

AUGUST 2024

Ph.D. in Civil Engineering

ABUBAKER SAMI DHEYAB DHEYAB

**REPUBLIC OF TÜRKİYE
GAZİANTEP UNIVERSITY
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES**

**LOCAL SCOUR REDUCTION AROUND BRIDGE PIERS
BY USING NANOMATERIALS**

**Ph.D. THESIS
IN
CIVIL ENGINEERING**

**BY
ABUBAKER SAMI DHEYAB DHEYAB
AUGUST 2024**

LOCAL SCOUR REDUCTION AROUND BRIDGE PIERS
BY USING NANOMATERIALS

Ph.D. Thesis
in
Civil Engineering
Gaziantep University

Supervisor
Prof. Dr. Mustafa GÜNAL

by
Abubaker Sami Dheyab DHEYAB
August 2024



©2024[Gaziantep University]

**LOCAL SCOUR REDUCTION AROUND BRIDGE PIERS BY USING
NANOMATERIALS**

submitted by **DHEYAB, Abubaker Sami Dheyab** in partial fulfillment of the requirements for the degree of Doctor of Philosophy in **Civil Engineering, Gaziantep University** is approved by,

Prof.Dr. Çiydem AYKAÇ
Director of the Graduate School of Natural and Applied Sciences

Prof.Dr. Nildem TAYŞI
Head of the Department of Civil Engineering

Prof. Dr. Mustafa GÜNAL
Supervisor, Civil Engineering
Gaziantep University

Exam Date: 15 August 2024

Examining Committee Members:

Prof. Dr. Mustafa GÜNAL
Gaziantep University

Prof.Dr. Hanifi ÇANAKÇI
Hasan Kalyoncu University

Prof.Dr. Aytaç GÜVEN
Gaziantep University

Prof. Dr. Ali AYTEK
Gaziantep Islam Science and Technology University

Assist. Prof.Dr. Ayşe Yeter GÜNAL
Gaziantep University

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Abubaker Sami Dheyab DHEYAB

ABSTRACT

LOCAL SCOUR REDUCTION AROUND BRIDGE PIERS BY USING NANOMATERIALS

DHEYAB, Abubaker Sami Dheyab
Ph.D. in Civil Engineering
Supervisor: Prof. Dr. Mustafa GÜNAL
August 2024
134 pages

Local scour is a significant factor that contributes to bridge failures. Local scour occurs when the flow of water over bridge piers causes erosion and transports sediments around the piers of the bridge. This study aimed to investigate the influence of nano materials on the local scour mechanism. To achieve this, an experimental investigation was conducted using nanomaterials, specifically nano clay and nano-silica. Under varied hydraulic circumstances and with three different pier diameters, sand was mixed with different fractions of nanomaterials: nano clay and nano-silica. The findings indicate that nanomaterials have the potential to serve as an alternative approach for mitigating the extent of local scour. The effective utilization of nanomaterials, such as nano clay and nano-silica, can be achieved by adding them into sand through mixing. Experimental observations revealed that the maximum reduction ratio of local scour depth is 59.6% for the nanosilica-sand bed case and 68% for the nanosilica-sand bed case. The optimal ratios of nano materials have been determined. In addition, this investigation has demonstrated the impact of using nano materials (nano clay and nanosilica) on various factors related to local scour. Finally, the prediction equations were developed using data obtained from experimental investigation to determine the depth of local scour in a bed of nano materials (nanosilica and nanoclay) and non-uniform sand.

Key Words: Local scour, Nano clay, Nano Silica, Fine sediment, Pier scour.

ÖZET

KÖPRÜ AYAKLARI ETRAFINDA OLUŞAN YEREL OYILMANIN NANO MALZEME KULLANILARAK AZALTILMASI

DHEYAB, Abubaker Sami Dheyab
Doktora Tezi, İnşaat Mühendisliği
Danışman: Prof. Dr. Mustafa GÜNAL
Ağustos 2024
134 sayfa

