facilities and extraordinary inspection and repairs following major floods. The maintenance programme should include removal of

- rubbish,
- sediment and
- debris

Channel linings should be promptly repaired to prevent extensive damage during subsequent floods. The growth of weeds, brush and trees in a channel may reduce the conveyance efficiency well below design values. The channel may also reshape and realign itself in response to natural or man-made morphological changes. For this reason, a channel must not be re-graded simply to maintain the as built geometry. In many instances, the re-grading effort will prove expensive and fruitless as the channel will only revert to a more natural shape and alignment. Major channel reconstruction should be undertaken only when it is determined that extensive reconstruction is necessary to repair damages or increase the hydraulic capacity of the channel. This does not preclude maintenance gangs from accomplishing channel cleaning and minor erosion repair (Highway Drainage Guidelines, 1992).

2.13 Design and Construction of Pipe Culverts in Ghana

2.13.1 Design

The return period used for the hydrological analysis is 15 years. The maximum runoff from the catchment is obtained fro the Rational Formula (equation 2.7). Most of the culverts are designed as performing under inlet conditions. The pipe discharge is obtained from the equation:

$$Q_c = AV \tag{2.8}$$

where Q_c = Pipe Discharge Capacity (m^3/s)

A = Sectional Area (m^2)

V = Average Velocity of Flow (m/s)

The actual sectional area of discharge includes a clearance of 20 – 30% to serve as a freeboard (Road Design Guide, 1991).

If nomographs are to be used then Headwater to Diameter ratio (HW/D) of 0.8 is to be used to determine the pipe discharge. The 0.2 serves as a freeboard. A minimum velocity of 0.8 m/s is adopted to avoid sedimentation of the pipes. The maximum velocity is 3.0 m/s to prevent scouring at the culvert outlets (Road Design Guide, 1991).

2.13.2 Construction

Most of the concrete pipes used in the country are precast, non-reinforced and normally in one-metre spans. The excavation for the culvert is compacted to 93% MDD to a depth of 150mm immediately before concrete is cast (Standard Specifications for Road and Bridge Works, 2006). A concrete surround of 150mm minimum is placed to protect the pipes from possible damage and to make them water proof. Most of the culverts are fitted at the ends with headwalls, wingwalls, aprons and cut off walls. The angle of flare for the wingwalls is 30 – 75 degrees (Road Design Guide, 1991). The depth of headwalls is 500mm minimum depending on the amount of fill on the culvert. The thickness of the apron is such that it should be flushed with the inverts of the pipes. A cutoff wall of 500mm minimum depth is provided to protect the ends from scouring. The backfill for the culvert is compacted to a dry density of 93% MDD (Standard Specifications for Road and Bridge Works, 2006). The outlet channels are lined with concrete in settlements and they are seldom done in the remote sections of the roads. Flow speed reduction measures are normally incorporated to reduce the flow energy and thereby prevent scouring at the outlets. Figure 2.7 shows some 900mm diameter concrete pipe culverts under construction on the project road.

Figure 2.7 – 900mm diameter pipe culverts under construction
[Wenchi Sampa Road Project (2001)]

CHAPTER 3

3. METHODOLOGY

3.1 The Project Road

The study was conducted on the first 30km section of the road from Wenchi to Sampa. This is a Regional Road, R93, under Ghana Highway Authority Road classification system. The upgrading of this section of the road was started in the Year 2000 and was completed in the Year 2005. The road is located on the right hand side of a ridge travelling in the direction of Wenchi and that almost all the streams and runoffs move from left side to cross the road to the right side of the terrain. Apart from two long span bridges on River Tain and River Nimpeni, which were constructed several years ago, all other cross drainage structures were made up of concrete circular pipes. The study road is as shown in Figure 3.1.

Figure 3.1 The Project Road

3.2 Rainfall, Topography and Geology of the area

The project road is located in an area where the rainy season is limited to about five months in the year. The area lies in the savannah zone of the country where there is not much vegetation cover. The topography is gently undulating to stronger rolling. The parent rocks are phyllites, schists, granites, sandstone, sandy and pebbly beds, shale, mudstone, quarzites, conglomerate, metamorphosed lavas and pyroclastic rocks (The Agro-Ecological Zones of Ghana, 1996). The natives are mostly farmers and the occurrence of bush fires are annual events.

3.3 Survey Approach

Two approaches were taken to achieve the study objectives. These were the following:

- A field survey of all the existing 1No.900mm diameter pipe culverts and its multiples was conducted. The other bigger sized culverts, which included 1200mm diameter pipes and 1800mm diameter pipes, were also inspected so that a very good hydraulic performance analysis of the 900mm diameter pipe culverts could be made.
- A questionnaire was administered to some personnel of the Ghana Highway Authority in the Brong Ahafo Region regarding construction and maintenance practices of pipe culverts.

3.3.1 Field Survey

The field survey was conducted on the entire 30km stretch of the road as shown in Figure 3.1 above. The survey was done in four parts:

- Survey of the approach roadway and embankment,

- Survey of the waterway or the channel,
- Survey of the culvert barrel and end treatments and
- Survey of the aprons and energy dissipators

All survey findings are documented in Appendix B. The approach roadway and the embankment were inspected for signs of erosion or failure of the embankment slope over the culvert. The embankment protection against erosion such as slope paving or vegetation was also inspected. In conjunction with the design drawings the approach fills were determined to evaluate whether the culverts had functional inlet invert levels.

