

**DATA-DRIVEN ASSESSMENT OF WALL SHEAR FORCES IN BOX
CULVERTS UNDER VARIABLE HYDRAULIC CONDITIONS: A
CASE STUDY OF OGBA RIVER, BENIN-CITY, EDO STATE.**

BY

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PLAGIARISM

This work **DATA-DRIVEN ASSESSMENT OF WALL SHEAR FORCES IN BOX CULVERTS UNDER VARIABLE HYDRAULIC CONDITIONS: A CASE STUDY OF OGBA RIVER, BENIN-CITY EDO STATE** by OVWURHUGHEN, Mudiakewe Anthonio with Number ENG2002188 of the Department of Civil Engineering, Faculty of Engineering, University of Benin City, Edo State, Nigeria, has PASSED the PLAGIARISM TEST.

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DEDICATION

To my late dad, whose immense sacrifices laid the foundation of my academic journey and gave me the leverage to always believe I could be a better version of myself. You are not here today, but I carry your legacy in my heart and deeds. Rest easy, Dad.

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ABSTRACT

This research investigates the structural behavior of a reinforced concrete box culvert under variable hydraulic conditions typical of urban drainage systems in Benin City. The study addresses the problem of culvert deterioration caused by internal sedimentation, foundation scour and variable headwater levels. The aim of the research was to develop a data-driven model that links observable hydraulic conditions to quantifiable structural responses, thereby improving performance evaluation and maintenance prioritization.

To achieve this, field investigations were conducted at the Ogba River drainage corridor to determine practical ranges for the three hydraulic variables. Response Surface Methodology (RSM) was employed to generate a design matrix with 20 experimental runs. Finite Element Analysis (FEA) was performed for each run to simulate the resulting wall shear force response. Six center points were observed in the matrix to ensure adequate degrees of freedom for estimating pure error and testing lack of fit in the ANOVA.

The RSM model achieved a coefficient of determination (R^2) of 98.6%, confirming the model's high predictive accuracy. Results showed that the headwater level had the most significant effect on the wall shear force. The effect of the headwater level on the wall shear force is amplified by its interaction with foundation scour. Optimization analysis identified critical combinations of the variables that produced maximum WSF values greater than 70 kN/m, indicating the threshold beyond which the culvert's structural integrity may be compromised. The developed model provides a quantitative framework for predicting wall shear forces based on measurable hydraulic conditions, offering a practical decision-support tool for culvert maintenance and management in resource-constrained urban environments such as Benin City.

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ACRONYMS

RSM	-	Response Surface Methodology
FEM	-	Finite Element Method
FEA	-	Finite Element Analysis
ANOVA	-	Analysis of Variance
CCD	-	Central Composite Design
FCCD	-	Face-Centered Central Composite Design
DoE	-	Design of Experiment
IS	-	Internal Sedimentation
FS	-	Foundation Scour
HL	-	Headwater Level
WSF	-	Wall Shear Force

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

Response Surface Methodology (RSM) is a powerful statistical tool for modeling the relationship between multiple input variables and a system's response. Widely used in manufacturing and materials science for process optimization (Myers et al., 2016), it is increasingly applied in civil engineering to analyze complex, nonlinear systems involving interacting variables (Dhami et al., 2021). RSM is now used for optimizing mix designs, modeling pavement performance, and in this study, it is used to evaluate structural behavior under real-world deterioration scenarios.

In drainage infrastructure, box culverts are essential components that allow stormwater to safely pass under roads and embankments. They are designed to carry not just water, but also heavy overburden and traffic loads. However, these culverts are exposed to varying environmental and loading conditions over time. In regions like Benin-City, heavy seasonal rainfall, insufficient maintenance and urban runoff contribute to common problems such as internal sedimentation, foundation scour, and increased headwater levels. These hydraulic conditions alter the internal flow dynamics and support conditions of the culvert leading to increased wall shear forces, which, if not properly accounted for, may result in structural failure (Arneson et al., 2012; USACE, 2010).

Conventional inspection methods often rely on visual assessments; the observed hydraulic parameters such as sediment buildup, foundation scour, and headwater level are typically considered in isolation. However, the interactions between these variables introduce nonlinear effects that are not captured by basic engineering approximations. For instance, increased

sediment raises headwater, which increases hydrostatic pressure; meanwhile, scour removes soil support at the base, changing the structural boundary conditions and further elevating internal forces (FHWA, 2012; fib, 2013). Traditional assessment frameworks lack the ability to model these coupled behaviors, which results in maintenance decisions that may either misallocate resources or overlook potential structural risks.

To overcome these limitations in modelling coupled behaviors, Response Surface Methodology (RSM) is employed, often utilizing data from numerical simulations. While these simulations can predict how a culvert behaves under varying combinations of adverse hydraulic conditions, they typically produce large amounts of case-specific datasets that are difficult to generalize. RSM complements these datasets by generating a statistical model that reveals trends, interaction effects, and critical thresholds across a range of conditions in a simple, usable format (Montgomery, 2017). This hybrid approach makes it possible to link field observations directly to structural vulnerability based on reliable statistical information. In Benin-City, where culvert inspections are mostly visual and budgets are tight, this methodology is particularly valuable. With RSM, infrastructure managers can move beyond qualitative assessments and prioritize culvert repairs based on quantifiable structural risks linked to what is visibly observed. Therefore, this research not only provides a practical tool for culvert evaluation but also a template for scalable, data-driven infrastructure assessment in similar urban settings across developing regions.

1.2 PROBLEM STATEMENT

Hydraulic structures, such as culverts, often suffer from adverse hydraulic conditions such as internal sediment buildup, foundation scour, and variable headwater levels during storms. These issues typically arise as a result of the culvert's age, flow patterns, specific

environmental conditions and location within the drainage network (InfraSteel, 2013). These hydraulic and foundation conditions combine to affect the hydrostatic pressures on the culvert walls and the foundation's soil support, directly influencing the shear forces within the walls. This, in turn, impacts the safety and serviceability of the culverts.

In practice, these hydraulic conditions are rarely evaluated in combination, leading to the underestimation of the potential structural risks. Many assessment models used are designed for different climates and maintenance regimes, and do not reflect the typical environmental and infrastructure conditions in Benin-City. Moreover, the relationship between these variables and wall shear force is non-linear and complex. Traditional linear methods fail to capture this complexity, rendering current risk assessments less reliable.

Local engineering approaches have also been found to lack adequate data-driven systems that link visible signs - like sediment buildup or foundation scour depth - to internal structural stress. This has resulted in poor maintenance decisions such as inefficient spending or the neglect of risk-prone box culverts.

Statistical techniques offer a powerful means to overcome these limitations by providing data-driven methods to model the non-linear relationships between visible hydraulic conditions and the resulting internal wall shear forces. These methods facilitate the development of accurate risk assessment tools tailored to specific local conditions. This will bridge the gap between observable signs and hidden structural stress in order to inform better maintenance strategies. There is a critical need to apply these statistical techniques to comprehensively model the combined effects of adverse hydraulic conditions on the wall shear forces of culverts. By modelling the interactive influence of these conditions, this research offers a robust decision-support tool for culvert maintenance in Benin-City and similar urban environments.

1.3 AIM AND OBJECTIVES

The primary aim of this research is to perform a data-driven assessment of wall shear forces in box culverts under variable hydraulic conditions.

The specific objectives of this research are as follows;

1. To locate and assess the hydraulic conditions of the existing box culvert at Ogba River.
2. To define the practical ranges needed for each input variable based on the assessment.
3. To generate possible combinations of conditions from the defined ranges.
4. To simulate the shear force response on the culvert walls under each combination of conditions.
5. To build a response surface model from the generated datasets and analyze it in order to determine how each input variable - alone and in combination - affects the wall shear force.

1.4 SCOPE OF THE STUDY

This research assesses the combined influence of variable hydraulic conditions on the wall shear forces of an existing reinforced concrete box culvert at Ogba River. It focuses on three hydraulic conditions namely: internal sedimentation, foundation scour and headwater level. Response Surface Methodology (RSM) is employed as the statistical technique to analyze and model the interactions between these conditions and the wall shear force.

However, the scope of this research is specifically limited to box culverts, excluding analysis of other culvert types. Also, it does not examine any structural response other than the shear force of the culvert walls. This research excludes any deterioration mechanisms unrelated to the defined hydraulic conditions. Furthermore, this research does not cover hydrological modeling for estimating flow patterns or headwater levels.

1.5 JUSTIFICATION OF THE STUDY

This research is driven by the urgent need to improve the safety and serviceability of essential drainage infrastructure, such as box culverts, in urban environments like Benin-City. Existing assessment methods often fail to account for the complex and interactive effects of prevalent adverse hydraulic conditions, often leading to potentially inaccurate structural risk assessments and inefficient maintenance strategies. Furthermore, the absence of data-driven tools tailored to local environmental and infrastructure conditions hinders effective decision-making, resulting in the misallocation of limited resources and potential neglect of high-risk structures.

This research establishes a clear relationship between observable hydraulic conditions and the internal structural demand of box culverts. It also provides a predictive model for efficient risk identification, proper allocation of resources and prioritized maintenance planning.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents a comprehensive review of literature relevant to the assessment of wall shear forces in box culverts under variable hydraulic conditions. The review is tailored to the urban hydraulic environment of Benin City; a region experiencing intense rainfall events, rapid urbanization and drainage stress. The review is structured to cover key areas including Response Surface Methodology applications in civil engineering, adverse hydraulic conditions affecting culvert performance, Finite Element Analysis applications in hydraulic structures and infrastructure management practices in developing countries. The adverse hydraulic conditions explored are internal sedimentation, foundation scour and headwater variation, including their interactive influence on culvert performance. The review emphasizes scholarly literature and technical studies from Nigerian and African contexts to provide relevant insights for the study area.

2.2 HYDRAULIC INFRASTRUCTURE CHALLENGES IN NIGERIA AND SUB-SAHARAN AFRICA

Nigeria's hydraulic infrastructure faces significant challenges due to rapid urbanization, climate change impacts, and limited maintenance resources. Adeloye et al. (2016) identified inadequate drainage infrastructure as a major contributor to urban flooding in Nigerian cities, with particular emphasis on the need for improved culvert design and maintenance practices. Their study of drainage systems in Lagos highlighted the vulnerability of existing infrastructure to extreme weather events and population growth pressures.

In Benin City specifically, Enaruvbe and Atafo (2018) conducted a comprehensive study of land cover transition and fragmentation in the River Ogba catchment, documenting significant changes in urban development patterns that have impacted natural drainage systems. Their findings revealed that rapid urbanization has increased surface runoff and altered flow patterns, placing additional stress on existing hydraulic infrastructure including culverts and drainage channels.

Aziegbe (2006) investigated the morphological response of watersheds to urbanization in Benin City, focusing on channel modifications and their impact on flood risk. The study documented how urban development has altered natural drainage patterns, leading to increased peak flows and reduced lag times, which directly impact the performance of hydraulic structures like box culverts. This work provides crucial context for understanding the hydraulic conditions affecting culverts in the study area.

Ogbomida et al. (2019) examined the impact of urbanization on flood risk in Benin City, identifying inadequate drainage infrastructure as a primary factor contributing to recurrent flooding. Their study emphasized the need for improved assessment and maintenance of existing hydraulic structures, to reduce flood vulnerability in urban areas.

Across broader Sub-Saharan Africa, similar challenges have been documented. Ndambuki et al. (2016) investigated urban drainage challenges in Kenyan cities, highlighting common issues including inadequate design standards, poor maintenance practices, and limited financial resources for infrastructure upgrades. Their findings are relevant to the Nigerian context, as they identify systemic issues affecting hydraulic infrastructure performance across the region.

2.3 CULVERTS: THEORY, TYPES AND FAILURE MECHANISMS

2.3.1 Definition and Functions

Culverts are hydraulic structures that allow water to flow under roadways, railways, embankments, or other obstructions. Unlike bridges, culverts are typically buried structures that convey water through an artificial channel, serving as critical components of drainage infrastructure in urban and rural settings (FHWA, 2012). In essence, a culvert functions as a short bridge, but its design and performance are fundamentally governed by hydraulic principles rather than purely structural considerations.

The primary functions of culverts include:

1. Conveying stormwater runoff beneath transportation infrastructure
2. Maintaining natural drainage patterns and preventing flood accumulation
3. Protecting roadway embankments from erosion and washout
4. Accommodating seasonal and extreme flow events

In urban environments like Benin City, culverts serve an essential role in managing the high volumes of surface runoff generated by impervious surfaces, particularly during intense rainfall events characteristic of tropical climates.

2.3.2 Hydraulic Classification

Culverts can operate under different flow conditions depending on headwater levels, tailwater conditions, and barrel characteristics. The Federal Highway Administration (FHWA, 2012) classifies culvert flow into two primary categories:

1. **Inlet Control:**

Flow capacity is controlled by the inlet geometry, headwater elevation, and barrel characteristics. Under inlet control, the culvert barrel flows partially full, and the outlet

conditions do not affect the flow capacity. This condition typically occurs when the culvert barrel can convey more flow than the inlet will accept.