Yerel oyulma,, köprü başarısızlıklarına katkıda bulunan önemli bir faktördür. Bu fenomen, köprünün ayakları etrafındaki sedimanların akışı tarafından neden olan erozyon kuvvetinin sonuçlarına işaret eder. Bu çalışma, düzensiz bir kum yatağının yatağını koruma ve oyulma duyarlılığını azaltma amacıyla yenilikçi bir yöntem geliştirmeyi amaçlamıştır. Bu amaçla, nanomalzemeler, özellikle nano kil ve nanosilika kullanılarak deneysel bir araştırma yapılmıştır. Farklı oranlardaki nanomalzemeler (nano kil ve nanosilika), çeşitli hidrolik koşullar altında kumla karıştırıldı ve üç farklı ayak çapı kullanıldı. Sonuçlar, nanomalzemelerin yerel oyulma derinliğini azaltmak için alternatif bir çözüm olarak kullanılabileceğini göstermektedir. Nanomalzeme (nano kil ve nanosilika), kumla karıştırılarak etkili bir şekilde kullanılabilir. Deneysel gözlemler, yerel oyulma derinliğinin maksimum azalma oranının nanosilika-kum yatağı durumu için %59,6 ve nanokil-kum yatağı durumu için %68 olduğunu ortaya koymaktadır. Nanomalzemelerin en uygun oranları belirlenmiştir. Ayrıca, bu çalışma, yerel oyulma ile ilgili çeşitli faktörler üzerinde nanomalzemelerin (nano kil ve nanosilika) kullanımının etkisini göstermiştir. Son olarak, tahmin denklemleri, bu çalışmada elde edilen verilere dayalı olarak nanomalzemelerden (nano kil ve nanosilika) oluşan bir yatakta yerel oyulma derinliğini tahmin etmek için türetilmiştir.

Anahtar Kelimeler: Nano kil, Nano Silika, Düzensiz sediment, Köprü ayağı, Yerel oyulma.



DEDICATION *"Dedicated to my family"*

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor, Prof.Dr. MUSTAFA GÜNAL, for his unwavering support, guidance, and mentorship throughout my academic journey. his expertise, patience, and encouragement have been invaluable in shaping my research and helping me achieve my academic goals. I am truly fortunate to have had the privilege of working under their guidance.

I also want to extend my heartfelt appreciation to my family for their constant love and support. To my parents, Prof. Dr. Sami DHEYAB and Ibtisam SHIHAB, who have been my pillars of strength, thank you for your sacrifices, encouragement, and belief in me. Your unwavering faith in my abilities has been my driving force.

A special mention goes to the soul of our family, my dear mom, Ibtisam SHIHAB. Your boundless love and selflessness have been a source of inspiration and motivation. Your memory lives on in my heart, and it is your spirit that has fueled my determination to excel.

I am grateful for the support of my wife, Dina ALGHADHANFARI, whose love, patience, and understanding have been my anchor throughout this journey. Her unwavering belief in me has made all the difference.

To my beloved daughter, Yasmin Abubaker SAMI, your endless curiosity and enthusiasm have brought joy and inspiration into my life. You have been my motivation to strive for excellence and set an example for you to follow.

I extend my appreciation to my siblings and their families, Omar, Ahmed, Ali, Othman, Ayat, and all my extended family members (nieces and nephews) and friends who have stood by me during this journey

I would like to express my sincere thanks to my father-in-law, AbdulNasir ALGHADHANFARI, and my mother-in-law, Zinah Aldamaloji and their family (Aunty Nawal, Aunty Rajaa, Hala, Aya, Ahmed, Mohammed, Zaid), for their unwavering support and acceptance. Your warmth and encouragement have made me feel like a cherished part of the family.

Lastly, I am thankful for the support of my fellow researchers and colleagues who have shared their knowledge and insights, enriching my academic experience.

This accomplishment would not have been possible without the collective support and love of all these wonderful people in my life. Thank you for being a part of my journey

TABLE OF CONTENTS

	Page
ABSTRACT	i
ÖZET.....	i
DEDICATION	iii
ACKNOWLEDGEMENTS.....	iv
TABLE OF CONTENTS.....	vi
LIST OF TABLES	ix
LIST OF FIGURES	x
LIST OF ABBREVIATIONS	xv
CHAPTER 1 INTRODUCTION	1
1.1 General.....	1
1.2 General Scour	3
1.3 Localized Scour	4
1.3.1 Contraction scour	4
1.3.2 Local scour	4
1.4 Research Objective	7
1.5 Layout of Thesis	8
CHAPTER 2 LITERATURE REVIEW	10
2.1 Introduction	10
2.2 Mechanism of Scouring	11
2.2.1 Hydraulic aspects	11
2.2.2 Structural aspects	17
2.2.3 Geo-tech aspects	19
2.2.4 Time	36
2.3 Local Scour Prediction	39
2.3.1 Empirical equations	39