The waterways or channels were surveyed for the nature of the horizontal and vertical alignments. The horizontal alignment was used to evaluate the straightness or otherwise of the channels. The channel bends and their respective distances from the inlets and outlets of the culverts were noted. The profiles of the channels were investigated using level instrument to measure the levels at both ends of the culverts and beyond for every culvert location. The slopes for the culvert barrels, upstream and downstream channels were then calculated. Any abrupt changes in the longitudinal slopes of the channels were noted. The velocities of flow in the culvert barrels were computed for all the culverts using the Manning's formula (equation 2.6). Channels were also checked for aggradation and degradation.

The patterns of the streams or channels were determined as the channel being straight, meandered or braided has influence on the flow through the culvert and therefore its hydraulic performance. The weedy channels were also noted and checked for deposition.

The culvert headwalls, wingwalls, cutoff walls and slope protection were checked for any deficiencies and deterioration including undermining, scour and slope failure. The lengths of the culvert barrels were all noted since they were major determinant of the friction losses in the culvert barrels. Culverts were checked whether they were located in their natural channels and were normal to the road centreline. Debris or sediments built-up within the barrels were all documented.

The aprons which reduce erosion at inlets and outlets of the culvert were checked for deterioration, missing stones and undermining of slab due to scour. The culverts were checked whether they had any energy dissipaters which reduce the velocities of outflow and the downstream erosion.

3.3.2 Administration of Questionnaire to Road Managers on pipe culvert maintenance

The questionnaire requested information about the Agency's inspection programme, maintenance programme and the types of pipe culverts used as cross drainage structures in the region. The survey questions were designed to provide a logical approach to pipe culvert assessment. As an overview of the survey approach, it was important to know if the Agency had incorporated the culverts on the project road into their maintenance programme. This was so because the section of the road being studied was reconstructed and completed in the year 2005. The questionnaire sought to find the frequency of inspection and maintenance, and whether the culverts were immediately inspected after heavy downpour. The questionnaire also asked the Agency the type of maintenance interventions carried on the pipe culverts.

The final areas of interest on the questionnaire were to find from the Agency the last time that any maintenance activity was carried out on the culverts on the road and whether human beings were made to enter the culverts to clean them. A copy of the questionnaire is provided as Appendix B. Two questionnaires were sent to the Regional Office of the Ghana Highway Authority in Sunyani to be completed.

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1 Data Collected

Fifty-five pipe culverts were investigated during the study on the 30km stretch of the project road. These included forty-five 900mm diameter pipe culverts, five 1200mm diameter pipe culverts and five 1800mm diameter pipe culverts. The forty-five 900mm diameter pipe culverts consisted of thirty-four single barrels and eleven multiple barrels. All the culverts were circular in shape, made with concrete material and had headwalls and wingwalls, and cutoff walls (toe walls) as culvert end treatments. All but one culvert alignment were normal to the road centreline. The results have been documented in Appendix B. The results have further been grouped under the following and their effects to be discussed:

- culvert location,
- channel alignment,
- slope of the area,
- multi-barrel culverts,
- stream or runoff channel pattern
- weedy channel
- silted inlet and outlet, and
- channel degradation

4.2 The effects of Culvert Location and Channel Alignment

Twenty-four 900mm pipe culverts were located in the existing bed (Table 4.1). Two of them had their outlets scoured, and they were located in the 2.5 – 4.5% slope areas (Appendix B). Eleven were silted, and they were found in 0.5 – 1.0% slope areas.

The silted culverts had their flow areas reduced. The 900mm pipe culverts were located on the existing alignments and aligned to give the stream or runoff a direct entrance and a direct exit (Fig. 4.2 and Fig. 4.3). Eleven of them had their culvert barrel slopes almost the same as the channel bed slopes and the alignments were straight resulting in steady flow velocities.

The other twenty-one 900mm diameter pipe culverts which were located at low areas (0.5 – 1.0% slope areas) and impoundment areas created by the roadway embankment, had no channels upstream. The inlets received runoff from a wide area upstream and the side drains. Twelve of them were silted. Six of them had constant slopes with the channels and had no adverse effect.

Table 4.1 - 900mm diameter pipe culvert locations

Item	Existing channel	New channels
Total Number of culverts	24	21
No. with scoured outlet	2	4
No. silted	11	12
No. of culverts with the same bed slope as channel	11	6

An important feature of the Project Road is that it is aligned along a path with gentle undulations in the East-West direction and perpendicular to steeper slopes in the North-South direction. The 900mm diameter pipe culvert is located in the lowest points of the undulations where there are no clearly defined water channels. With the roads acting as dikes to the flow of water in the North-South direction, most of the water flowing into the culverts approach the inlets in directions perpendicular to the culvert barrels (see Fig. 4.1). Three distinct flows Q_1, Q_2 and Q_3 approach the inlet of the culvert as shown in Figure 4.1 with Q_1 and Q_2 greater than Q_3. This results in a lot of turbulence at the inlet resulting in energy losses. Scouring or siltation will result depending on the soil at the inlet and the resultant energy levels there.