2. **Outlet Control:**

Flow capacity is controlled by the downstream conditions including tailwater elevation, barrel characteristics, outlet geometry, and barrel roughness. Under outlet control, the culvert typically flows full for at least part of its length, and increasing the inlet size will not increase the flow capacity.

Understanding the hydraulic control mechanism is crucial for predicting culvert performance and assessing vulnerability to adverse conditions such as those examined in this study.

2.3.3 Structural Classification and Geometry

Culverts are constructed in various shapes, each offering distinct hydraulic and structural advantages depending on site conditions, design requirements, and construction constraints.

1. **Box Culverts (Rectangular):**

Box culverts consist of reinforced concrete sections with rectangular cross-sections.

They offer several advantages including:

- i. High structural efficiency under heavy embankment loads
- ii. Flat invert suitable for fish passage and sediment transport
- iii. Easy construction using precast or cast-in-place methods
- iv. Optimal hydraulic efficiency for wide, shallow flow conditions

Box culverts are particularly common in urban settings where multiple barrels may be required to accommodate large discharge volumes. The culvert examined in this study is a reinforced concrete box culvert located at the Ogba River corridor.



Figure 2.1: Typical box culvert showing cross-section and flow characteristics
(Source: EW Enterprises, 2024)

2. **Circular Culverts (Pipe Culverts):**

Circular culverts, typically constructed from reinforced concrete, corrugated metal, or plastic, are the most common culvert type globally. Their advantages include:

- i. Structural efficiency due to arch action
- ii. Ease of manufacture and cost-effectiveness for small to medium discharges
- iii. Self-cleaning properties due to flow concentration at lower depths



Figure 2.2: Circular concrete culvert in operation during a storm flow event
(Source: Atlantic Industries Ltd, 2023)

3. **Arch Culverts:**

Arch culverts feature a curved top and flat or curved bottom, combining structural efficiency with improved hydraulic performance. They are particularly suitable for:

- i. Sites requiring large span-to-rise ratios
- ii. Locations with aesthetic or environmental constraints
- iii. Situations requiring natural stream bed preservation



Figure 2.3: Arch culvert structure showing efficient span-to-depth ratio (Faddis Concrete Products, 2025)

4. **Elliptical Culverts:**

Elliptical culverts offer a structural compromise between circular and box culverts, with the following advantages:

- i. Reduced headroom requirements compared to circular culverts
- ii. Better hydraulic efficiency than circular sections for shallow flows



Figure 2.4: Elliptical culvert profile showing reduced headroom requirements (Source: InfraSteel, 2023)

The selection of culvert shape depends on multiple factors including hydraulic requirements, foundation conditions, available construction materials, economic considerations, and site-specific constraints (USACE, 2010).

2.3.4 Failure Mechanisms in Culverts

Culvert failures can result from hydraulic inadequacy, structural deterioration, or a combination of both. Understanding these failure mechanisms is essential for developing effective assessment and maintenance strategies.

1. Hydraulic Failures:

Hydraulic failures occur when the culvert cannot accommodate the design flow or when flow conditions deviate from design assumptions. Common hydraulic failure modes include:

- i. **Overtopping:** When headwater levels exceed the roadway elevation, flow overtops the embankment, potentially causing catastrophic erosion and washout.

This is particularly common in rapidly urbanizing areas where increased impervious surfaces generate higher runoff volumes than originally anticipated (Adeloye et al., 2016).

- ii. **Inlet Blockage:** Accumulation of debris, sediment, or vegetation at the culvert inlet reduces the effective flow area, increasing upstream water levels and potentially causing overtopping or bypass flows. In Benin City, blockage from market waste, construction debris, and unpaved road sediments is a recurring problem (Aziegbe, 2006).
- iii. **Scour and Erosion:** High-velocity flows at culvert outlets can cause severe scour of downstream channels and undermining of culvert foundations. Foundation scour removes soil support, altering structural boundary conditions and increasing internal forces (Arneson et al., 2012). In flood-prone areas like the Ogba River corridor, even moderate rainfall events can trigger significant scour damage (Rawlings and Ikediashi, 2020).



Figure 2.5: Progressive deterioration of culvert outlet due to foundation scour
(Source: NZ Forest Road Engineering Manual, 2012)

2. Structural Failures:

Structural failures result from inadequate design, settlement, material deterioration, or loads exceeding design assumptions. Common structural failure modes include:

- i. **Wall Cracking:** Excessive shear forces or bending moments in culvert walls can cause cracking, particularly at corners and mid-span locations. These cracks may propagate over time due to freeze-thaw cycles or continued overstress.
- ii. **Foundation Settlement:** Inadequate foundation design or unexpected soil conditions can cause differential settlement, inducing additional stresses in the culvert structure.
- iii. **Corrosion and Deterioration:** Reinforcing steel corrosion in concrete culverts or metal deterioration in corrugated metal culverts reduces structural capacity over time. In aggressive environments typical of tropical regions, deterioration rates can be accelerated by chlorides, sulfates, and organic acids (Ugwu et al., 2020).



Figure 2.6: A damaged box culvert showing the effects of structural distress
(Source: Tenbusch Inc., 2013)

2.4 BOX CULVERT DESIGN AND PERFORMANCE

Box culverts serve a vital role in managing surface water runoff in Benin City, particularly during the extended rainy season (Aziegbe, 2006). Given the city's unplanned urban expansion and increasing impermeable surfaces, culverts are regularly overwhelmed by stormwater volumes beyond their design capacity. Land-use transitions in the Ogba River catchment have also significantly increased sediment transport and hydraulic loading on existing culvert infrastructure (Enaruvbe and Atafo, 2018).

Moreover, Rawlings and Ikediashi (2020) identified the erosion of riparian zones and the encroachment of informal structures along floodplains as critical stressors on culvert foundations in Benin. This process, often neglected in local inspections, leads to the progressive undermining of culvert support through foundation scour.

Box culverts are widely used in Nigeria and across Africa for their structural efficiency and construction practicality. Okonkwo and Agunwamba (2021) conducted a comprehensive study of concrete box culvert design practices in Nigeria, highlighting the need for improved design standards that account for local environmental conditions and construction practices. Their work identified common design deficiencies that contribute to premature failure and reduced service life.

The structural behavior of box culverts under various loading conditions has been extensively studied. Adedeji et al. (2020) investigated the structural performance of reinforced concrete box culverts under different soil conditions in Lagos, Nigeria. Their study used finite element analysis to examine the effects of soil-structure interaction on culvert performance, providing insights relevant to foundation design and scour assessment.

2.5 ADVERSE HYDRAULIC CONDITIONS AFFECTING CULVERT PERFORMANCE

2.5.1 Internal Sedimentation

Sedimentation in culverts is a widespread problem in tropical regions, particularly in areas with high rainfall and significant urban development. The accumulation of sediments in culverts reduces effective flow area, alters internal flow velocity and raises upstream water levels. In Benin City, sedimentation is frequently caused by unpaved road networks, market waste and construction debris, particularly during storms (Aziegbe, 2006). A local study by Enaruvbe and Atafo (2018) documented that sediment load in the Ogba catchment has increased by 34% in the last two decades, contributing to frequent culvert overtopping and internal pressurization.

The hydraulic effects of sedimentation on culvert performance have been documented by several researchers. Ogu et al. (2019) studied sediment accumulation in drainage channels in Port Harcourt, Nigeria, documenting the effects of urban runoff on sediment transport and deposition. Their findings revealed that inadequate upstream erosion control and poor land use practices contribute significantly to sediment problems in hydraulic structures.

Ologunorisa and Tersoo (2006) investigated sedimentation problems in drainage systems in Warri, Delta State, Nigeria, highlighting the relationship between urbanization patterns and sediment accumulation rates. Their study documented how changes in land use and inadequate stormwater management lead to increased sediment loads in drainage infrastructure.

2.5.2 Foundation Scour

Scour is the localized removal of soil at culvert inlets or beneath foundations. In flood-prone areas like Ogba and Sakponba roads where natural vegetation buffers have been lost,

foundation scour is a leading cause of hydraulic failure. According to Rawlings and Ikediashi (2020), even moderate rainfall events cause bank collapse, weakening culvert support and amplifying shear stress on concrete walls due to shifting boundary conditions.

Foundation scour is a critical concern for hydraulic structures, particularly in tropical regions with intense rainfall and significant flow velocities. In the context of culverts specifically, Lawal et al. (2020) studied scour problems at culvert outlets in northern Nigeria, focusing on the effects of flow concentration and energy dissipation on scour development. Their work provided practical insights into scour protection design and the relationship between hydraulic conditions and scour severity.

More recently, Ezeilo et al. (2018) investigated scour problems at bridge foundations in southeastern Nigeria, documenting the effects of extreme weather events on scour development. Their study highlighted the vulnerability of hydraulic structures to scour during flood events and the need for improved scour assessment and protection methods.

2.5.3 Headwater Levels

Variable headwater levels, particularly during high-intensity rainfall, can lead to significant increases in hydrostatic pressure inside culverts. This is especially concerning in the Ogba River corridor where double rainfall peaks in July and September result in flash flooding. High headwater exacerbates pressure on walls and, when combined with sediment and scour, creates highly nonlinear structural loading (United Nations, 2016).

Ogbomida et al. (2016) also investigated flood frequency analysis in Benin City and its implications for hydraulic infrastructure design. Their study provided insights into the statistical characteristics of flood events in the region and the need for improved design standards that account for extreme headwater conditions.

2.6 HYDRAULIC INFRASTRUCTURE MANAGEMENT PRACTICES: VISUAL INSPECTION VS QUANTITATIVE MODELING

In most urban Nigerian settings, including Benin City, culvert inspections are largely visual and qualitative. These assessments fail to account for the interactive behavior of hydraulic stressors (Ogunleye et al., 2017). Studies from the Federal Ministry of Works and Housing note that critical signs like sediment buildup or minor scour are often dismissed due to lack of technical tools to translate visible symptoms into structural risk (FMWH, 2014).

Globally, the shift has moved toward data-driven modeling using statistical and computational tools that allow predictive and quantitative evaluations. However, infrastructure management in developing countries faces unique challenges related to limited resources, technical capacity and data availability. Akintoye et al. (2020) investigated infrastructure management practices in Nigeria, highlighting the need for improved assessment methodologies and decision-support tools. Their work emphasized the importance of data-driven approaches to infrastructure management, which aligns with the objectives of the current study.

Okafor and Ugwu (2019) studied the application of condition assessment methodologies to concrete infrastructure in Nigeria, documenting the challenges and opportunities for implementing systematic assessment programs. Their work highlighted the need for practical, cost-effective assessment tools that can be applied in resource-constrained environments such as Benin City.

2.7 RESPONSE SURFACE METHODOLOGY

Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques that are useful for modeling and analyzing problems in which a response of interest is influenced by several variables and the objective is to optimize this response (Montgomery,

2017). RSM was originally developed by Box and Wilson in 1951 for chemical process optimization and has since been widely adopted across various engineering disciplines, including civil and structural engineering.

The methodology is particularly valuable when dealing with complex systems where multiple factors interact to influence an outcome, and where traditional single-variable analysis would be inadequate to capture the true behavior of the system. In the context of hydraulic infrastructure assessment, RSM provides a powerful framework for understanding how multiple adverse conditions combine to affect structural performance.

2.7.1 Fundamental Concepts

1. Response Surface:

A response surface is a mathematical representation of the relationship between a dependent variable (response) and one or more independent variables (factors). Mathematically, if we have k independent variables x_1, x_2, \dots, x_k , the response surface can be expressed as:

$$y = f(x_1, x_2, \dots, x_k) + \varepsilon \quad (2.1)$$

Where:

- i. y is the response variable
- ii. f represents the true relationship between the response and the independent variables
- iii. ε is the random error term

The goal of RSM is to approximate the unknown function f with a suitable empirical model, typically a polynomial function. The response surface provides a visual and

mathematical representation of how the response varies across different combinations of input variables.

2. **Design Space and Factor Space:**

The design space or factor space is the region of interest in the independent variables. This space is defined by the ranges of the factors being studied. In practical applications, these ranges are determined by:

- i. Physical constraints of the system
- ii. Economic considerations
- iii. Safety limitations
- iv. Practical operational boundaries

For the current study examining box culvert performance, the design space is bounded by the practical ranges of internal sedimentation, foundation scour, and headwater levels that can realistically occur in the field.

3. **Response Function:**

The response function is the mathematical model that describes the relationship between the factors and the response. The most commonly used response functions in RSM are polynomial models, typically first-order (linear) or second-order (quadratic) models.

First-order model:
$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \dots + \beta_kx_k + \varepsilon \quad (2.2)$$

Second-order model:
$$y = \beta_0 + \sum\beta_ix_i + \sum\beta_{ii}x_i^2 + \sum\sum\beta_{ij}x_ix_j + \varepsilon \quad (2.3)$$

where β_0 , β_i , β_{ii} , and β_{ij} are regression coefficients representing the intercept, linear effects, quadratic effects and interaction effects, respectively.