2.3.3 Artificial Intelligence and Machine Learning:.....	41
2.3.2 Numerical modeling.....	41
2.4 Nano Materiales	44
2.4.1 Nano clay	44
2.4.2 Nano Silica.....	45
2.4.3 Application of nanomaterials	45
CHAPTER 3 THEORETICAL STUDY	49
3.1 Introduction	49
3.2 Dimensional Analysis.....	49
CHAPTER 4 EXPERIMENTAL WORK AND EQUIPMENT	51
4.1 Experiments Setting	51
4.2 Pier Models.....	53
4.3 Sand Properties.....	54
4.4 Nano Materials Properties	55
4.5 Flow Conditions	56
4.6 Experimental Procedure	58
4.6.1 Experimental steps	58
4.6.2 Preparing the Nanomaterials-Sand beds	63
4.7 The structure of the study	64
CHAPTER 5 RESULTS AND DISCUSSION.....	67
5.1 Introduction	67
5.2 Control Tests	67
5.2.1 Experimental Measurements Calibration.....	68
5.2.2 Effect of Main Parameters	70
5.2.3 Local scour Time And Bed Topography	74
5.3 Nano Clay - Sand Bed	80
5.4 Nano Silica - Sand Bed	97
CHAPTER 6 LOCAL SCOUR PREDICTION	113
6.1 Introduction	113
6.2 Regression Analysis	113
CHAPTER 7 CONCLUSION AND RECOMMENDATION.....	118
7.1 Conclusion.....	118
7.2 Recommendations	121

REFERENCES.....	122
CURRICULUM VITAE.....	133



LIST OF TABLES

	Page
Table 2.1 Critical velocity equation	24
Table 2. 2 The ISO-14688-1: 2017 standard categorizes soil classes based on their d_{50} size.	26
Table 2.3 Sediment classification.....	28
Table 2.4 Formulas for local scour.....	40
Table 4.1 The properties of the bed materials	56
Table 4.2 Experiment parameters.....	57
Table 5.1 The summary of the control test results.	68
Table 5.2 Formulas for local scour.....	69
Table 5.3 Results summary of the mixing nano clay with sand.....	80
Table 5.4 Results summary of the mixing nano-silica with sand.....	98

LIST OF FIGURES

	Page
Figure 1.1 The failure of the Çaycuma bridge in Zonguldak Province, which is located near the Black Sea in Turkey (April 2012). The source of the pictures is the Anadolu Agency (Ajansı).....	2
Figure 1.2 Scour classification	3
Figure 1.3 Contraction Scour (FHWA-RD-03-052, 2005).	4
Figure 1.4 Vortexes formation around a bridge pier	5
Figure 1.5 Vortex around the pier (Whitehouse, 1998).	6
Figure 2.1 The framework of the bridge pier scouring research (Wang et al., 2017a).	10
Figure 2.2 Factors of the scour bridge foundation (Wang et al., 2017a).	11
Figure 2.3 Variation in the depth of local scour with the intensity of flow. (Liang et al., 2020; MELVILLE, 2008b).....	12
Figure 2.4 The relationship between flow depth and local scour depth (MELVILLE, 2008b).....	14
Figure 2.5 ds/b with large-scale turbulence (Robert Ettema, 2006).....	15
Figure 2.6 Vortex shedding based on the pier Reynolds number (Irvine, 2009).	16
Figure 2.7 Pier shapes (Akhlaghi et al., 2020).	17
Figure 2.8 Scour depth divergence with pier orientation (Laursen & Toch, 1956)..	19
Figure 2.9 Types of sediments transport (Pizarro et al., 2020a).	20
Figure 2.10 a. Acting forces on the sediment particle, b. Top view of the particles, c. tetrahedron formed (Dey & Zanke, 2004).....	21
Figure 2.11 Shield diagram.	23
Figure 2.12 The coarseness of the sediments variation and the depth of local scour ds (MELVILLE, 2008b).	25
Figure 2.13 The mechanism of local scour based on the soil type (Prendergast & Gavin, 2014; Wang et al., 2017b).	28
Figure 2.14 Sediment nonuniformity and local scour depth comparing (MELVILLE, 2008b).....	29