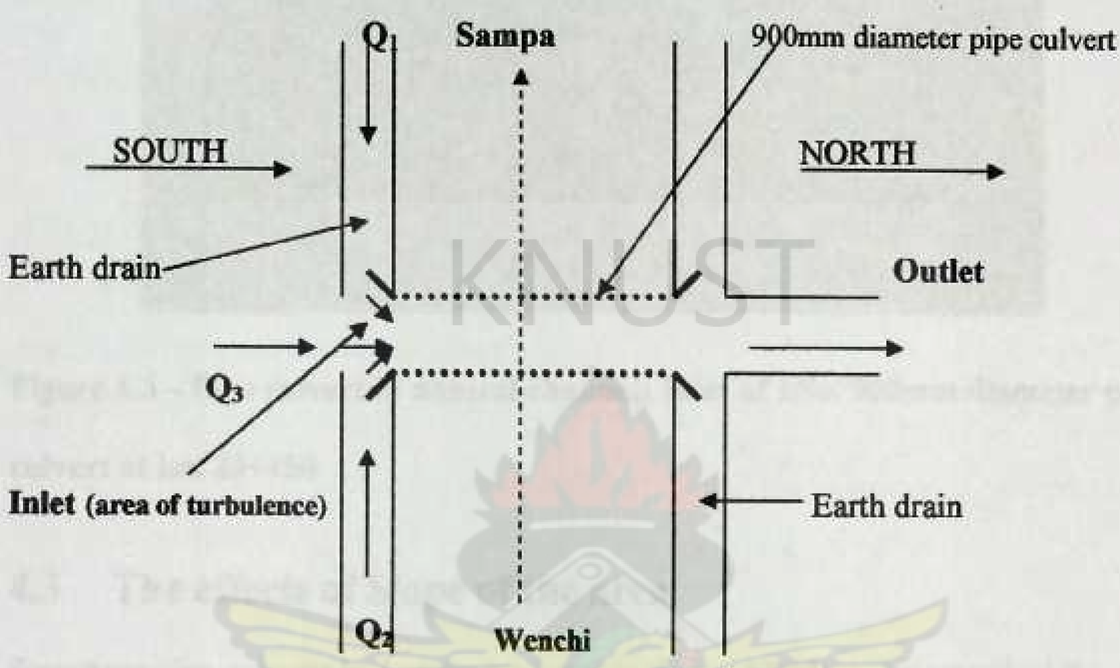


Figure 4.1 – Flow approaching 900mm diameter pipe culvert inlet

Figure 4.2 – Pipe culvert in natural channel: Outlet of 1No. 900mm diameter pipe culvert at km 4+425

Figure 4.3 – Pipe culvert in natural channel: Inlet of 1No. 900mm diameter pipe culvert at km 23+450

4.3 The effects of Slope of the area

Seventeen pipe culverts had upstream average slope of 3.0% and sixteen had the same slope downstream (Table 4.2). All the pipe culverts with this average slope had average flow velocity of 4.3m/s in the culvert barrels at design discharges. Six of them had abrupt changes in the slopes either at the inlet or the outlet and these had either scouring or deposition of sediments at the inlets and outlets.

There was one pipe culvert which had silt deposition at the inlet but serious scouring at the outlet (Fig. 4.4). This pipe culvert had an upstream slope of 4.0%, culvert barrel slope of 2.0% and downstream slope of 4.5%. This phenomenon occurred because the change of 4.0% slope upstream to the flatter grade of 2.0% in the culvert resulted in the loss of energy at the inlet. At moderate flow rates the culvert cross section was larger than that of the stream or runoff so the flow depth and sediment transport capacity were reduced. Four pipe culverts had abrupt change in the culvert alignments to a steeper slope of the channel alignments (that is, from 2.0% to 4.5% slope), and these had a lot of turbulent flows at the inlets and high outlet flow velocities (more than 5.2m/s). Local scour thus occurred at the inlets and the outlets of the culverts, with some exposing the apron slab. Seventeen pipe culverts with constant average slope of 3.0% at both ends had no defect because of uniform flow through the channels and the culverts. Twenty-one out of the thirty-eight pipe culverts in the terrain of 0.5 – 1.0% slopes were silted. Figure 4.5 and Figure 4.6 show two of them. This happened because of relatively low velocities of flow.

Table 4.2 - Upstream and Downstream Slopes

Slope Range (%)	Av. Slope (%)	Av. barrel flow velocities (m/s)	Number of Culverts	
			Upstream	Downstream
0.5 – 1.0	0.75	2.12	20	18
1.0 – 2.5	1.75	3.24	8	11
2.5 – 4.5	3.0	4.30	17	16

Figure 4.4 – Scoured outlet of 1No. 900mm diameter pipe culvert at km 4+900 – 2.0 – 4.5% slope area – The result of inadequately sized outlet earth channel

Figure 4.5 – Silted inlet of 1No. 900mm diameter pipe culvert at km 2+590 – 0.5 – 1.0% slope area – loss of energy to carry sediment through culvert barrel (hence deposition)

Figure 4.6 – Silted inlet of 3No. 900mm diameter pipe culvert at km 28+125 – 0.5 – 1.0 % slope area (loss of energy as in Figure 4.5)

4.4 The effects of multi-barrel culverts

These consist of 900mm diameter pipe culverts with two or more barrels at the same location. The total number was eleven with five silted, and three outlets scoured (Table 4.3). The silted 900mm diameter multi-barrel pipe culverts had their inner pipes mostly affected. Figure 4.7 shows one of them. This was due to the curved nature of the alignment before the inlet. There was no upstream channel and the inlet received runoff mostly from the side drains. The high energy flow from the side drains upstream, after passing the bend at the inlet, suffered energy loss and that all the sediments could not be transported through the pipes. The inner pipe therefore had sediment built up.

Table 4.3 - Multi-barrel pipe culverts

Item	Multi-barrel culverts
Total Number	11
Number Silted	5
Number with outlet scoured	3

Figure 4.7 – Silted inner barrel of 2No. 900mm dia. pipe culvert at km 21+800 (Possible rise in Tailwater Level thus reducing average velocity in barrel)

4.5 The effects of Stream or Runoff Channel Pattern

Forty pipe culverts had runoff channels being straight, three being meandered and two braided (Table 4.4). All the braided channels were found in the 0.5 – 1.0% slope areas and were silted. Figure 4.8 shows one of them. This was due to low flow velocities (such as 1.7m/s) which had made the supply of sediment load exceed the runoff transport capacity. The meandered channels had abrupt changes in their alignment slopes and they were all degraded (Fig. 4.9). These happened due to high flow velocities (such as 5.2m/s) which caused turbulence at the bends resulting in erosion.