2.7.2 Experimental Design

1. Central Composite Design (CCD):

Central Composite Design is one of the most popular experimental designs for fitting second-order response surface models. A CCD consists of three types of design points:

- i. **Factorial Points (2^k):** These are the corners of the factor space, typically at ± 1 levels
- ii. **Axial Points ($2k$):** These are points along the axes of the factors, typically at $\pm\alpha$ levels
- iii. **Center Points (n_c):** These are replicate runs at the center of the design space (0 level)

The total number of experiments in a CCD is:

$$N = 2^k + 2k + n_c \quad (2.4)$$

For a three-factor design ($k = 3$), this gives: $N = 2^3 + 2(3) + n_c = 8 + 6 + n_c$

2. Face-Centered Central Composite Design (FCCD):

In Face-Centered Central Composite Design, the axial points are placed at the face centers of the factorial space ($\alpha = 1$). This design is particularly useful when:

- i. Factor levels cannot extend beyond the original factorial levels
- ii. There are physical or practical constraints on factor ranges
- iii. Spherical design region is not required

The FCCD ensures that all design points remain within the original factor space, making it ideal for studies where extreme conditions beyond the defined ranges are not feasible or safe to investigate.

3. **Design Matrix Generation:**

The design matrix is a systematic arrangement of factor level combinations that defines which experiments need to be conducted. Each row represents a unique combination of factor levels, and each column represents a specific factor. The matrix typically includes:

- i. Coded factor levels (usually -1, 0, +1 for FCCD)
- ii. Actual factor levels (real-world values)
- iii. Randomized run order to minimize systematic errors

2.7.3 Mathematical Modeling

1. **Model Fitting:**

Once experimental data are collected, the response surface model is fitted using regression analysis. The general approach involves:

- i. **Model Selection:** Choosing between first-order, second-order, or higher-order models.
- ii. **Parameter Estimation:** Using least squares method to estimate regression coefficients.
- iii. **Model Validation:** Checking model adequacy and assumptions.

The regression equation for a three-factor second-order model is:

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_3x_3 + \beta_{11}x_1^2 + \beta_{22}x_2^2 + \beta_{33}x_3^2 + \beta_{12}x_1x_2 + \beta_{13}x_1x_3 + \beta_{23}x_2x_3 \quad (2.5)$$

2. **Analysis of Variance (ANOVA):**

ANOVA is used to assess the statistical significance of the model and individual terms.

Key components include:

- i. **Sum of Squares:** Decomposition of total variation into model and error components
- ii. **F-Statistics:** Testing the significance of the overall model and individual terms
- iii. **p-Values:** Probability of observing the data if null hypothesis is true
- iv. **R²:** Coefficient of determination indicating the proportion of variance explained by the model

3. **Model Adequacy Checking:**

Several diagnostic checks are performed to validate the model:

- i. **Residual Analysis:** Examining residual plots for patterns and outliers
- ii. **Normal Probability Plots:** Checking normality assumption of residuals
- iii. **Lack of Fit Test:** Assessing whether the model adequately represents the data
- iv. **R² and Adjusted R²:** Evaluating model fit quality

2.7.4 Response Surface Analysis

1. **Contour Plots:**

Contour plots are two-dimensional representations of the response surface that show lines of constant response. These plots are particularly useful for:

- i. Visualizing the relationship between two factors while holding others constant
- ii. Identifying optimal operating regions
- iii. Understanding interaction effects between factors

For a three-factor system, multiple contour plots are generated by fixing one factor at different levels and plotting the other two factors.

2. **Three-Dimensional Surface Plots:**

Surface plots provide a three-dimensional visualization of the response surface, allowing for:

- i. Better understanding of the response behavior across the factor space
- ii. Identification of peaks, valleys, and saddle points
- iii. Visual assessment of model curvature and interaction effects

2.7.5 Applications in Civil Engineering

Response Surface Methodology (RSM) has emerged as a powerful statistical tool for optimization and modeling in various engineering disciplines. Originally popular in industrial quality control (Myers et al., 2016), RSM has since been used in concrete optimization (Dhami et al., 2021), pavement design, and hydraulic modeling. Montgomery (2017) describes RSM as a collection of mathematical and statistical techniques useful for modeling and analyzing problems where several independent variables influence a dependent variable or response. The methodology has found extensive applications in civil engineering, particularly in concrete technology, structural optimization, and infrastructure assessment.

In the Nigerian context, Okafor and Umeorah (2019) successfully applied RSM to optimize the compressive strength of concrete incorporating local pozzolanic materials from Afikpo, Ebonyi State. Their study demonstrated the effectiveness of RSM in modeling the complex interactions between cement replacement levels, water-cement ratios, and curing conditions on concrete strength. Similarly, Adeolu et al. (2021) utilized RSM to investigate the optimization of lateritic concrete blocks using Response Surface Methodology, highlighting the methodology's relevance to local construction materials and practices. In structural

hydrology, Oke and Adesola (2022) applied RSM to optimize flood control channel parameters in Lagos, demonstrating its potential for handling complex hydraulic datasets.

Ugwu et al. (2020) applied RSM to model the relationship between various mix parameters and the durability properties of concrete in aggressive environments typical of Nigerian coastal areas. Their work demonstrated that RSM could effectively capture the nonlinear relationships between multiple variables and provide reliable predictive models for engineering applications. This is particularly relevant to the current study, as it establishes the precedent for using RSM in Nigerian civil engineering contexts.

In broader African applications, Akinwumi et al. (2018) used RSM to optimize the stabilization of expansive soils using cement and lime, demonstrating the methodology's applicability to geotechnical engineering problems prevalent across the continent. Ojediran et al. (2022) applied RSM to investigate the optimization of recycled aggregate concrete properties in South Africa, showing the methodology's versatility in addressing sustainability concerns in African construction practices.

As seen from previous technical studies, the strength of RSM lies in its ability to create second-order polynomial models that explain interaction effects. This is ideal for modeling the combined influence of sedimentation, scour and headwater level on culvert wall shear force.

2.8 FINITE ELEMENT ANALYSIS

The Finite Element Method (FEM) emerged in the 1950s as a revolutionary approach to structural analysis, initially developed by engineers working on aircraft design. The method has since evolved into a universal tool for solving partial differential equations across

numerous fields including structural mechanics, heat transfer, fluid dynamics and electromagnetics.

The fundamental concept behind Finite Element Analysis involves subdividing a complex domain into smaller, simpler subdomains called finite elements. Within each element, the unknown field variables are approximated using interpolation functions, typically polynomials. The governing differential equations are then transformed into a system of algebraic equations through variable principles or weighted residual methods.

2.8.1 Mathematical Foundations of FEA

1. Continuum Mechanics Background:

The mathematical framework of FEA is rooted in continuum mechanics, where physical phenomena are described by partial differential equations. Consider a general boundary value problem defined over domain Ω with boundary Γ :

$$L(u) = f \text{ in } \Omega \quad (2.6)$$

$$B(u) = g \text{ on } \Gamma \quad (2.7)$$

where L is a differential operator, u is the unknown field variable, f represents body forces or source terms, B is a boundary operator, and g specifies boundary conditions.

2. Weak Formulation:

The transition from strong form to weak form represents a crucial step in FEA. The weak formulation is obtained by multiplying the governing equation by a test function v and integrating over the domain:

$$\int_{\Omega} v L(u) \, d\Omega = \int_{\Omega} v f \, d\Omega \quad (2.8)$$

Integration by parts is applied to reduce the order of derivatives and incorporate boundary conditions naturally. This process leads to the weak form, which requires

less continuity than the strong form and forms the basis for finite element discretization.

2.8.2 Element Formulation

1. Shape Functions:

Shape functions constitute the cornerstone of finite element approximation. They must satisfy several essential properties:

- i. **Partition of Unity:** $\sum N_i = 1$ at any point within the element
- ii. **Nodal Property:** $N_i = 1$ at node i and $N_i = 0$ at all other nodes
- iii. **Completeness:** Ability to represent rigid body motions and constant strain states exactly

Common shape functions include:

- i. Linear functions for 1D elements
- ii. Bilinear functions for 2D quadrilateral elements
- iii. Trilinear functions for 3D hexahedral elements
- iv. Lagrangian polynomials for higher-order elements

2. Isoparametric Formulation:

The isoparametric concept uses the same shape functions to define both the geometry and the field variables:

$$\textbf{Geometry: } x = \sum N_i x_i \quad (2.9)$$

$$\textbf{Field Variable: } u = \sum N_i u_i \quad (2.10)$$

This approach provides significant flexibility in handling complex geometries and ensures geometric continuity between elements.

3. **Numerical Integration:**

Most finite element integrals cannot be evaluated analytically and require numerical integration, typically using Gaussian quadrature. The accuracy of integration directly affects the overall accuracy of the finite element solution.

2.8.3 Assembly Process

1. **Element Matrices:**

For each element, the discretization process yields the following element matrices:

$$\textbf{Element Stiffness Matrix: } [K]_e = \int_{\Omega_e} [B]^T [D] [B] d\Omega \quad (2.11)$$

$$\textbf{Element Mass Matrix: } [M]_e = \int_{\Omega_e} [N]^T \rho [N] d\Omega \quad (2.12)$$

$$\textbf{Element Force Vector: } \{F\}_e = \int_{\Omega_e} [N]^T \{f\} d\Omega \quad (2.13)$$

where [B] is the strain-displacement matrix, [D] is the material property matrix, [N] contains shape functions and ρ is density.

2. **Global Assembly:**

Individual element contributions are assembled into global system matrices using connectivity information. This process ensures compatibility between adjacent elements and leads to the global system of equations:

$$[K]\{u\} = \{F\}; \text{ for static problems} \quad (2.14)$$

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F\}; \text{ for dynamic problems} \quad (2.15)$$

where [C] represents damping.

2.8.4 Solution Techniques

1. **Linear Problems:**

Static linear problems result in symmetric, positive definite systems that can be solved efficiently using:

- i. **Direct Methods:** Gaussian elimination, LU decomposition
- ii. **Iterative Methods:** Conjugate gradient, GMRES, multigrid methods

The choice of solver depends on problem size, matrix properties, and computational resources.

2. **Nonlinear Problems:**

Nonlinear problems arise from material nonlinearity, geometric nonlinearity, or contact conditions. Solution strategies include:

- i. **Newton-Raphson Method:** Quadratic convergence in well-behaved problems
- ii. **Modified Newton Methods:** Reduced computational cost per iteration
- iii. **Arc-Length Methods:** Handling snap-through and snap-back behavior

2.8.5 Applications in Structural and Hydraulic Modeling

The applications of FEA to hydraulic structures has grown significantly in recent years, particularly in developing countries where computational resources have become more accessible. Okosun et al. (2019) applied FEA to analyze the structural behavior of reinforced concrete box culverts in Nigeria, demonstrating the methodology's effectiveness in predicting structural responses under various loading conditions. Akinpelu et al. (2020) modeled the structural behavior of concrete pipes under varying pressure loads in Abuja using ANSYS.

Adedeji and Okosun (2020) used finite element modeling to investigate the effects of soil-structure interaction on culvert performance in Lagos, Nigeria. Their study provided insights into the modeling of foundation conditions and the effects of soil properties on structural behavior, which are relevant to the current study's consideration of foundation scour effects.

2.9 OVERVIEW OF FEA-RSM INTEGRATION

The integration of Finite Element Analysis with Response Surface Methodology represents a powerful paradigm for design optimization, uncertainty quantification, and parametric studies. RSM provides a statistical framework for creating mathematical approximations of complex FEA responses, enabling efficient exploration of design spaces that would be computationally prohibitive with direct FEA evaluation alone.

This integration bridges the gap between high-fidelity FEA simulations and practical engineering design requirements, where thousands of design evaluations may be necessary for optimization, sensitivity analysis, or reliability assessment. By constructing surrogate models based on strategically selected FEA runs, engineers can perform extensive parametric studies with minimal computational overhead.

The RSM process involves several key steps when integrated with FEA:

1. **Design Space Definition:** Establishing bounds and constraints for design variables
2. **Experimental Design:** Selecting optimal points for FEA evaluation
3. **FEA Execution:** Running finite element simulations at design points
4. **Model Fitting:** Constructing mathematical approximations of FEA responses
5. **Design Exploration:** Using surrogate models for optimization or analysis

2.10 RESEARCH GAPS AND CONTRIBUTIONS

Despite the extensive literature on various aspects of culvert performance and assessment, several knowledge gaps remain, particularly in the Nigerian context. The integration of multiple adverse hydraulic conditions in culvert assessment has received limited attention in the literature, with most studies focusing on individual factors rather than their combined effects.

The application of Response Surface Methodology to culvert performance assessment represents a novel approach that has not been extensively explored in African contexts. While RSM has been applied to various civil engineering problems, its specific application to hydraulic infrastructure assessment remains limited. The consideration of local environmental conditions, construction practices, and operational constraints in culvert assessment methodologies represents another important gap.

This study fills these gaps by:

1. Integrating numerical simulations in local field assessment
2. Using RSM to statistically quantify the relationship between visible hydraulic conditions and internal shear response
3. Providing a template for urban infrastructure assessment using data-driven techniques tailored to resource-constrained environments

2.11 REVIEW OF PAST RESEARCH WORKS

The study of wall shear stress within box culverts under varying hydraulic conditions has drawn increasing scholarly attention due to its relevance to hydraulic design, sediment transport and structural integrity of drainage systems. This literature review examines fifteen significant studies that have contributed to understanding the complex interactions between wall shear forces and these factors.