Figure 2.15 Yangtze River estuary, the source of the photos (Yu et al., 2020) and (Webmaster, 2020)	32
Figure 2.16 Filyos River estuary (Kaya et al., 2007).	32
Figure 2.17 The experimental setting and observed scour (Debnath & Chaudhuri, 2010a).	34
Figure 2.18 Scour around different shapes of the pier in the clay-sand bed (Debnath & Chaudhuri, 2012).	34
Figure 2.19 Local scour depth based on the clay ratio (Chaudhuri & Debnath, 2013).	35
Figure 2. 20 Developing the local scour with time in clear-water conditions (Melville, 2008a).	37
Figure 2. 21 Effect of the time and flow shallowness, sediment coarseness (Melville, 2008a).	38
Figure 2. 23 Example of the CFD local scour model (Alasta et al., 2022)	43
Figure 2.22 The montmorillonite structure (Steinmetz, 2007).	45
Figure 4.1 Schematic layout of the flume	52
Figure 4.2 Experiment Setting during the run.	52
Figure 4.3 The pier models with 3 cm, 5 cm, and 7.5 cm.	53
Figure 4.4 Sieve analysis of sand.	54
Figure 4.5 (a) Nano clay powder. (b) Nano silica powder.	55
Figure 4.6 Test section and Pier installation.	60
Figure 4.7 Sand-bed leveling.	61
Figure 4.8 Leveled bed and ready for run.	62
Figure 4.9 Flowchart the mixing steps.	65
Figure 4.10 Flow chart of the study.	66
Figure 5.1 Experimental measurements calibration.....	70
Figure 5.2 The relation between the variables.	71
Figure 5.3 Correlations coefficient of variables.	71
Figure 5.4 Relation between the d_s/D and shallowness.	72
Figure 5.5 Local scour depth through the time of the experiments.....	75
Figure 5.6 Scour pattern for scenario CD3H1.....	75
Figure 5.7 Scour pattern for scenario CD3H2.....	76
Figure 5.8 Scour pattern for scenario CD3H3.....	76
Figure 5.9 Scour pattern for scenario CD5H1.....	77

Figure 5.10 Scour pattern for scenario CD5H2.....	77
Figure 5.11 Scour pattern for scenario CD5H3.....	78
Figure 5.12 Scour pattern for scenario CD7H1.....	78
Figure 5.13 Scour pattern for scenario CD7H2.....	79
Figure 5.14 Scour pattern for scenario CD7H3.....	79
Figure 5.15 Correlation between scour depth and nano clay fraction based on flow depth, for 3 cm pier diameter cases.	84
Figure 5.16 The ratio of d_s reduction for 3 cm pier.	84
Figure 5. 17 Correlation between scour depth and nano clay fraction based on flow depth, for 5 cm pier diameter cases.	85
Figure 5.18 The ratio of d_s reduction for 5 cm pier.	85
Figure 5.19 Correlation between scour depth and nano clay fraction based on flow depth, for 7.5 cm pier diameter cases.	86
Figure 5.20 The ratio of d_s reduction for 7.5 cm pier.	86
Figure 5.21 Changes in scour depth (d_s) in the scenarios of a D 3 cm with h 5.7 cm (Nano clay- sand bed) over time.....	87
Figure 5.22 Changes in scour depth (d_s) in the scenarios of a D 3 cm with h 7.55 cm (Nano clay- sand bed) over time.....	87
Figure 5.23 Changes in scour depth (d_s) in the scenarios of a D 3 cm with h 9.1 cm (Nano clay- sand bed) over time.....	88
Figure 5.24 Changes in scour depth (d_s) in the scenarios of a D 5 cm with h 5.7 cm (Nano clay- sand bed) over time.....	88
Figure 5.25 Changes in scour depth (d_s) in the scenarios of a D 5 cm with h 7.55 cm (Nano clay- sand bed) over time.....	89
Figure 5.26 Changes in scour depth (d_s) in the scenarios of a D 5 cm with h 9.1 cm (Nano clay- sand bed) over time.....	89
Figure 5.27 Changes in scour depth (d_s) in the scenarios of a D 7.5 cm with h 5.7 cm (Nano clay- sand bed) over time.....	90
Figure 5.28 Changes in scour depth (d_s) in the scenarios of a D 7.5 cm with h 7.55 cm (Nano clay- sand bed) over time.....	90
Figure 5.29 Changes in scour depth (d_s) in the scenarios of a D 7.5 cm with h 9.1 cm (Nano clay- sand bed) over time.....	91
Figure 5.30 Correlation of d_s/D Ratio and Fr_0 as a function of Nano Clay fraction for a D 3 cm.	92