Table 4.4 - Stream/Runoff Channel Pattern

Type of channel	*Straight*	*Meandered*	*Braided*
Total number	40	3	2
Number silted	21	0	2
No. with outlet scoured	3	3	0

Figure 4.8 – Braided outlet of 3No. 900mm diameter pipe culvert at km 28+125

Figure 4.9 – Meandered outlet of 2No. 900mm diameter pipe culvert at km 3+188

4.6 The effects of Weedy Channel

Due to lack of maintenance fourteen of the culvert channels had become weedy. Figure 4.10 and Figure 4.11 show two of such culvert channels. The resultant effect was that all the affected culverts had silted up (Table 4.5). This was due to the high roughness of the channels which reduced flow depths. Sediments deposited in the culvert by upstream flow were therefore not able to be transported downstream.

Table 4.5 - Weedy Channels

Item	Weedy Channels
Total Number	14
Number Silted	14
Number with outlet scoured	0

Figure 4.10 – Weedy outlet of 1No. 900mm diameter pipe culvert at km 3+410

Figure 4.11 – Weedy outlet of 2No. 900mm diameter pipe culvert at km 9+475

4.7 Silted Inlets and Outlets

Twenty-three pipe culverts had their inlets or outlets or both silted (Table 4.6). These culverts also had their channels aggraded. These culverts were found mostly in areas of average slope of 0.75% where relatively low flow velocities existed (1.7m/s minimum). All the silted culverts were more than one-third full with sediments. Figure 4.12 shows one of the affected culverts. The sediments deposited in the pipes reduced the cross-sectional area. The flow rates through the affected culverts were, therefore, reduced and that the performance of the culverts was minimal. Continuing build-up of sediment deposits would eventually block some of the culverts.

Table 4.6 - Silted 900mm diameter pipe culverts

Item	900mm diameter pipe culvert
Total number	23
General slope of area	0.5 – 1.0%
Average flow velocity	1.7m/s
Average silted area of pipe	More than 1/3

Figure 4.12 – Silted inlet of 1No. 900mm diameter pipe culvert at km 29+525

4.8 Degraded Pipe Culvert Channels

Six of the pipe culverts had their channels degraded, some seriously (Table 4.7). Three of the degraded channels had become meandered. Two of the six pipe culverts had their outlets scoured exposing the apron slabs. These could be as the results of local scouring and not general scouring which had caused the channel degradation (Figure 4.13). All the degraded channels were located in 2.5 – 4.5% slope areas where high flow velocities existed. Those with serious outlet scour, exposing the apron slabs, could fail structurally.

Table 4.7 - Degraded Pipe Culvert Channel

Item	Degraded Channel
Total Number of Culverts	6
Number with meandered channel	3
Number with outlet scoured	2

Figure 4.13 – Degraded outlet of 1No. 900mm dia. pipe culvert at km 4+900

4.9 The performance of 1200mm- and 1800mm diameter pipe culverts

All the bigger size culverts with site conditions similar to the affected 900mm diameter pipe culverts performed in the same manner. These are culverts located in areas with streams which flow in well-defined channels during the rainy seasons but dried up during the six to seven months of dry season in the area. Weeds often grow in the channels, thus creating conditions similar to the location of the 900mm diameter pipe culverts. There was one 1800mm diameter pipe culvert at km 5+075 (Fig. 4.14) which had abrupt change in the channel alignment slope from 4.0% to 1.0% at the inlet and had a weedy outlet channel. The resultant effect was that the inlet and outlet were all silted and the outlet channel aggraded. There was another at km 19+500 (Fig. 4.15) with abrupt change in the alignment direction downstream. This was silted up and had both the inlet and outlet ponded. This meant that irrespective of the size of the culverts, the existing site conditions determined the flow rate through them.

Figure 4.14 – Weedy and silted inlet of 1No. 1800mm diameter pipe culvert at km 5+075

Figure 4.15 – Weedy and silted outlet of 2No. 1800mm diameter pipe culvert at km 19+500

4.10 Review of the Questionnaire

Two questionnaires were sent to the Regional Office of Ghana Highway Authority to be completed. All the two responded. The questionnaire was to find out from them the inspection and maintenance programmes they had for the pipe culverts in the Region including those on the project road.

According to the respondents (Table 4.8), the pipe culverts were inspected once a year. However, the culverts were not inspected immediately after heavy downpour to see the effects of the flood that would occur. The culverts were maintained once a year. The type of maintenance interventions carried out included desilting of culverts, scour checks at the inlets and outlets, and desilting and clearing of weedy channels. The last time that any maintenance activity was carried out was September, 2007, five months after which this study was done.

Most of the culvert channels were overgrown with weeds. Their state was the same as the surrounding vegetation. Most of the silted culverts were more than half full. Those with scoured outlets were so serious that the apron slabs had been undermined. The inability to inspect the culverts immediately after heavy downpour would not provide the opportunity to assess the total performance of the culverts.