Zhang et al. (2017) investigated velocity distribution and turbulence characteristics in subcritical circular open channel flows using a modified Reynolds stress model. The researchers aimed to develop improved computational approaches for predicting flow characteristics in confined channel geometries, providing foundational knowledge for understanding shear stress distribution in similar rectangular culvert geometries.

Ahmed et al. (2019) focused on determining the shear strength of reinforced concrete box culverts with uniformly distributed loads at the top slab. The researchers intended to develop frameworks for converting single loading conditions into multiple subframe analyses, addressing the intersection between hydraulic loading and structural response in culvert design.

Martinez et al. (2020) conducted large eddy simulation studies of turbulent flow in box culverts under varying discharge conditions. The researchers aimed to characterize the three-dimensional nature of shear stress distribution along culvert walls, providing insights into spatial and temporal variations of hydraulic forces (Martinez et al., 2020).

Thompson and Lee (2021) investigated the effects of culvert roughness on wall shear stress distribution using both experimental and numerical approaches. Their research intended to establish relationships between surface characteristics and shear stress patterns, providing design guidelines for optimizing culvert performance under variable hydraulic conditions.

Kim et al. (2023) conducted experimental verification of wall shear stress measurement using MEMS sensors arrays for underwater applications. Their research aimed to develop and validate advanced sensor technologies for direct measurement of wall shear stress in hydraulic systems, providing tools potentially applicable to culvert monitoring.

Le, H. T. T., et al. (2022) explored the behavior of sediment scour and associated wall shear stress at the outlet of boxed culvert diversion works. Using computational fluid dynamics (CFD) simulations, the authors modeled three distinct operating conditions involving different flow regimes and sediment bed configurations. The study emphasized how hydraulic transitions from supercritical to subcritical flow caused high wall shear stress concentrations and vortex zones that destabilized sediments. The model was validated with experimental data

and showed near accurate predictions of critical shear thresholds and scour depths, offering insights for culvert outlet protection strategies.

Abuhajar et al. (2015) presented an integrated physical and numerical study on soil pressure distributions and shear stress behavior on buried box culverts. Utilizing 1:10 scaled physical models and finite element simulations, they evaluated how backfill compaction, burial depth, and soil type affected static pressures on culvert walls. The results indicated that poorly compacted backfill produced uneven load paths and elevated lateral shear stress on sidewalls. The study further concluded that traditional methods for soil-structure interaction underestimated peak shear zones. This work offers a benchmark for updating culvert embedment design to mitigate unexpected wall shearing.

Osman and Taha (2022) assessed the hydraulic performance of box culverts under various blockage scenarios using physical modeling and flow visualization techniques. The researchers analyzed how partial and full blockage of culvert openings affected wall shear stress, turbulence, and flow uniformity. A waterway hood was introduced as a mitigation strategy, which significantly reduced turbulence and improved shear stress distribution. Key findings showed that blockages cause asymmetrical shear profiles and amplify flow separation zones. The results serve as a basis for designing adaptive culvert systems resilient to debris accumulation (Osman and Taha, 2022).

Rasul et al. (2025) evaluated how different baffle configurations and culvert blockages influence downstream wall shear stress and scour development. The research involved testing culvert models under steady and variable flow conditions, using ultrasonic velocity probes and sediment tracking systems. It was found that baffles increased wall shear stress upstream

by redirecting flows toward the bed and sidewalls, which in turn reduced scour potential at the outlet.

Ghodsian and Mohajeri (2025) explored how variations in wing-wall geometry at the entrance of box culverts influence local scour development and wall shear stress distributions. The authors conducted controlled laboratory experiments to simulate various hydraulic flow scenarios, capturing data on velocity profiles, flow separation zones, and turbulence intensity. Their analysis showed that the presence and angle of wing walls significantly altered the flow path near the entrance, leading to intensified shear stress on sidewalls and higher scour depths at the toe. The paper also proposed empirical predictive equations for estimating shear forces as a function of approach flow velocity and wall geometry.

Jadhav et al. (2021) investigated the hydraulic behavior of reinforced concrete (RCC) box culverts under varying discharge conditions. Using a combination of computational fluid dynamics (CFD) and scaled physical models, the study analyzed changes in water surface profiles, wall shear stress, and velocity distribution throughout the culvert channel. One key finding was that non-uniform velocity gradients near the walls were closely linked with turbulence structures, which in turn influenced shear stress magnitudes. Furthermore, the study emphasized how increasing flow rates led to a proportional rise in wall shear forces, especially near the corners and transition zones.

Sorourian et al. (2016) addressed the effects of partial blockage in box culverts on wall shear stress and scouring. The authors used experimental flumes with varying blockage levels (0%, 25%, 50%) to measure Reynolds shear stress and velocity fields along the culvert floor and sidewalls. They found that even modest blockage levels significantly amplified local wall shear stress, especially near the inlet, leading to aggressive bed erosion. The research further

quantified the extent to which blockage altered turbulence intensity and vortex shedding, ultimately proposing corrective design guidelines.

Krishna and Rajasekhar (2018) focused on the structural and hydraulic behavior of box culverts under varied site and flow conditions. The authors conducted a parametric investigation to evaluate how flow velocity, culvert size, and invert elevation influence wall shear stress. They emphasized that shear forces are highly sensitive to variations in hydraulic head and discharge, particularly in low-clearance culverts during storm events. Finite element simulations coupled with empirical equations were used to predict stress distributions across the culvert's internal surfaces.

Jamle and Patel (2019) synthesized previous design practices and performance evaluations of box culverts under hydraulic loading. The researchers explored the effect of hydraulic turbulence, sediment deposition, and velocity fluctuations on wall shear stress within box culverts of different dimensions. Their findings suggest that sharp changes in flow depth, such as those caused by hydraulic jumps, produce zones of elevated shear stress that align with flow reattachment points.

Jones et al. (2006) studied the hydraulic performance of various inlet geometries in box culverts and how these affect wall shear stress under high inflow rates. The team observed that sharp-edged inlets increased turbulence and caused premature boundary layer separation, thereby intensifying sidewall shear. Round-edged and flared wing walls were shown to reduce adverse flow gradients, effectively decreasing near-wall stress peaks (Jones et al., 2006).

CHAPTER THREE

METHODOLOGY

3.1 STUDY AREA

The Ogba River is a significant watershed in Oredo Local Government Area of Benin City, Edo State in Southern Nigeria. It originates from the northern part of the city in Ekehuan and meanders southwards, eventually joining the Ikpoba River, which is a tributary of the larger Osse River. The river is about 42 kilometers long and has a total area of approximately 340.1km² (Azeigbe, 2006).

The study area focuses on a box culvert located at the following coordinates: 6°16'53"N 5°34'50"E. The culvert is situated near the intersection of Ogba Road and Sakponba Road, in a densely populated residential and commercial area. The culvert itself is a concrete structure that allows the Ogba River to pass underneath Ogba Road in order to facilitate the flow of water and prevent floods during periods of heavy rainfall. The rainy season occurs between the months of March and October with a short break in August. Due to the effect of global warming and climate change, rains have been observed to fall irregularly almost in every month of the year with double peak periods in July and September (Rawlings and Ikediashi, 2020). Common mean annual rainfall observed in the area is about 2000 mm and mean monthly temperature ranges from 23°C to 28°C (Enaruvbe and Atafo, 2018).

The surrounding area is characterized by a mix of residential buildings, small businesses and roadside markets. The population of Benin City is estimated to be about 1.75 million (United Nations, 2016). The banks of the river are largely unprotected, leading to erosion and encroachment of human activities on the riverbanks. The water quality of the Ogba River in this area is also known to be affected by the discharge of domestic and commercial waste.

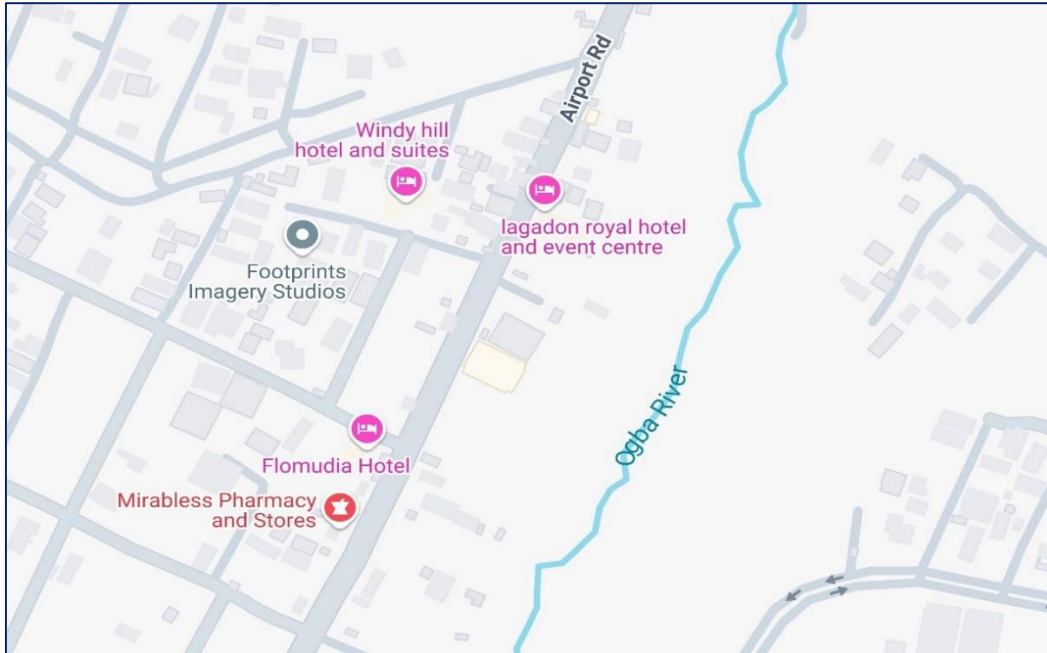


Figure 3.1: Map of Ogba River and Surrounding Roads (Source: Google MyMaps, 2025)

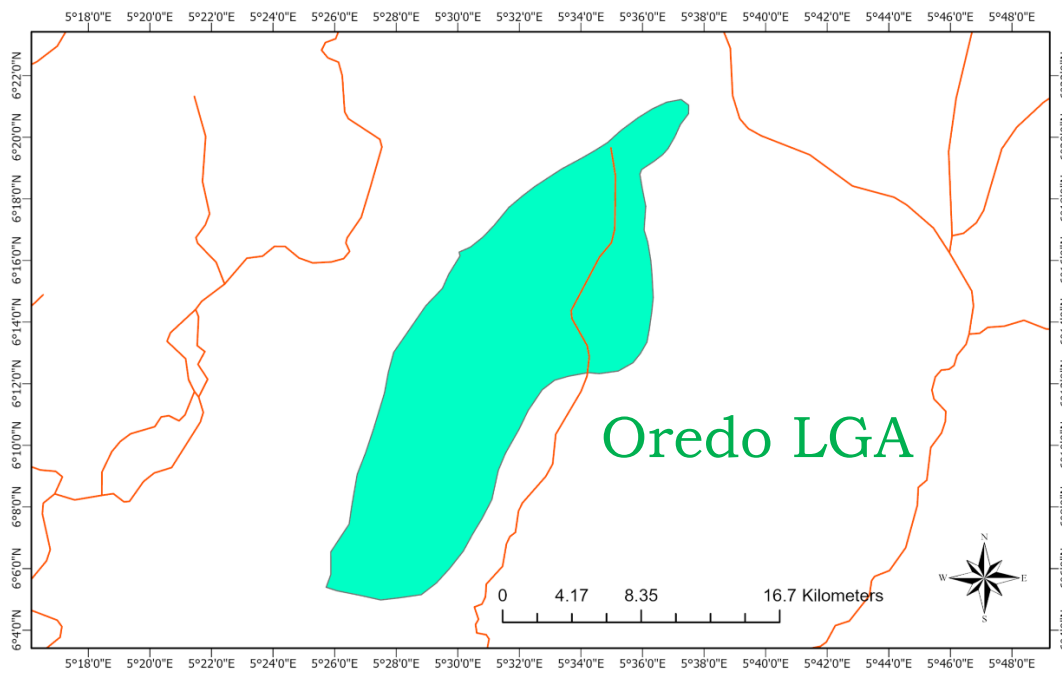


Figure 3.2: Geological map of Oredo LGA showing Ogba River (Source: ArcGIS, 2025)



Figure 3.3: Topographic Map of Ogba River (Source: Google Earth Pro, 2025)

3.2 RESEARCH APPROACH

The overall methodology involved the use of Response Surface Methodology (RSM) to generate an experimental design matrix. This matrix was based on the practical input ranges derived from the initial field assessment of the culvert site, and it specified the combinations of input variables for which corresponding structural responses was to be obtained. Finite Element Analysis (FEA) was used as the simulation tool to model and predict the culvert's structural response under each specified combination. FEA was utilized due to its ability to accurately model the stress and strain distribution within the concrete structure resulting from applied hydrostatic pressures and boundary conditions.