Figure 5.31 Correlation of ds/D Ratio and Fr_0 as a function of Nano Clay fraction for a D 5 cm.	92
Figure 5.32 Correlation of ds/D ratio and Fr_0 as a function of Nano Clay fraction for a D 7.55 cm.	93
Figure 5.33 Local Scour for Scenarios: NC1D3H1, NC1D3H2, NC1D3H3.	94
Figure 5.34 Local Scour for Scenarios: NC1D5H1, NC1D5H2, NC1D5H3.	95
Figure 5.35 Local Scour for Scenarios: NC2D7H1, NC2D7H2, NC2D7H3.	96
Figure 5.36 Correlation between scour depth and nano silica fraction based on flow depth, for 3 cm pier diameter cases.	100
Figure 5.37 The ratio of ds reduction for 3 cm pier.	101
Figure 5.38 Correlation between scour depth and nano silica fraction based on flow depth, for 5 cm pier diameter cases.	101
Figure 5.39 The ratio of ds reduction for 5 cm pier.	102
Figure 5.40 Correlation between scour depth and nano silica fraction based on flow depth, for 3 cm pier diameter cases.	102
Figure 5.41 The ratio of ds reduction for 7.5 cm pier.	103
Figure 5.42 Changes in scour depth (ds) in the scenarios of a D 3 cm with h 5.7 cm (Nano silica- sand bed) over time.	103
Figure 5.43 Changes in scour depth (ds) in the scenarios of a D 3 cm with h 7.55 cm (Nano silica- sand bed) over time.	104
Figure 5.44 Changes in scour depth (ds) in the scenarios of a D 3 cm with h 9.1 cm (Nano silica- sand bed) over time.	104
Figure 5.45 Changes in scour depth (ds) in the scenarios of a D 5 cm with h 5.7 cm (Nano silica- sand bed) over time.	105
Figure 5.46 Changes in scour depth (ds) in the scenarios of a D 5 cm with h 7.55 cm (Nano silica- sand bed) over time.	105
Figure 5.47 Changes in scour depth (ds) in the scenarios of a D 5 cm with h 9.1 cm (Nano silica- sand bed) over time.	106
Figure 5.48 Changes in scour depth (ds) in the scenarios of a D 7.5 cm with h 5.7 cm (Nano silica- sand bed) over time.	106
Figure 5.49 Changes in scour depth (ds) in the scenarios of a D 7.5 cm with h 7.55 cm (Nano silica- sand bed) over time.	107
Figure 5.50 Changes in scour depth (ds) in the scenarios of a D 7.5 cm with h 9.1 cm (Nano silica- sand bed) over time.	107

Figure 5.51 Correlation of ds/D Ratio and Fr_0 as a Function of Nano Silica Ratio for a 3 cm Diameter Pier.	108
Figure 5.52 Correlation of ds/D Ratio and Fr_0 as a Function of Nano Silica Ratio for a 5 cm Diameter Pier.....	108
Figure 5.53 Correlation of ds/D Ratio and Fr_0 as a Function of Nano Silica Ratio for a 7.5 cm Diameter Pier.	109
Figure 5.54 Local scour for scenarios: NC1D3H1, NC1D3H2, NC1D3H3.....	110
Figure 5.55 Local scour for scenarios: NC2D5H1, NC2D5H2, NC2D5H3.....	111
Figure 5.56 Local scour for scenarios: NC3D7H1, NC3D7H2, NC3D7H3.....	112
Figure 6.1 Predicted and observed ds/D (Nano clay-sand bed).	115
Figure 6.2 The correlation between the variables Nano clay-sand bed.	115
Figure 6.3 Predicted and observed ds/D (Nano Silica-sand bed).....	116
Figure 6.4 The correlation between the variables Nano silica-sand bed.....	117

LIST OF ABBREVIATIONS

V	The mean stream velocity
V_c	Critical velocity
ANN	Artificial Neural Network
ds	Depth of the local scour
D	Pier diameter
σ_g	The standard deviation of particle size
δ*	Displacement thickness
Re	Reynolds number
h	Flow depth
Re_p	Pier Reynolds number
FG	Submerged weight
FS	Seepage force
FD	Drag force
FL	Lift force
FLs	Shear effect
C_D	Drag coefficient
ρ_s	Density of sediment particles
ν	The kinematic viscosity of fluid
α_L	Lift coefficient
FL_m	Magnus effect
Ø_c	The critical Shields parameter
ρ	Density of fluid
u_d	Velocity at a distance <i>D</i> above the bed
ρ₀	Porosity of sediment particles
ω	Angular velocity of spinning particle
Ø	Shields parameter
d₅₀	The median particle size of sediment