Table 4.8 - Questionnaire on pipe culvert maintenance response

Item	Response
Frequency of inspection	Once a year
Culverts inspected immediately after heavy downpour	Not done
Frequency of maintenance	Once a year
Type of maintenance activities	Desilting of culverts, desilting and clearing of weedy channels, Scour checks at inlets and outlets
Date last maintenance carried out	September, 2007

CHAPTER 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The major conclusions of this study are the following:

- The twenty-three 900mm diameter pipe culverts that were silted were located in both existing beds and new channels created as a result of low slopes and roadway impoundment. The average slope of such areas was 0.75%, except rare cases where there was change in higher channel alignment grade upstream to flatter grade of the pipe culvert (such as, 4.0% slope upstream to 1.0% culvert barrel slope). The four 900mm diameter pipe culverts that had their inlets or outlets scoured were located in areas of relatively steeper slopes (2.5 – 4.5%). Fourteen 900mm diameter pipe culverts had weedy channels, and these could be found anywhere along the project road irrespective of the nature of the terrain. There were no signs of maintenance for the past two years. They were all silted. There were twenty-one 900mm diameter pipe culverts that had no channel upstream; the inlets of such culverts received runoff from wide area upstream and the side drains. The prevailing conditions at the culvert locations did not therefore improve the flow capacities of some of the 900mm diameter pipe culverts.
- Eighteen 900mm diameter pipe culverts had alignments with the same slopes as the upstream and downstream channels. The alignment grades were between 1.0% and 4.0%. Such culverts had steady flow velocities (between 2.5m/s and 4.9m/s) which enhanced their performances. These were the

culverts which were not silted or had their ends scoured even though the maximum flow velocity in concrete pipe to prevent scouring is 3.0m/s (Road Design Guide, 1991).

On the other hand, twenty 900mm diameter pipe culverts that were silted were all located in low slope areas (0.5 – 1.0%) where flow velocities were between 1.7m/s and 2.5m/s. However, the minimum flow velocity in concrete pipes to prevent silting is 0.8m/s (Road Design Guide, 1991) which is far lower than the 1.7m/s minimum attained. The change in the alignment grade from relatively steeper slope to flatter slope of the pipe culverts (such as, 4.0% to 1.0%) also resulted in the silting of two pipe culvert inlets. The lack of channels upstream for some of the 900mm diameter pipe culverts made the inlets to take runoff from the side drains which behaved as a bent alignment at the inlet. This situation resulted in the silting of the inner barrel of three double 900mm diameter pipe culverts. The deposition of sediments in such 900mm diameter pipe culverts reduced the flow area of the pipes which in turn reduced the flow capacity.

Fourteen 900mm diameter pipe culverts had weedy channels downstream. The high roughness of the channels reduced the sediment conveyance ability of the flow through the pipes. Deposition of sediments then occurred in the pipes. Flow rates in the pipes were therefore reduced.

- The 900mm diameter pipe culverts were not inspected immediately after heavy downpour to observe the effect of floods on their performances. The floods that occurred could trigger silting in the culverts or scouring at the culvert ends and these were not promptly rectified. The performance of the pipe culvert was therefore reduced in such circumstances.

5.2 Recommendations

The following recommendations are for consideration by the Ghana Highway Authority to enable it improve upon its regulatory policy:

- The 900mm diameter pipe culverts should be provided with excavated channels upstream and downstream in all locations, especially the multi-barrel ones, to prevent silting of the inner pipes. The excavated channels should be at least 25m.
- A constant slope should be established for the 900mm diameter pipe culvert alignment, the upstream channel and the downstream channel, especially in areas of 1.0% slope or higher to ensure steady flow velocities.
- The 900mm diameter pipe culverts should be inspected immediately after heavy downpour. Any damage caused by the flooding waters should be promptly rectified to prevent extensive damage.
- Due to the entry conditions at the inlets which result in scouring and or siltation measures such as catchpits, lining, etc. be studied and recommended for construction.
- The frequency of maintenance of 900mm diameter pipe culverts which is once a year should be maintained. However, the supervision of the works should be strengthened to ensure that they are done.
- Since this is the first serious study of culvert performance in the country, and restricted to only one Road, it is recommended that more such studies be carried out on other roads in the various ecological zones of the country so that comprehensive findings will be obtained for better designs.

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APPENDICES

APPENDIX A – Questionnaire for Road Managers on maintenance of Pipe Culverts

KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY
COLLEGE OF ENGINEERING
DEPARTMENT OF CIVIL ENGINEERING

Questionnaire for Road Managers on Maintenance of Pipe Culverts

Any information provided will be treated as highly confidential and will only be used for academic purposes.

Write the answer next to the question or tick the correct answer if a choice is given.

Organisation.............................. Position.........................
Years of Experience.....................

- What types of cross drainage structures are under your jurisdiction?

☐ Bridges ☐ Box Culverts ☐ Pipe Culvert
☐ Drifts ☐ Vented Fords

- List the sizes of the pipe culverts that can be found in the Region (eg. 600mm, 900mm diameters, etc)

....

- Which of them are used as cross drainage structures?

....

- What type of material are the pipe culverts made of? (eg. concrete, timber, etc)

....

- How are the pipe culverts maintained?

☐ By Contract ☐ By Force Account

- Do you inspect the pipe culverts immediately after heavy downpour?

☐ Yes ☐ No

- What is the frequency of inspection in a year? ....
- What is the frequency of pipe culvert maintenance in a year? ....
- What type of maintenance interventions are carried out?

☐ Desilting of culverts

☐ Scour checks at inlets and outlets

☐ Removal of debris blocking the inlets

☐ Desilting and clearing of weedy channel

☐ Construction of a basin or catch-pit structure at the outfall of the culvert to reduce the speed of flow

- If there is any maintenance intervention that was not mentioned above, please state it ....
- Please, have you incorporated the culverts on the reconstructed section of the Wenchi – Sampa road in your maintenance programmes?

☐ Yes ☐ No

- If Yes, when did it start? ....
- And when was the last time that any maintenance activity was carried out on the culverts on the road? ....
- Do human beings enter the 900mm pipe culverts to clean them?

☐ Yes ☐ No

- If Yes, what are some of their complaints? ....
....
....
- If No, then what other method(s) is/are used? ....
....