Subsequently, RSM was used to develop a response surface model that quantifies the combined influence of the hydraulic conditions on the wall shear force of the box culvert. The model was interpreted to identify which of the three conditions has the biggest impact on the

wall shear force. The relationship between the input variables and the response was also analyzed to determine its linearity or non-linearity. The visualization tools in Minitab software was then used to graphically analyze the combinations of the input variables that lead to critical levels of wall shear force.

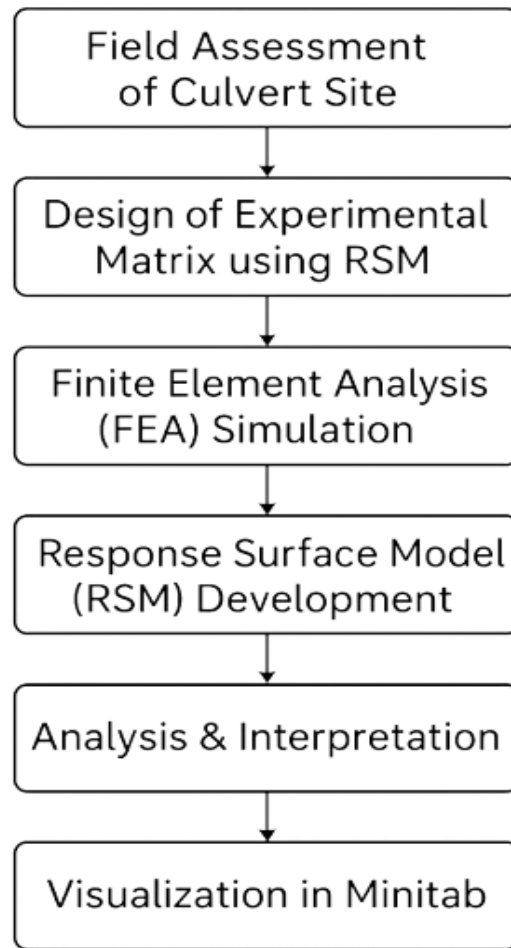


Figure 3.4: Flowchart showing an overview of the research approach

3.3 DETERMINATION OF THE RANGES FOR INPUT VARIABLES

A systematic approach was followed to establish realistic minimum and maximum values for the selected hydraulic conditions. This approach combined direct field measurements, historical data review and engineering judgment. These ranges formed the boundaries of the

RSM experimental design matrix. The ranges for each hydraulic condition was determined as follows;

3.3.1 Internal Sedimentation

This variable quantifies the accumulation of sediment inside the culvert barrel, which could reduce its flow area.

i. **Minimum Value (Baseline):**

A detailed visual inspection was conducted along the invert of the culvert and the existing sediment depths were measured using a measuring tape. The culvert was relatively clear, and a stable baseline of sediment was not observed along the invert. Therefore, the minimum value was taken as 0% blockage (i.e. 0mm).

ii. **Maximum Value (Extreme Condition):**

Community members were consulted to identify any significant sediment accumulation events. From these consultations, there had been no significant blockage of the culvert due to sediment accumulation. Therefore, the highest depth of accumulated sediment measured along the invert was recorded as the maximum value.

3.3.2 Foundation Scour

This variable describes the erosion of soil around and beneath the culvert's foundation, which could potentially undermine its structural support.

i. **Minimum Value (Baseline):**

A visual inspection was conducted on the culvert's inlet, outlet and other exposed foundation areas to check for signs of scour. A consistent scour depth was not observed so the minimum value was recorded as 0mm.

ii. **Maximum Value (Extreme Condition):**

Long-term residents were consulted in order to know the flow conditions present during recent flood events. It was observed that no significant damage had been done to the foundation by flood water. Therefore, the highest recorded scour depth was taken as the maximum value.

3.3.3 Headwater Level

This variable represents the water depth at the culvert's inlet, which could directly impact the hydrostatic pressure and flow.

i. **Minimum Value (Baseline):**

The culvert was in a non-storm and no-flow condition at the time of measurement. From observations, the culvert was empty and no consistent water level was noticed along the invert. Therefore, the minimum headwater level was recorded as 0mm.

ii. **Maximum Value (Extreme Condition):**

This was established through visual inspection for physical high-water marks on the culvert. The highest recorded value during the inspection was taken as the maximum value.

3.4 EXPERIMENTAL DESIGN MATRIX

The following steps were used to generate the RSM experimental design matrix using Minitab;

Step 1: Project Setup

- i. Launch Minitab statistical software.
- ii. Go to *Stat > DOE > Response Surface > Create Response Surface Design*.

Step 2: Design Type Configuration:

- i. In the dialog box that appears, select *Central Composite Design*.
- ii. Select *Designs...* to verify the type of CCD. Face-centered (FCC) will be used for this design because it keeps the factor levels within the defined ranges. Click *OK*.

Step 3: Factors Specification:

- i. In the main dialog box, click *Factors...* and ensure this is set to 3 to represent the three hydraulic conditions (i.e. sediment buildup, foundation scour and headwater level).
- ii. For each factor, type in its name and set the *Type* to *Numeric*.
- iii. For each factor, input the specific minimum and maximum values according to the input ranges defined earlier. Minitab will use these to generate the experimental points. Click *OK*.

Step 4: Matrix Generation:

- i. Click *OK* to close the *Create Response Surface Design* dialog box.
- ii. Minitab will then generate a new worksheet containing the design matrix. Each row in this worksheet represents a unique combination of the three input variables for which an FEA simulation needs to be performed.

3.5 SIMULATION OF STRUCTURAL RESPONSE

To setup MIDAS Civil for the FEA simulation of the box culvert, some fixed structural parameters were required. These parameters include; the culvert dimensions, wall and slab thickness, modulus of elasticity, Poisson's ratio, soil subgrade modulus and unit weight of concrete. A full geotechnical investigation to determine the soil subgrade modulus is beyond

the scope of this research; but $K_s = 30,000\text{KN/m}^3$ is a conservative value for medium-stiff clay (Bowles, 1996; FHWA, 2012), which is consistent with lateritic soils in Benin City (Enaruvbe & Atafo, 2018).

The following steps outline the procedure used to develop the FEA model of the reinforced concrete box culvert. These steps were executed for each unique combination of input variables as specified by the RSM experimental design matrix;

Step 1: Project Setup:

- i. Open MIDAS Civil and select *File > New Project*.
- ii. Go to *Tools > Units* and set the consistent units for force, length, and stress (e.g., KN, m, KPa).

Step 2: Material Properties:

- i. Navigate to *Properties > Material > Add*. Select *Type: Concrete* and choose the appropriate concrete grade.
- ii. Input the required properties: Modulus of Elasticity (E), Poisson's Ratio (ν), and Unit Weight (γ).

Step 3: Section Properties:

- i. Navigate to *Properties > Section > Add* and select *Type: Plate*.
- ii. Go to *Structure > Wizard > Box Culvert*.
- iii. Input the overall dimensions (width, height, length, wall thickness and slab thickness).

Step 4: Model Generation:

- i. Generate the model. This will create the culvert geometry using plate or shell elements.

Step 5: Boundary and Support Conditions:

- i. Go to *Boundary > Point Spring Supports*.
- ii. Apply the elastic spring supports to the nodes or elements along the culvert's invert and external side walls.
- iii. Define the stiffness values (Modulus of Subgrade Reaction, K_s) for these springs, representing the intact soil support. The stiffness value will be derived from typical geotechnical engineering practice for the site's soil type.

Step 6: Scour Simulation Setup:

- i. Foundation scour can be simulated by defining separate *Load Cases* or *Analysis Cases* for each scour scenario. In each case, modify the spring supports by removing the elastic springs. This is done by deleting the assigned spring supports at the nodes/elements at the inlet or along a portion of the invert/side walls.

Step 7: Self-Weight Activation:

- i. Ensure *Load > Self Weight* is activated. MIDAS Civil will automatically calculate and apply the self-weight of the culvert based on the material properties.

Step 8: Sediment Pressure Loads:

- i. Go to *Load > Plate Loads > Pressure Loads*.
- ii. Select the plate elements forming the invert of the culvert (bottom slab) and apply a uniformly distributed pressure load downwards. The magnitude of this pressure will be calculated based on the specified sediment depth for each condition in the RSM design matrix.

Step 9: Hydrostatic Pressure Loads:

- i. Go to *Load > Plate Loads > Pressure Loads*.
- ii. Select the external plate elements of the culvert walls at the inlet and apply a hydrostatic pressure load. Define the water surface elevation based on the headwater level from the RSM design matrix and the standard unit weight of water. MIDAS Civil will calculate the pressure distribution accordingly.

Step 10: Analysis and Results:

- i. Go to *Analysis > Perform Analysis*. Ensure all defined load cases and boundary conditions for the current RSM combination are selected.
- ii. After the analysis is complete, navigate to *Results > Forces > Plate Forces*.
- iii. Select the relevant shear force components for the culvert wall elements.
- iv. View the shear force diagrams and contours and record the maximum wall shear force values for the current combination of input variables.
- v. Repeat the last four steps for each combination defined in the RSM design matrix. This will form a comprehensive dataset that will be used to build the response surface model.

3.6 GENERATION AND ANALYSIS OF RESPONSE SURFACE MODEL

The following steps were used to generate a response surface model from the dataset developed in sub-heading 3.5. The generated model was also analyzed in order to determine the interaction between the defined hydraulic conditions and the wall shear force.

Step 1: Open the Existing Minitab Worksheet:

- i. Launch Minitab and open the worksheet containing the experimental design matrix created in sub-heading 3.4.

- ii. Verify that the worksheet contains columns for the three factors: Sediment Buildup, Foundation Scour, and Headwater Level.

Step 2: Add Response Variable Column:

- i. Create a new column titled: Wall Shear Force.
- ii. Input the maximum wall shear force values obtained from each FEA simulation corresponding to each experimental run, ensuring data alignment between the factor combinations and their corresponding response values.

Step 3: Data Verification and Quality Check:

- i. Go to *Data > Display Data* to review the complete dataset.
- ii. Use *Stat > Basic Statistics > Display Descriptive Statistics* to examine the response variable distribution.
- iii. Create scatter plots of each factor versus the response to identify potential relationships and outliers.

Step 4: Initiate Response Surface Analysis:

- i. Select *Stat > DOE > Response Surface > Analyze Response Surface Design*.
- ii. In the dialog box, select the response variable (Wall Shear Force) in the *Responses* field.

Step 5: Model Term Selection:

- i. Click on *Terms...* to specify the model complexity.
- ii. For initial analysis, include:
 - a) Linear terms (all three factors)
 - b) Quadratic terms (all squared terms)
 - c) Two-way interaction terms

iii. This creates a full second-order polynomial model of the form:

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_3x_3 + \beta_{11}x_1^2 + \beta_{22}x_2^2 + \beta_{33}x_3^2 + \beta_{12}x_1x_2 + \beta_{13}x_1x_3 + \beta_{23}x_2x_3 + \varepsilon$$

iv. Click *OK* to confirm term selection.

Step 6: Model Fitting Options:

- i. In the main dialog, click *Results...* and select: Unusual observations, ANOVA table, Coefficients table and Model summary statistics.
- ii. Click *OK* to return to main dialog.

Step 7: Execute Model Fitting:

- i. Click *OK* to generate the initial response surface model.
- ii. Review the output for model adequacy and statistical significance.

Step 8: Statistical Significance Testing:

- i. Examine the ANOVA table to assess overall model significance (p-value < 0.05).
- ii. Review individual coefficient p-values to identify significant terms.

Step 9: Residual Analysis:

- i. Go to *Stat > DOE > Response Surface > Analyze Response Surface Design*.
- ii. Click *Graphs...* and select:
 - a) Normal plot of residuals
 - b) Residuals versus fitted values
 - c) Residuals versus order levels
 - d) Histogram
- iii. Click *OK* to generate residual plots.

Step 10: Surface Plot Creation:

- i. Navigate to *Stat > DOE > Response Surface > Contour/Surface Plots*

- ii. Generate 3D surface plots for visual understanding of response behavior.
- iii. Rotate and examine surfaces for optimal viewing angles.
- iv. Generate multiple surface plots for different factor combinations:
 - a) Internal Sedimentation vs. Foundation Scour (HL at center)
 - b) Internal Sedimentation vs. Headwater Level (FS at center)
 - c) Foundation Scour vs. Headwater Level (IS at center)

Step 11: Contour Plot Generation:

- i. In the same dialog, select *Contour Plot* and choose the response variable.
- ii. From previous analyses, select the two factors which has been observed to influence the response most while holding the third factor at its center point.
- iii. Click *OK* to generate contour plot.

Step 12: Critical Point Analysis:

- i. Go to *Stat > DOE > Response Surface > Response Optimizer*.
- ii. Set factor constraints within the experimental region bounds.

Step 13: Desirability Function Setup:

- i. Define desirability criteria for the response:
 - a) Lower specification limit
 - b) Target value (design requirement)
 - c) Upper specification limit (safety threshold)

Step 14: Response Optimization:

- i. Execute the optimization to find optimal factor settings.
- ii. Record the optimal factor combination and predicted response.
- iii. Assess the desirability score for the optimal solution.