Fr₀	Densimetric Froude number
R	Hydraulic Radius
C_p	Clay fraction
t	Time
g	Gravitation acceleration
Fr	Froude number
S_s	The specific gravity of sediment
K₁	The pier shape's correction factor
K₄	The armoring of the coarse bed's correction factor
CFD	Computational Fluid Dynamics
ANN	Artificial Neural Networks
W	Water content
DEM	Discrete Element Method
FEM	Finite Element Method
K₂	The flow direction's correction factor
AI	Artificial Intelligence
ML	Machine Learning
K₃	The bed's correction factor
μ	Dynamic viscosity of water
ANFIS	Adaptive Neuro-Fuzzy Inference Systems
GRNN	Generalized Regression Neural Networks
β	Correction factors for pier shape
τ_c	Bed shear strength
SVM	Support Vector Machines
M_s	Mass of sand
σ_g	Standard deviation of sediment grain size
Rep	Pier Reynolds number
M_w	Mass of water
G_s	Specific Gravity of sand
M_n	Mass of Nano clay
G_n	Specific Gravity of nanomaterials
CD3H1	Control Test, 3 cm diameter, flow depth 5.7 cm
M_r	Mixing ratio

CD3H2	Control Test, 3 cm diameter, flow depth 7.55 cm
CD3H3	Control Test, 3 cm diameter, flow depth 9.1 cm
CD5H1	Control Test, 5 cm diameter, flow depth 5.7 cm
CD5H2	Control Test, 5 cm diameter, flow depth 7.55 cm
CD5H3	Control Test, 5 cm diameter, flow depth 9.1 cm
CD7H1	Control Test, 7.5 cm diameter, flow depth 5.7 cm
CD7H2	Control Test, 7.5 cm diameter, flow depth 7.55 cm
CD7H3	Control Test, 7.5 cm diameter, flow depth 9.1 cm
NC1D3H1	Nano clay 0.25%, 3 cm diameter, flow depth 5.7 cm
NC2D3H1	Nano clay 0.5%, 3 cm diameter, flow depth 5.7 cm
NC3D3H1	Nano clay 0.75%, 3 cm diameter, flow depth 5.7 cm
NC4D3H1	Nano clay 1%, 3 cm diameter, flow depth 5.7 cm
NC1D3H2	Nano clay 0.25%, 3 cm diameter, flow depth 7.55 cm
NC2D3H2	Nano clay 0.5%, 3 cm diameter, flow depth 7.55 cm
NC3D3H2	Nano clay 0.75%, 3 cm diameter, flow depth 7.55 cm
NC4D3H2	Nano clay 1%, 3 cm diameter, flow depth 7.55 cm
NC1D3H3	Nano clay 0.25%, 3 cm diameter, flow depth 9.1 cm
NC2D3H3	Nano clay 0.5%, 3 cm diameter, flow depth 9.1 cm
NC3D3H3	Nano clay 0.75%, 3 cm diameter, flow depth 9.1 cm
NC4D3H3	Nano clay 1%, 3 cm diameter, flow depth 9.1 cm
NC1D5H1	Nano clay 0.25%, 5 cm diameter, flow depth 5.7 cm
NC2D5H1	Nano clay 0.5%, 5 cm diameter, flow depth 5.7 cm
NC3D5H1	Nano clay 0.75%, 5 cm diameter, flow depth 5.7 cm
NC4D5H1	Nano clay 1%, 5 cm diameter, flow depth 5.7 cm
NC1D5H2	Nano clay 0.25%, 5 cm diameter, flow depth 7.55 cm
NC2D5H2	Nano clay 0.5%, 5 cm diameter, flow depth 7.55 cm
NC3D5H2	Nano clay 0.75%, 5 cm diameter, flow depth 7.55 cm
NC4D5H2	Nano clay 1%, 5 cm diameter, flow depth 7.55 cm
NC1D5H3	Nano clay 0.25%, 5 cm diameter, flow depth 9.1 cm
NC2D5H3	Nano clay 0.5%, 5 cm diameter, flow depth 9.1 cm
NC3D5H3	Nano clay 0.75%, 5 cm diameter, flow depth 9.1 cm
NC4D5H3	Nano clay 1%, 5 cm diameter, flow depth 9.1 cm
NC1D7H1	Nano clay 0.25%, 7 cm diameter, flow depth 5.7 cm