APPENDIX B – Field Survey Results

FIELD SURVEY RESULTS (900mm diameter concrete pipe culvert)

Highway Location	Number of barrels	Length (m)	Designed Fill (m)	Culvert Alignment, slope and velocity	Channel Alignment	Runoff Channel Pattern	Local Effects	Upstream Effects	Downstream Effects
0+500 (new)	1	14	0.53	Normal to Road centreline, Slope = 1.0% Flow velocity =2.5m/s	Curved at 10m after culvert outlet to left	Straight	Aggradation of bed, Silted culvert	Flow restricted to side drains, Silted inlet, depth of pipe=0.6m, slope =1.0%	Aggradation, Silted outlet, effective depth of pipe=0.7m, slope = 1.2%
0+650 (old)	2	14	0.69	Normal to road centreline, Slope =1.0% Flow velocity =2.5m/s	Straight	Straight	Stable channel, Clean channel	None, slope = 1.0%	None, slope = 1.3%
2+250 (old)	2	14	1.0	Normal to road centreline, slope =0.6%, flow velocity =1.9m/s	Straight	Straight	Silted channel, Weedy channel	Flow restricted to side drains, slope = 0.6%	Deposition of sediments, slope = 0.7%
2+590 (new)	1	14	1.2	Normal to road centreline, Slope =0.6% Flow velocity =1.9m/s	Straight	Straight	No well defined channel upstream –wide area contributes to runoff, Weedy channel downstream	Signs of aggradation, Effective depth of pipe=0.7m, slope = 0.6%	Aggradation, Effective depth of pipe=0.5m, slope = 0.65%
3+188 (new)	2	14	1.2	Normal to road centreline, Slope =2.0% Flow velocity =3.5m/s	Winding, Abrupt change at inlet	Meandered	Channel dropped just after the outlet, Unstable channel	Silted inlet – effective depth of pipe=0.5m, slope = 4.0%	Serious scouring at the outlet exposing apron slab, Degradation, slope = 4.5%
3+410 (new)	1	14	1.0	Normal to road centreline, Slope =1.0% Flow velocity =2.5m/s	Straight, Abrupt change at inlet	Straight	High slope at the upstream end, Loose material from abandoned borrow pit, Silted and weedy channel	Non-vegetative cover, Effective depth of pipe=0.4m, slope = 4.0%	Aggradation of the bed, Effective depth of pipe=0.3m, slope = 1.0%

FIELD SURVEY RESULTS (900mm diameter concrete pipe culvert)

Highway Location	Number of barrels	Length (m)	Designed Fill (m)	Culvert Alignment, slope and velocity	Channel Alignment	Runoff Channel Pattern	Local Effects	Upstream Effects	Downstream Effects
4+425 (old)	1	14	0.71	Normal to Road centreline, Slope = 4.0% Flow velocity = 4.9m/s	Straight	Straight	No defined channel upstream	None, slope = 4.0%	None, Slope = 4.0%
4+560 (old)	1	14	1.4	Normal to Road centreline, Slope = 4.0% Flow velocity = 4.9m/s	Curved left 10m after culvert outlet, Abrupt change at outlet	Straight	Degradation	Signs of Degradation, slope = 4.0%	Serious degradation but culvert outlet firm, slope = 4.5%
4+900 (new)	1	14	1.1	Normal to road centreline, Slope = 2.0% Flow velocity = 3.5m/s	Winding, Abrupt change at outlet	Braided upstream and Meandered downstream	Degradation, Unstable channel	Scouring under the apron, slope = 4.0%	Serious degradation, Serious scouring under the apron. Outlet structure undermined, slope =4.5%
5+550 (new)	1	14	2.3	Normal to road centreline, Slope = 2.0% Flow velocity = 3.5m/s	Straight	Straight	No defined channel upstream	None, slope = 3.5%	None, slope =3.6%
5+850 (old)	1	14	2.6	Normal to road centreline, Slope = 2.0% Flow velocity = 3.5m/s	Straight	Straight	No defined channel upstream	None, slope = 3.5%	None, slope = 3.5%
6+450 (new)	1	14	1.8	Normal to road centreline, Slope = 2.0% Flow velocity = 3.5m/s	Straight	Straight	No defined channel upstream	None, slope = 3.0%	None, slope = 3.5%

FIELD SURVEY RESULTS (900mm diameter concrete pipe culvert)

Highway Location	Number . of barrels	Length (m)	Designed Fill (m)	Culvert Alignment, slope and velocity	Channel Alignment	Runoff Channel Pattern	Local Effects	Upstream Effects	Downstream Effects
6+700 (new)	2	14	2.1	Normal to road centreline, Slope = 2.0% Flow velocity = 3.5m/s	Winding, Abrupt change at outlet	Meandered	Silted Aprons, Narrow channel, Degradation, Stream crossing	Degradation, slope = 4.0 %	Degradation, slope = 4.0%
9+475 (old)	2	16	1.6	Normal to road centreline, Slope = 0.8% Flow velocity = 2.2m/s	Straight	Straight	Silted culvert, Weedy channel, Stream crossing	Aggradation, Effective depth of pipe = 0.65m, slope = 0.8%	Aggradation, Effective depth of pipe = 0.6m, slope = 0.9%
10+100 (old)	1	14	1.5	Normal to road centreline, Slope = 0.8% Flow velocity = 2.2m/s	Straight	Straight	No defined channel upstream, silted and weedy channel downstream	Flow restricted to side drains, slope = 0.8%	Silted and weedy, slope = 0.9%
10+300 (new)	1	14	1.1	Normal to road centreline, Slope = 0.6% Flow velocity = 1.9m/s	Straight	Straight	No defined channel upstream, Outlet silted, Very weedy channel downstream	Flow restricted to side drains, slope = 0.5%	Silted and weedy, slope = 0.6%
10+400 (new)	1	14	0.5	Normal to road centreline, Slope = 0.9% Flow velocity = 2.3m/s	Straight	Straight	No defined channel upstream, silted outlet	Flow restricted to lined side drains, slope = 0.8%	Aggradation, Very weedy, slope = 0.9%
11+550 (new)	2	16	1.2	Normal to road centreline, Slope = 2.0% Flow velocity = 3.5m/s	Straight, Abrupt change at outlet	Straight	Degradation	Degradation, slope = 2.5%	Degradation, slope = 4.0%