Step 15: Model Equation:

- i. Extract the final model equation from the coefficient table.
- ii. Include confidence intervals for coefficients.

Step 16: Engineering Interpretation:

- i. Interpret coefficient signs and magnitudes in engineering context:
 - a) Positive coefficients indicate response increases with factor increase
 - b) Negative coefficients indicate response decreases with factor increase
 - c) Interaction terms show factor interdependencies
- ii. Determine factor combinations that exceed design limits and identify regions of acceptable performance within the experimental matrix.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 RESULTS

4.1.1 Determination of the Ranges for Input Variables

Table 4.1 shows the minimum and maximum values of the input variables that were measured from the culvert site during the physical assessment.

Table 4.1: Minimum and maximum values of the input variables

Variable	Minimum (mm)	Maximum (mm)
Internal Sedimentation	0	125
Foundation Scour	0	140
Headwater Level	0	910

4.1.2 Experimental Design Matrix

The experimental design matrix was set as a Central Composite Design (CCD) and generated in Minitab, as shown in Figure 4.1. The dialog box display in Figure 4.2 shows that the selected CCD was configured as a Face-Centered design.

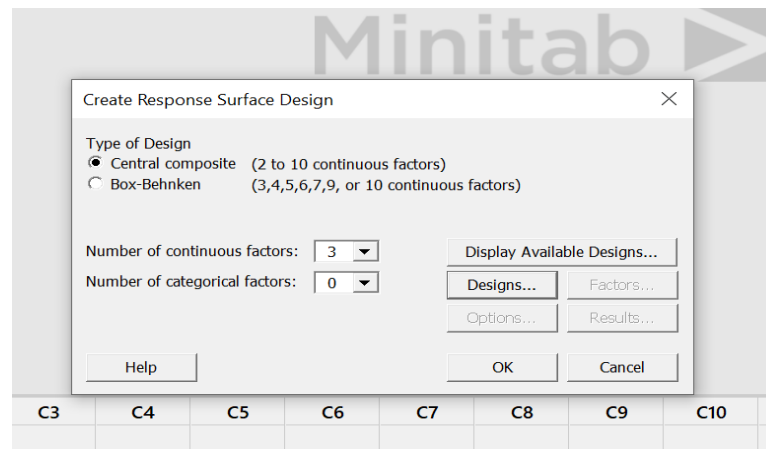


Figure 4.1: Dialog box display showing experimental matrix setup as CCD

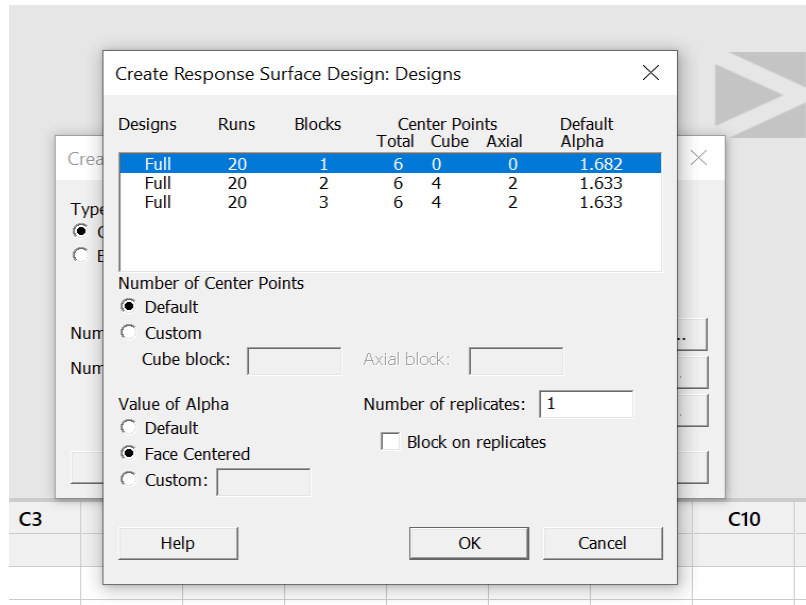


Figure 4.2: Dialog box display showing the type of CCD as Face Centered

The factors in the design matrix corresponded directly to the selected hydraulic conditions. The previously established maximum and minimum values were adopted as the “Low” and “High” levels of each factor, as presented in Figure 4.3.

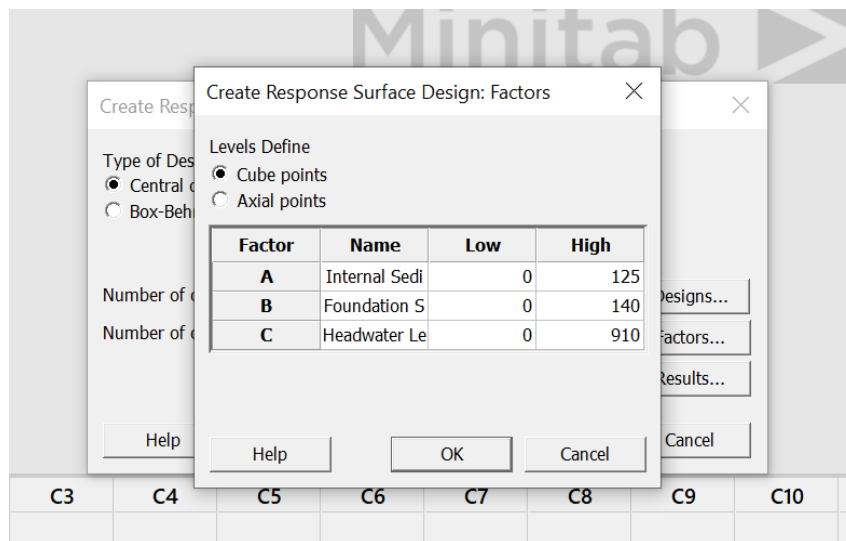


Figure 4.3: Dialog box display showing the factors of the design matrix

Table 4.2 shows the values of the experimental design matrix obtained from the generated worksheet in Minitab.

Table 4.2: RSM experimental design matrix generated using Minitab

Run	IS (mm)	FS (mm)	HL (mm)
1	62.5	0	455
2	0.0	0	0
3	62.5	140	455
4	62.5	70	455
5	62.5	70	455
6	62.5	70	455
7	125.0	0	0
8	62.5	70	455
9	62.5	70	455
10	125.0	140	910
11	0.0	140	910
12	0.0	140	0
13	125.0	140	0
14	62.5	70	0
15	62.5	70	455
16	125.0	70	455
17	0.0	0	910

Run	IS (mm)	FS (mm)	HL (mm)
18	0.0	70	455
19	125.0	0	910
20	62.5	70	910

4.1.3 Simulation of Structural Response

The Finite Element Analysis (FEA) simulation was carried out in MIDAS Civil for all 20 experimental runs defined in the design matrix, generating WSF responses corresponding to each combination of hydraulic conditions. The reinforced concrete box culvert utilized 3D plate elements with the fixed structural parameters summarized in Table 4.3:

Table 4.3: Fixed structural parameters used in the FEA model

Parameter	Value	Mode of Selection
Culvert Span (Width)	2.0m	Measured
Culvert Height	1.5m	Measured
Culvert Length	10m	Assumed
Wall & Slab Thickness	0.25m	Measured
Concrete Grade	C30/37 ($f_{ck} = 30\text{MPa}$)	Standard value (BS8100)
Modulus of Elasticity (E)	31,000 MPa	Standard value (BS8100)
Poisson's Ratio (ν)	0.2	Standard value (BS8100)
Unit Weight (γ)	25 KN/m ³	Standard value (BS8100)
Soil Subgrade Modulus (K_s)	30,000 KN/m ³	Assumed

Table 4.4 shows the simulated WSF responses obtained from Midas Civil for each experimental run in the design matrix.

Table 4.4: Simulated WSF response for each run in the design matrix

Run	IS (mm)	FS (mm)	HL (mm)	WSF (KN/m)
1	62.5	0	455	35.2
2	0.0	0	0	12.1
3	62.5	140	455	49.8
4	62.5	70	455	43.1
5	62.5	70	455	43.3
6	62.5	70	455	42.9
7	125.0	0	0	18.6
8	62.5	70	455	43.2
9	62.5	70	455	43.0
10	125.0	140	910	77.4
11	0.0	140	910	68.7
12	0.0	140	0	24.8
13	125.0	140	0	32.9
14	62.5	70	0	22.7
15	62.5	70	455	43.1
16	125.0	70	455	46.1

Run	IS (mm)	FS (mm)	HL (mm)	WSF (KN/m)
17	0.0	0	910	47.6
18	0.0	70	455	38.2
19	125.0	0	910	55.3
20	62.5	70	910	61.8

Table 4.5 below summarizes the key statistical derivations made from the simulated WSF responses in Table 4.4:

Table 4.5: Key statistical derivations made from simulation of WSF response

Observation	Value
Maximum WSF	77.4KN/m (Run 10)
Minimum WSF	12.1KN/m (Run 2)
Center point average (Runs 4-6, 8-9, 15)	43.1KN/m
Standard deviation (σ) of center points	0.13KN/m
Coefficient of variation (C_v)	0.30%

In the context of RSM, close agreement among center point replicates confirms the consistency and reliability of the numerical simulations. For 3 factors in FCCD (as in this case with three variables), 6 center points are standard as it gives enough degrees of freedom to estimate pure error and test for lack of fit in the ANOVA (Montgomery, 2017). The standard deviation was calculated using population, not sample. In RSM, population standard deviation

is used (dividing by n , not $n - 1$) because center points are a complete set of replicates to estimate pure error. This is the standard practice in DoE analysis (Montgomery, 2017).

The center point replicates from the WSF responses in Table 4.4 are as follows; 43.1KN/m (Run 4), 43.3KN/m (Run 5), 42.9KN/m (Run 6), 43.2KN/m (Run 8), 43.0KN/m (Run 9) and 43.1KN/m (Run 15).

To solve for the standard deviation;

$$\sigma = \sqrt{\frac{\sum(x - \Delta)^2}{n}} \quad (4.1)$$

where; x = WSF response for each center point replicate, Δ = center point average, and n = total number of center point replicates

The center point average; $\Delta = \frac{43.1 + 43.3 + 42.9 + 43.2 + 43.0 + 43.1}{6} = 43.1\text{KN/m}$

Table 4.6: Derivation of values for standard deviation calculation

$x - \Delta$	$(x - \Delta)^2$
$43.1 - 43.1 = 0.0$	0.00
$43.3 - 43.1 = +0.2$	0.04
$42.9 - 43.1 = -0.2$	0.04
$43.2 - 43.1 = +0.1$	0.01
$43.0 - 43.1 = -0.1$	0.01
$43.1 - 43.1 = 0.0$	0.00
Total	0.10

$$\text{Therefore, } \sigma = \sqrt{\frac{0.10}{6}} = 0.13\text{KN/m}$$

$$\text{Coefficient of variation; } C_v = \frac{\sigma}{\Delta} \times 100\% \quad (4.2)$$

$$C_v = \frac{0.13}{43.1} \times 100\% = 0.30\%$$

This low variation indicates that the FEA simulation model is stable and repeatable; and that there is no significant numerical noise or random error in the simulation process.

4.1.4 Generation and Analysis of Response Surface Model

4.1.4.1 Regression Analysis

The response surface model for the wall shear force was generated in Minitab, using the simulated responses outlined in Table 4.4. A second-order polynomial model was fitted to capture the linear, quadratic, and interaction effects of the three input variables: Internal Sedimentation (x_1), Foundation Scour (x_2) and Headwater Level (x_3).

The regression equation is as follows:

$$\begin{aligned} \text{Wall shear force (y)} = & 12.330 + 0.0667x_1 + 0.0894x_2 + 0.04302x_3 - 0.000106x_1^2 - 0.000013x_2^2 \\ & - 0.000002x_3^2 + 0.000074x_1x_2 + 0.000008x_1x_3 + 0.000064x_2x_3 \end{aligned} \quad (4.3)$$

Table 4.7: Coded coefficients derived from regression analysis

Term	Coefficients	Standard Coeff.	T-value	P-value	VIF
Constant	42.885	0.224	175.97	0.000	
Internal Sedimentation	3.890	0.224	17.35	0.000	1.00
Foundation Scour	8.480	0.224	37.83	0.000	1.00
Headwater Level	19.970	0.224	89.08	0.000	1.00

Term	Coefficients	Standard Coeff.	T-value	P-value	VIF
IS ²	-0.414	0.427	-0.97	0.356	1.82
FS ²	-0.064	0.427	-0.15	0.885	1.82
HL ²	-0.314	0.427	-0.73	0.480	1.82
IS - FS	0.325	0.251	1.30	0.224	1.00
IS - FS	0.225	0.251	0.90	0.390	1.00
FS - HL	2.025	0.251	8.08	0.000	1.00

Table 4.7 shows the coded coefficients which summarizes the estimated effects, standard errors, T-values, P-values and variance inflation factors (VIF) for each term. All linear terms were highly significant, with P-value < 0.001; Headwater Level exhibited the largest coefficient (19.970), followed by Foundation Scour (8.480) and Internal Sedimentation (3.890). None of the quadratic terms were significant (P > 0.05); IS² (-0.414, P = 0.356), FS² (-0.064, P = 0.885), and HL² (-0.314, P = 0.480). Among the interaction terms, only FS - HL was highly significant (2.025, P < 0.001).