NC2D7H1	Nano clay 0.5%, 7 cm diameter, flow depth 5.7 cm
NC3D7H1	Nano clay 0.75%, 7 cm diameter, flow depth 5.7 cm
NC4D7H1	Nano clay 1%, 7 cm diameter, flow depth 5.7 cm
NC1D7H2	Nano clay 0.25%, 7 cm diameter, flow depth 7.55 cm
NC2D7H2	Nano clay 0.5%, 7 cm diameter, flow depth 7.55 cm
NC3D7H2	Nano clay 0.75%, 7 cm diameter, flow depth 7.55 cm
NC4D7H2	Nano clay 1%, 7 cm diameter, flow depth 7.55 cm
NC1D7H3	Nano clay 0.25%, 7 cm diameter, flow depth 9.1 cm
NC2D7H3	Nano clay 0.5%, 7 cm diameter, flow depth 9.1 cm
NC3D7H3	Nano clay 0.75%, 7 cm diameter, flow depth 9.1 cm
NC4D7H3	Nano clay 1%, 7 cm diameter, flow depth 9.1 cm
NS1D3H1	Nano Silica 0.25%, 3 cm diameter, flow depth 5.7 cm
NS2D3H1	Nano Silica 0.5%, 3 cm diameter, flow depth 5.7 cm
NS3D3H1	Nano Silica 0.75%, 3 cm diameter, flow depth 5.7 cm
NS4D3H1	Nano Silica 1%, 3 cm diameter, flow depth 5.7 cm
NS1D3H2	Nano Silica 0.25%, 3 cm diameter, flow depth 7.55 cm
NS2D3H2	Nano Silica 0.5%, 3 cm diameter, flow depth 7.55 cm
NS3D3H2	Nano Silica 0.75%, 3 cm diameter, flow depth 7.55 cm
NS4D3H2	Nano Silica 1%, 3 cm diameter, flow depth 7.55 cm
NS1D3H3	Nano Silica 0.25%, 3 cm diameter, flow depth 9.1 cm
NS2D3H3	Nano Silica 0.5%, 3 cm diameter, flow depth 9.1 cm
NS3D3H3	Nano Silica 0.75%, 3 cm diameter, flow depth 9.1 cm
NS4D3H3	Nano Silica 1%, 3 cm diameter, flow depth 9.1 cm
NS1D5H1	Nano Silica 0.25%, 5 cm diameter, flow depth 5.7 cm
NS2D5H1	Nano Silica 0.5%, 5 cm diameter, flow depth 5.7 cm
NS3D5H1	Nano Silica 0.75%, 5 cm diameter, flow depth 5.7 cm
NS4D5H1	Nano Silica 1%, 5 cm diameter, flow depth 5.7 cm
NS1D5H2	Nano Silica 0.25%, 5 cm diameter, flow depth 7.55 cm
NS2D5H2	Nano Silica 0.5%, 5 cm diameter, flow depth 7.55 cm
NS3D5H2	Nano Silica 0.75%, 5 cm diameter, flow depth 7.55 cm
NS4D5H2	Nano Silica 1%, 5 cm diameter, flow depth 7.55 cm
NS1D5H3	Nano Silica 0.25%, 5 cm diameter, flow depth 9.1 cm
NS2D5H3	Nano Silica 0.5%, 5 cm diameter, flow depth 9.1 cm

NS3D5H3	Nano Silica 0.75%, 5 cm diameter, flow depth 9.1 cm
NS4D5H3	Nano Silica 1%, 5 cm diameter, flow depth 9.1 cm
NS1D7H1	Nano Silica 0.25%, 7 cm diameter, flow depth 5.7 cm
NS2D7H1	Nano Silica 0.5%, 7 cm diameter, flow depth 5.7 cm
NS3D7H1	Nano Silica 0.75%, 7 cm diameter, flow depth 5.7 cm
NS4D7H1	Nano Silica 1%, 7 cm diameter, flow depth 5.7 cm
NS1D7H2	Nano Silica 0.25%, 7 cm diameter, flow depth 7.55 cm
NS2D7H2	Nano Silica 0.5%, 7 cm diameter, flow depth 7.55 cm
NS3D7H2	Nano Silica 0.75%, 7 cm diameter, flow depth 7.55 cm
NS4D7H2	Nano Silica 1%, 7 cm diameter, flow depth 7.55 cm
NS1D7H3	Nano Silica 0.25%, 7 cm diameter, flow depth 9.1 cm
NS2D7H3	Nano Silica 0.5%, 7 cm diameter, flow depth 9.1 cm
NS3D7H3	Nano Silica 0.75%, 7 cm diameter, flow depth 9.1 cm
NS4D7H3	Nano Silica 1%, 7 cm diameter, flow depth 9.1 cm

CHAPTER 1

INTRODUCTION

1.1 General

Scour is a natural occurrence that happens when a river's flow erodes and removes sediment from the riverbed, banks, and areas near structures like bridge piers. The erosion is a result of the hydrodynamic force generated by the water flow, which effectively removes the sediment and conveys it in a downstream direction (Richardson, 2001).