FIELD SURVEY RESULTS (900mm diameter concrete pipe culvert)

Highway Location	Number of barrels	Length (m)	Designed Fill (m)	Culvert Alignment, slope and velocity	Channel Alignment	Runoff Channel Pattern	Local Effects	Upstream Effects	Downstream Effects
12+950 (new)	1	14	1.6	Normal to road centreline, Slope = 1.2% Flow velocity = 2.7m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 1.2%	Signs of degradation, slope = 1.5%
13+275 (new)	1	14	2.2	Normal to road centreline, Slope = 1.0% Flow velocity = 2.5m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 1.2%	Silted and weedy, slope = 1.2%
14+075 (new)	1	14	0.96	Normal to road centreline, Slope = 1.0% Flow velocity = 2.5m/s	Straight	Straight	No defined channel upstream, Aggradation	Flow restricted to side drains, pond of water at the inlet, slope = 1.2%	Aggradation, slope = 1.0%
14+275 (new)	1	14	0.90	Normal to road centreline, Slope = 0.8% Flow velocity = 2.2m/s	Straight	Straight	No defined channel upstream, Silted aprons	Flow restricted to side drains, silted inlet - depth of pipe= 0.65m, slope = 0.8%	Silted outlet – effective depth of pipe = 0.7m, slope = 0.9%
14+425 (Old)	1	14	1.4	Normal to road centreline, Slope = 1.0% Flow velocity = 2.5m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 1.2%	None, slope = 1.3%
14+625 (old)	1	14	0.8	Normal to road centreline, Slope = 2.5% Flow velocity = 3.9m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 3.0%	None, slope = 2.5%
14+800 (old)	1	14	0.5	Normal to road centreline, Slope = 2.5% Flow velocity = 3.9m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 3.0%	None, slope = 2.5%

FIELD SURVEY RESULTS (900mm diameter concrete pipe culvert)

Highway Location	Number of barrels	Length (m)	Designed Fill (m)	Culvert Alignment, slope and velocity	Channel Alignment	Runoff Channel Pattern	Local Effects	Upstream Effects	Downstream Effects
15+000 (old)	1	14	1.6	Normal to road centreline, slope =2.5%, Flow velocity = 3.9m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 3.0%	None, slope = 2.5%
15+550 (old)	1	14	2.1	Normal to road centreline, slope =2.5%, Flow velocity = 3.9m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 3.5%	None, slope = 2.5%
15+725 (old)	2	14	0.97	Normal to road centreline, slope =2.5%, Flow velocity = 3.9m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 3.5%	None, slope = 2.5%
16+725 (new)	1	14	0.84	Normal to road centreline, slope =1.1%, Flow velocity = 2.6m/s	Straight	Straight	Very wide channel upstream	None, slope = 1.1%	Signs of degradation, slope = 1.5%
17+775 Yabraso Town(old)	2	12	0.51	Normal to road centreline, slope =0.6%, Flow velocity = 1.9m/s	Straight	Straight	Lined channel but outfall weedy	None, slope = 0.5%	Aggradation, slope = 0.65%
18+500 (old)	1	14	1.4	Normal to road centreline, centreline, slope =1.0%, Flow velocity = 2.5m/s	Straight	Straight	Signs of degradation	Degradation of side drains, slope = 1.2%	Signs of degradation, slope = 1.5%
19+ 050 (old)	1	14	1.6	Normal to road centreline, centreline, slope =1.0%, Flow velocity = 2.5m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 0.65	None, slope = 1.0%
21+100 (old)	1	14	0.5	Normal to road c centreline, slope =0.7%, Flow velocity = 2.1m/s	Straight	Straight	No defined channel upstream, Aggradation, weedy channel	Flow restricted to side drains, silted inlet-depth of pipe = 0.7m, slope = 0.6%	Aggradation and weedy, Effective depth of pipe = 0.7m, slope = 0.8%

FIELD SURVEY RESULTS (900mm diameter concrete pipe culvert)

Highway Location	Number of barrels	Length (m)	Designed Fill (m)	Culvert Alignment, slope and velocity	Channel Alignment	Runoff Channel Pattern	Local Effects	Upstream Effects	Downstream Effects
21+700 (old)	1	14	1.4	Normal to road centreline, slope =0.6%, Flow velocity = 1.9m/s	Straight	Straight	No defined channel upstream, signs of aggradation, weedy channel	Flow restricted to side drains, slope = 0.5%	Aggradation and weedy, depth of pipe = 0.65m, slope = 0.6%
21+800 (old)	2	14	0.8	Normal to road centreline, , slope =0.9%, Flow velocity = 2.3m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 0.8%	Silted pipe -depth =0.65m degradation of the channel just after apron slope = 0.9%
23+325 (old)	1	14	0.62	Normal to road centreline, slope = 0.7%, Flow velocity = 2.1m/s	Straight	Straight	No defined channel upstream, aggradation and weedy channel	Flow restricted to side drains, slope = 0.6%	Aggradation and weedy, depth of pipe = 0.7m, slope = 0.7%
23+450 (new)	1	14	1.1	Normal to road centreline, slope = 0.7%, Flow velocity = 2.1m/s	Straight	Straight	Very wide channel upstream	None, slope = 0.6%	None, slope = 0.7%
26+350 (old)	1	14	1.1	Normal to road centreline, slope = 0.6%, Flow velocity = 1.9m/s	Straight	Straight	Poorly defined channel upstream, aggradation, weedy channel	None, slope = 0.5%	Aggradation and weedy, depth of pipe = 0.7m, slope = 0.65%