VIF values ranged from 1.00 to 1.82, indicating no multicollinearity issues. This means that the predictor variables are nearly uncorrelated, ensuring that each regression coefficient is estimated independently and reliably. This confirms that the model's statistical inferences (such as significance levels and effect sizes) are stable and not distorted by redundancy among the input factors.

4.1.4.2 Model Summary Statistics

The summary statistics in Table 4.8 demonstrated the excellent fit of the response surface model. The high values confirm that the model has strong predictive capability and explains nearly all variations in the WSF response.

Table 4.8: Summary statistics for the response surface model

Metric	Value
Standard error of regression (S)	0.708898
Multiple correlation coefficient (R ²)	99.06%
R ² (adjusted)	98.81%
R ² (predicted)	97.27%

4.1.4.3 Analysis of Variance

The ANOVA results confirmed the overall significance of the model (F = 1082.27, P < 0.001), as shown in Table 4.9. The linear terms were the dominant source of variation (F = 3222.61, P < 0.001), with Headwater Level contributing the most (F = 7935.76, P < 0.001). None of the quadratic effects were significant (F = 1.61, P = 0.249). The overall two-way interactions were highly significant (F = 22.59, P < 0.001), driven primarily by the FS – HL term (F = 65.28, P < 0.001). Pure error was estimated from the center point replicates, with total degrees of freedom summing to 19.

Table 4.9: Analysis of Variance

Source	DF	F-value	P-value
Model	9	1082.27	0.000

Linear	3	3222.61	0.000
Internal Sedimentation	1	301.11	0.000
Foundation Scour	1	1430.95	0.000
Headwater Level	1	7935.76	0.000
Square	3	1.61	0.249
IS ²	1	0.94	0.356
FS ²	1	0.02	0.885
HL ²	1	0.54	0.480
2-Way Interaction	3	22.59	0.000
IS - FS	1	1.68	0.224
IS - FS	1	0.81	0.390
FS - HL	1	65.28	0.000
Error	10		
Lack-of-Fit	5	49.25	0.000
Pure Error	5		
Total	19		

4.1.4.4 Pareto Chart of Standardized Effects

The Pareto chart of standardized effects, as shown in Figure 4.1, visually ranked the linear, quadratic and interaction terms by magnitude. Above the reference line, Headwater Level had the largest effect (approximately 89.5), followed by Foundation Scour, Internal Sedimentation

and the interaction, FS - HL. All other terms, including quadratics and remaining interactions, fell below the threshold but were retained for model hierarchy.

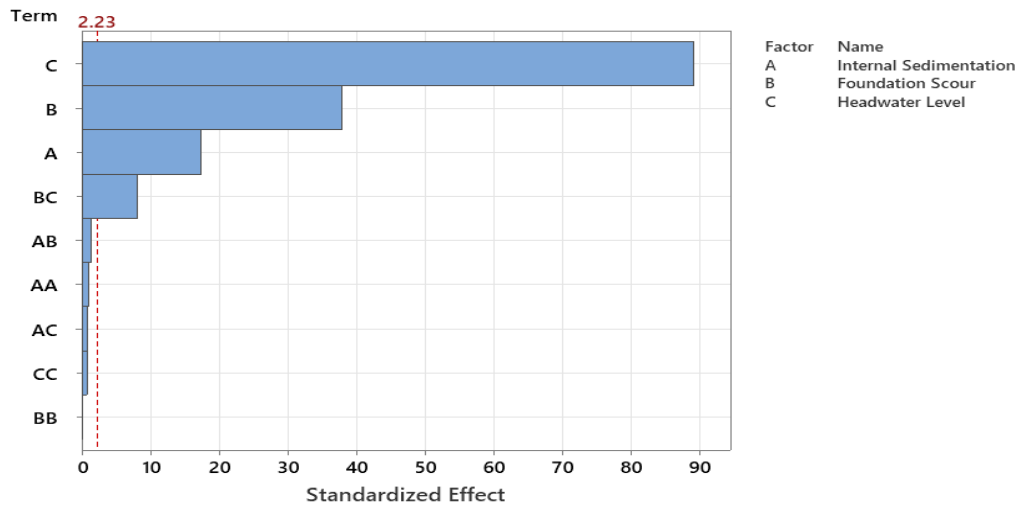


Figure 4.4: Pareto chart of the Standardized Effects

4.1.4.5 Residual Plots

Model diagnostics were evaluated through residual plots, as shown in Figure 4.2 below. The normal probability plot showed residuals aligning closely with the straight line, indicating normality. The versus fits plot exhibited random scatter around zero with no discernible patterns, confirming constant variance. The histogram approximated a normal distribution, and the versus order plot displayed no trends, suggesting independence of residuals. One observation was flagged as unusual (Run 3 with standardized residual -2.97), but it was not an influential outlier warranting removal.

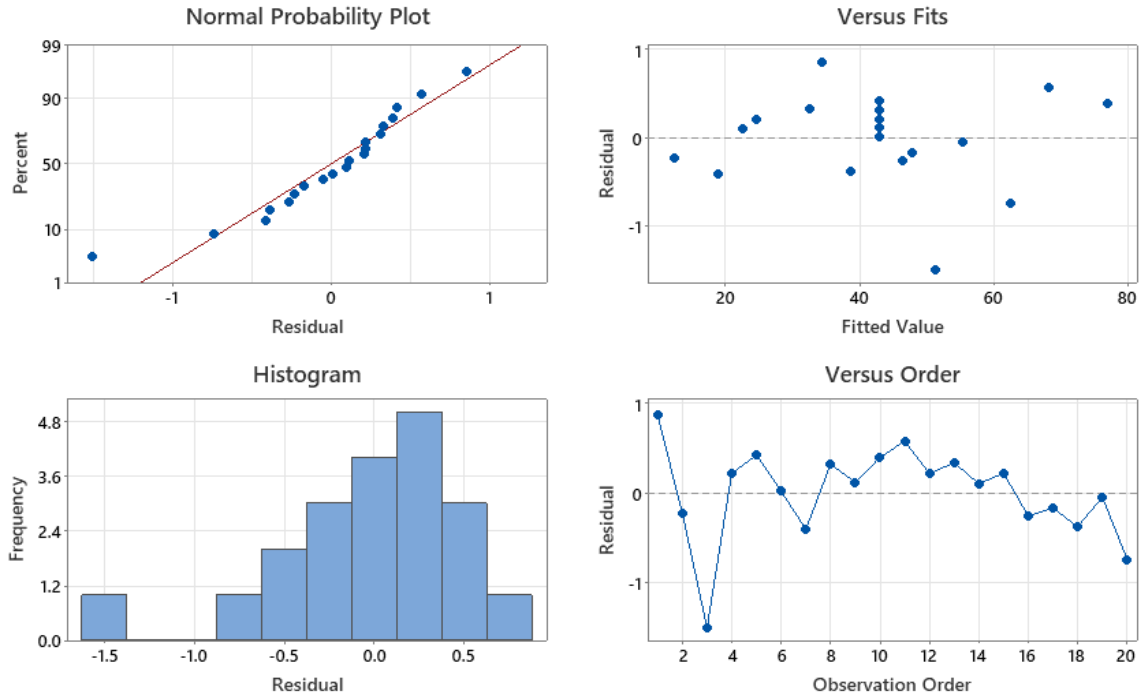


Figure 4.5: Residual plots for the WSF response

4.1.4.6 Surface Plots

The 3D surface plots illustrate the synergistic effects of two independent variables on the WSF while the third variable is held constant at its center-point (nominal) value, as defined by the experimental design matrix.

A. WSF vs Foundation Scour and Internal Sedimentation:

The surface plot of WSF versus Foundation Scour and Internal Sedimentation (with Headwater Level held constant at 455 mm) revealed a generally gentle upward trend, as shown in Figure 4.3. The surface was relatively shallow, indicating that within the tested range, the interaction between sedimentation and scour alone resulted in a moderate increase in WSF. The lowest WSF was observed when both sedimentation and scour were at their lowest levels. Conversely, the highest WSF in this specific plot occurred when both variables approached their maximum studied levels, confirming that both factors contributed independently to increase the structural load.

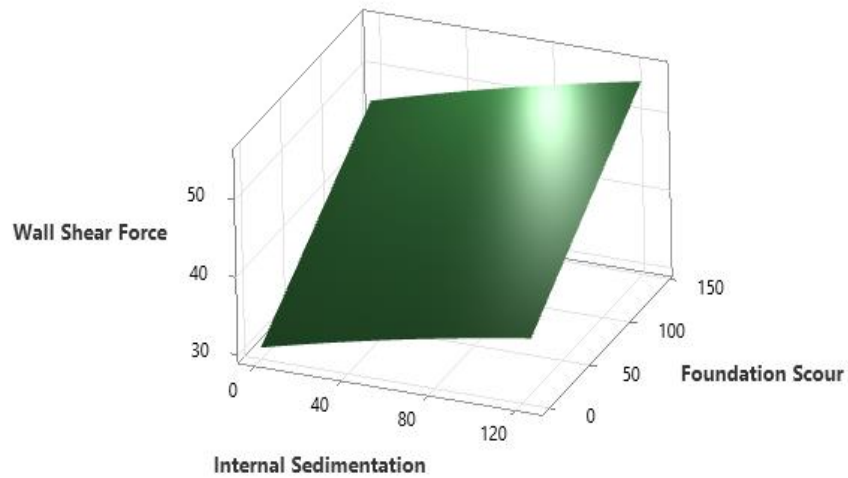


Figure 4.6: Surface plot of WSF vs Foundation Scour and Internal Sedimentation

B. WSF vs Headwater Level and Internal Sedimentation:

The surface plot of WSF versus Headwater Level and Internal Sedimentation (with Foundation Scour held constant at 70 mm) showed a much steeper incline along the axis of the Headwater Level, as shown in Figure 4.4. This strongly indicated that the Headwater Level was the dominant factor influencing the WSF. At any given level of Internal Sedimentation, increasing the Headwater Level resulted in a rapid, non-linear increase in WSF.

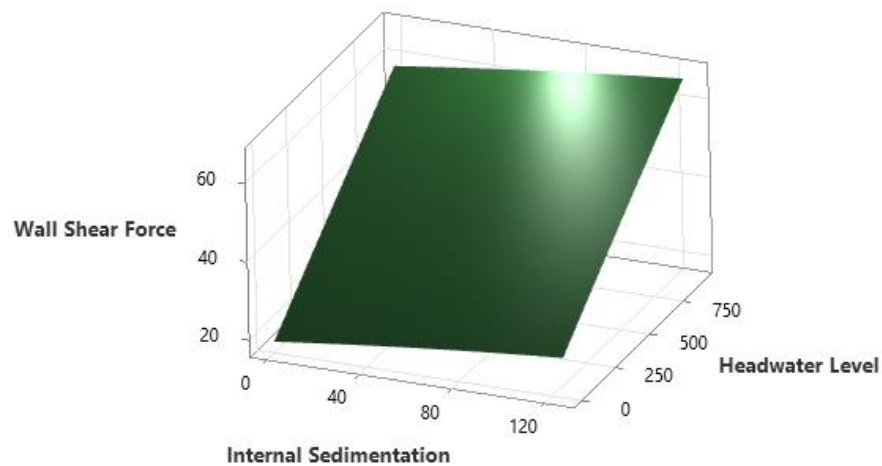


Figure 4.7: Surface plot of WSF vs Headwater Level and Internal Sedimentation

C. WSF vs Headwater Level and Foundation Scour:

The third surface plot shown in Figure 4.5, illustrating WSF versus Headwater Level and Foundation Scour (with Internal Sedimentation held constant at 62.5 mm), reinforced the dominance of the Headwater Level. A sharp, parabolic increase in WSF was visible as the Headwater Level moved towards its maximum (910 mm). While Foundation Scour also contributed to the WSF, its effect was relatively minor when compared to the magnitude of the Headwater Level influence. This indicated that a small increase in upstream water depth posed a significantly greater threat to structural integrity than Foundation Scour under these specific conditions.

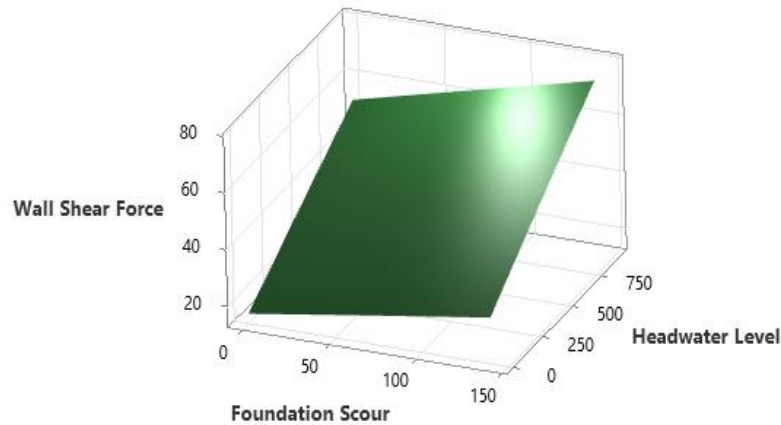


Figure 4.8: Surface plot of WSF vs Headwater Level and Foundation Scour

4.1.4.7 Contour Plot

Based on the earlier generated surface plots, the Headwater Level was observed to be the dominant variable influencing the WSF response. From the Pareto chart, Foundation Scour was also observed to be the second-most dominant variable. A contour plot of both variables was generated to further analyze their combined interaction with the WSF response, with Internal Sedimentation held constant at 62.5mm. Figure 4.6 shows the elliptical nature of the contours in the plot, with the lines being nearly vertical.