FIELD SURVEY RESULTS (900mm diameter concrete pipe culvert)

Highway Location	Number of barrels	Length (m)	Designed Fill (m)	Culvert Alignment, slope and velocity	Channel Alignment	Runoff Channel Pattern	Local Effects	Upstream Effects	Downstream Effects
26+850 (old)	1	14	0.95	Normal to road centreline, slope = 0.6%, Flow velocity = 1.9m/s	Straight	Straight	Aggradation, weedy channel	Silted Inlet - depth of pipe = 0.65m, slope = 0.55%	Aggradation, pipe depth = 0.60m slope = 0.65
27+ 775 Nsawkaw Town(old)	2	20	1.1	Normal to road centreline, slope = 1.0%, Flow velocity = 2.5m/s	Straight	Straight	Flow from lined drains improves velocities	None, slope = 1.0%	None, slope = 1.2%
28+125 End of Nsawkaw (old)	3	17	1.2	Normal to road centreline, slope = 0.6%, Flow velocity = 1.9m/s	Straight	Braided	Aggradation, stream crossing	Silted inlet- effective depth of pipe = 0.5m, slope = 0.5%	Aggradation - effective depth of pipe = 0.5m, slope = 0.6%
29+300 (new)	1	14	0.51	Normal to road centreline, slope = 1.0%, Flow velocity = 2.5m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 0.5%	None, slope = 1.0%
29+525 (new)	1	14	0.65	Normal to road centreline, slope = 0.6%, Flow velocity = 1.9m/s	Straight	Straight	No defined channel upstream, aggradation	Silted inlet- effective depth of pipe = 0.6m, slope = 0.5%	i. Silted outlet- effective depth = 0.5m, slope = 0.6%

FIELD SURVEY RESULTS (1200mm diameter concrete pipe culvert)

Highway Location	Number of barrels	Length (m)	Designed Fill (m)	Culvert Alignment, slope and velocity	Channel Alignment	Runoff Channel Pattern	Local Effects	Upstream Effects	Downstream Effects
0+461 (old)	2	14	0.5	Normal to road centreline, slope = 1.0%, Flow velocity = 2.5m/s	Straight	Straight	No defined channel upstream	Flow restricted to side drains, slope = 1.2%	None, slope = 1.4%
5+200 (new)	1	14	0.8	Normal to road centreline, slope = 1.0%, Flow velocity = 2.5m/s	Straight, abrupt change at inlet	Straight	Aggradation, weedy channel	Weedy channel, aggradation, slope = 3.5%	Aggradation and weedy, effective depth = 0.7m, slope = 1.0%
7+900 (old)	3	14	1.0	Normal to road centreline, slope = 1.1%, Flow velocity = 2.6m/s	Straight	Straight	Ponding of water, aggradation, weedy channel	Ponding and weedy channel, slope = 1.1%	Weedy channel, slope = 1.4%
19+200 (new)	1	14	1.2	Normal to road centreline, slope = 1.0%, Flow velocity = 2.5m/s	Straight	Straight	Wide area upstream	None, slope = 1.2%	None, slope = 1.5%
24+825 (old)	2	14	0.9	Normal to road centreline, slope = 2.5%, Flow velocity = 3.9m/s	Straight	Straight	Wide area upstream	None, slope = 3.0%	None, slope = 3.0%

FIELD SURVEY DATA (1800mm diameter pipe culvert)

Highway Location	Number of barrels	Length (m)	Designed Fill (m)	Culvert Alignment, slope and velocity	Channel Alignment	Runoff Channel Pattern	Local Effects	Upstream Effects	Downstream Effects
4+125 (new)	3	15	1.4	Normal to road centreline, slope = 1.2%, Flow velocity = 2.7m/s	Straight upstream, curved downstream	Straight downstream, meandered downstream	Ponded pipe, silted outlet, weedy channel	Signs of aggradation and weedy, slope = 1.0%	Weedy and aggraded, slope = 1.3%
5+075 (new)	1	15	0.8	Normal to road centreline, slope = 2.5%, Flow velocity = 3.9m/s	Straight upstream, curved downstream	Straight downstream, meandered downstream	Aggradation, weedy channel	Aggradation and weedy channel, depth = 1.2m, slope = 3.5%	Aggradation and weedy, Effective depth = 1.3m, slope = 2.5%
5+100 (new)	1	15	1.0	Normal to road centreline, slope = 2.5%, Flow velocity = 3.9m/s	Straight	Straight	Weedy channel	Weedy, slope = 3.5%	Weedy, slope = 2.5%
7+325 (new)	2	15	1.2	Normal to road centreline, slope = 2.5%, Flow velocity = 3.9m/s	Winding	Meandering	Meandering but no effect	None, slope = 2.5%	None, slope = 2.5%
19+500 (old)	2	15	1.8	Skewed, slope = 1.0%, Flow velocity = 2.5m/s	Winding, abrupt change in alignment direction	Meandering	Ponded inlet and outlet, aggradation	Ponded inlet and aggradation, slope = 3.5%	Ponded outlet and aggradation, slope = 1.0%