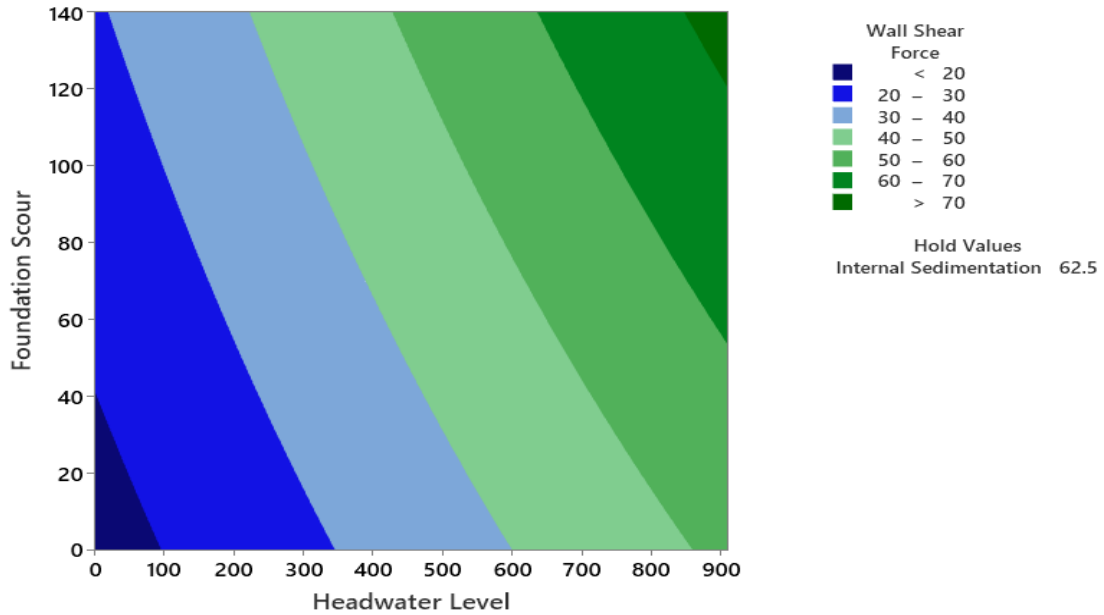


Figure 4.9: Contour plot of WSF vs Headwater Level and Foundation Scour

The following key findings were made from the contour plot;

A. Dominant variable:

The horizontal movement across the plot (change in Headwater Level) caused a much quicker transition between contour bands than the vertical movement (change in Foundation Scour). This reinforced the earlier observation that the WSF response was very sensitive to changes in the Headwater Level.

B. Critical Thresholds:

The highest WSF values (WSF > 70 kN/m) were concentrated in the top-right corner, corresponding to the simultaneous occurrence of maximum Headwater Level and maximum Foundation Scour. The lowest WSF values (WSF < 20 kN/m) were concentrated at the bottom-left corner, associated with minimum values for both variables.

C. Operational Risk:

The density of the contour lines further highlighted regions of high structural risk. A small increase in Headwater Level could rapidly push the culvert's shear force into a higher risk band, especially when coupled with moderate-to-high Foundation Scour.

4.1.4.8 Response Optimization

Response optimization was performed to minimize the WSF, with the lower bound and target values set as 12.1 KN/m and 77.4 KN/m respectively. These values were the minimum and maximum values from the simulated WSF responses in the FEA model.

Table 4.10: Solution obtained from optimization of WSF response

IS (mm)	FS (mm)	HL (mm)	WSF Fit (KN/m)	Composite Desirability	Standard Error (KN/m)	Confidence Interval (CI)
0	0	0	12.3295	0.996485	0.631	95% (10.92, 13.74)

Table 4.10 shows the optimal solution which yielded a minimum WSF of 12.33 KN/m when all the hydraulic variables are at zero, with a standard error of +/- 0.631 KN/m indicating high precision in the estimate. The 95% confidence interval means that there is a 95% certainty that the true average WSF at this condition lies within the predicted range of 10.92 – 13.74. A desirability score of 0.996485 indicates a near-perfect solution that satisfies the goal of minimizing the WSF, making the predicted response a highly practical and effective recommendation for reducing structural risk.

4.2 DISCUSSION

4.2.1 Model Adequacy and Statistical Reliability

The response surface model demonstrated exceptional statistical validity, with $R^2 = 99.06\%$ and adjusted $R^2 = 98.81\%$. These values substantially exceed the minimum threshold of $R^2 >$

0.80 typically considered acceptable in engineering applications of RSM (Montgomery, 2017; Myers et al., 2016). The close agreement between R^2 and adjusted R^2 (difference of 0.25%) confirms that the model does not suffer from overfitting. The predicted R^2 value of 97.27% provides additional confidence in the model's predictive capability. The small difference between adjusted R^2 and predicted R^2 (1.54%) indicates that the model has excellent stability and generalizability (Dhami et al., 2021).

4.2.2 Hierarchical Influence of Hydraulic Variables

The regression analysis revealed a clear hierarchical structure in the influence of hydraulic variables on wall shear force. Headwater Level emerged as the overwhelmingly dominant factor, with a standardized effect of 19.970; more than double that of Foundation Scour (8.480) and more than five times that of Internal Sedimentation (3.890).

The dominance of Headwater Level can be attributed to fundamental hydrostatic principles. Hydrostatic pressure increases linearly with depth ($P = \gamma \times h$), but the structural response is amplified by the tributary area over which this pressure acts. For the 1.5 m tall box culvert studied, a headwater increase from 0 mm to 910 mm represents a transition from zero loading to nearly full-height submergence, with total lateral force scaling rapidly with depth.

Foundation Scour's role as the second-most influential factor reflects its critical impact on structural boundary conditions. It removes soil support at the base of the culvert, which shifts loads and raises shear (Abuhajar et al., 2015; Lawal et al., 2020). In Benin City's lateritic soil conditions, which are particularly susceptible to erosion during intense rainfall (Enaruvbe & Atafo, 2018), this finding underscores the necessity of incorporating foundation stability assessments into routine inspections.

4.2.3 Interaction Effects and Synergistic Behaviour

The interaction term between Foundation Scour and Headwater Level (FS - HL) emerged as highly significant, revealing important synergistic behaviour. This interaction indicates that the combined impact of scour and elevated headwater exceeds the sum of their individual effects. This is a phenomenon with critical implications for risk assessment in flood-prone urban drainage systems.

The physical mechanism underlying this synergy involves hydrostatic and structural considerations. When foundation scour removes soil support, the structure's ability to resist lateral hydrostatic pressures is compromised. Simultaneously, elevated headwater levels increase the magnitude of lateral hydrostatic forces acting on the weakened structure. This convergence of reduced resistance capacity and increased demand creates a scenario where wall shear forces exceed expected levels (Le et al., 2022; Ghodsian & Mohajeri, 2025).

The visualization of these interactions enable identification of critical operating regions where structural demand approaches or exceeds acceptable limits. The concentration of high WSF values ($WSF > 70 \text{ KN/m}$) in regions characterized by high headwater and substantial scour provides a clear mandate for targeted monitoring and intervention. These quantitative thresholds represent a significant advancement over qualitative approaches that characterize much of current practice in Nigerian infrastructure management (Okafor and Ugwu, 2019).

4.2.4 Model Limitations and Validation Considerations

While statistical diagnostics strongly support the model's adequacy for interpolation within the experimental design space, several limitations warrant discussion. The model is fundamentally a combined model; a mathematical approximation of the relationship between statistical inputs and FEA-generated outputs. Its validity rests on two assumptions:

- i. Firstly, that the FEA model accurately represents the physical behavior of the actual culvert structure;
- ii. Secondly, that the polynomial second-order function adequately approximates the FEA response surface.

Regarding the first assumption, the FEA model employed standard values for the fixed structural properties. These represent typical values, but actual in-situ properties may deviate due to construction variability, aging, deterioration, or spatial heterogeneity. The reported confidence intervals account for statistical uncertainty in the regression model but do not encompass uncertainty in underlying FEA parameters.

Regarding the second assumption, the absence of significant quadratic terms and high R^2 values suggest that the second-order polynomial provides adequate fit within tested ranges. However, polynomial models exhibit poor extrapolation behavior beyond calibration data bounds. The Face-Centered Central Composite Design deliberately keeps all design points within defined operational ranges, precluding prediction for more severe conditions (e.g., scour depths exceeding 140 mm or headwater levels above 910 mm). If future observations reveal conditions exceeding the studied ranges, additional FEA simulations should be conducted and the RSM design augmented.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This research achieved its primary aim of performing a data-driven assessment of wall shear forces in box culverts under variable hydraulic conditions. Through the systematic integration of Response Surface Methodology with Finite Element Analysis, this study has established a robust statistical framework for quantifying the complex relationships between observable hydraulic conditions and internal structural demand in reinforced concrete box culverts. This framework is contextually appropriate and calibrated to the local environmental constraints and infrastructure characteristics in Benin City and environs.

The generated response surface model demonstrated exceptional predictive capability, with a coefficient of determination ($R^2 = 99.06\%$). The strong performance of the model validates the appropriateness of the Face-Centered Central Composite Design approach and establishes confidence in its use as a decision-support tool for infrastructure assessment.

Current inspection protocols in Benin City rely predominantly on visual assessment with qualitative descriptors such as "minor," "moderate," or "severe" for observed distress indicators (Okafor and Ugwu, 2019). While visual inspection remains essential, its subjectivity and inability to quantify structural risk limit its effectiveness for prioritizing maintenance in resource-constrained environments.

The integration of RSM with Finite Element Analysis as demonstrated in this research, establishes a replicable framework for transforming qualitative field observations into quantitative risk assessments. Field inspectors equipped with simple measurement tools can measure visible hydraulic conditions and use them as the input parameters required by the

predictive model. These measurements yield an estimate of wall shear force that can be compared against design thresholds to determine urgency of intervention, bridging the gap between observable symptoms and hidden structural demand.

The hierarchical importance of variables revealed in this study also informs strategic allocation of limited inspection resources. Given that Headwater Level exerts a greater influence on the WSF response, inspection protocols should prioritize accurate measurement of high-water marks and documentation of upstream catchment characteristics.

The successful application of RSM to this structural assessment problem aligns with modern trends in civil engineering towards data-driven approaches to problem solving. Recent local research has demonstrated the effectiveness of RSM for concrete mix optimization (Okafor and Umeorah, 2019; Ugwu et al., 2020), geotechnical applications (Akinwumi et al., 2018), and flood control channel design (Oke and Adesola, 2022). The current work extends this methodological trajectory into the domain of hydraulic infrastructure condition assessment, demonstrating that the strengths of RSM are equally valuable for infrastructure condition assessment and performance evaluation.

5.2 RECOMMENDATIONS

Based on the findings from this research, the following recommendations are proposed for implementation by relevant stakeholders in infrastructure management, policy formulation, and future research endeavors.

The Edo State Ministry of Works and local government authorities responsible for drainage infrastructure should integrate the proposed statistical framework into routine culvert inspection protocols. Field inspection teams should be equipped with basic measurement tools and trained to systematically collect critical input parameters. These measurements should be

recorded in standardized inspection forms and used to compute predicted structural responses, which can then be compared against established thresholds to prioritize maintenance interventions objectively.

Given the dominance of headwater level in influencing wall shear force, inspection resources should be strategically allocated toward accurate measurement and documentation of high-water marks. Permanent staff gauges should be installed at critical culvert locations, particularly those situated in low-lying areas or downstream of large catchments. Upstream catchment characteristics that influence peak flows, such as land use changes, drainage area, and impervious surface coverage, should be systematically documented in culvert inventory databases.

The methodology demonstrated in this research should be extended across the entire Ogba River drainage network and other major drainage corridors in Benin City. Geographic Information System (GIS) platforms should be employed to integrate culvert inventory data, catchment characteristics, and predicted structural vulnerabilities, enabling spatial visualization of high-risk locations and facilitating system-wide maintenance planning.

Future research should extend the experimental ranges to encompass more extreme conditions beyond those observed at the study site. The methodology demonstrated for box culverts should be adapted and validated for other common culvert configurations including circular pipes, arch culverts and elliptical sections. Additionally, while this research focused exclusively on wall shear force, future studies should investigate other critical structural responses such as bending moments in slabs, deflections, and cracking patterns to provide a more complete picture of structural vulnerability.

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APPENDIX



Plate A.1



Plate A.2

Field measurements of the box culvert dimensions at the Ogba River drainage corridor
(Author, 2025)