Scour is a severe problem and a significant reason for bridge failure (Ismael et al., 2015). In Turkey, From 2000 to 2019, 87 bridges collapsed due to various factors, including hydraulic issues, collisions and accidents, overload, construction-related problems, and fire incidents. The primary factor contributing to the failure of bridges was hydraulic issues. According to (Schaap & Caner, 2021), 42 bridge failures were attributed to hydraulic events, with 74% of these failures being caused by scouring. Specifically, pier scour was a factor in 45% of all bridge collapses.

Between 1969 and 1990, there were about 600 bridge failures in the United States. These collapses have been related to a phenomenon known as local scour (Shirole AM, 1991). The aforementioned matter led to significant economic losses, loss of human lives, and disruptions to operational activities (Schaap & Caner, 2021); (Fernando De Falco, 2002). During the period spanning from 1989 to 2000, a total of 500 occurrences of bridge collapses occurred in the United States due to scour and floods. It is worth mentioning that according to Prendergast and Gavin (2014), 53% of the recorded failures were specifically due to scour and flooding. Based on the findings of Lagasse et al. (2012), it was anticipated that the annual financial losses incurred in the United States due to flood damage restoration amount to approximately \$50 million. During the flood event that occurred in 1993 along the Mississippi and downstream Missouri

ivers, a significant number of bridges, specifically 28 in total, experienced collapse. Out of these, 22 bridges collapsed as a result of scour-induced effects, as documented by Prendergast and Gavin (2014). The failure of the Çaycuma bridge in Zonguldak Province, which is located near the Black Sea in Turkey, was attributed to pier scour, as depicted in Figure 1.1 (Schaap & Caner, 2021).



Figure 1.1 The failure of the Çaycuma bridge in Zonguldak Province, which is located near the Black Sea in Turkey (April 2012). The source of the pictures is the Anadolu Agency (Ajansı).

In general, scour can be classified into:

1. General Scour
 - Short Term
 - Long Term
2. Localized scour
 - Contraction Scour
 - Local Scour
 - Live-bed Scour
 - Clear-Water Scour

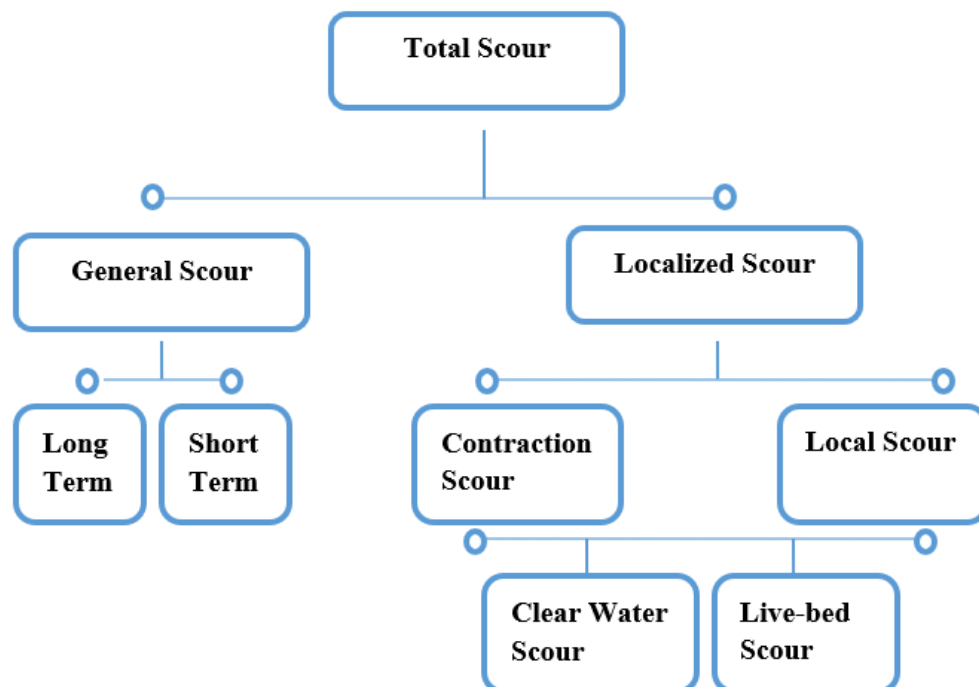


Figure 1.2 Scour classification

1.2 General Scour

General scour in river channels is a result of a combination of anthropogenic activities and natural processes. These factors cause alterations in important hydraulic characteristics of the channel, such as flow depth, flow rates, stream shape, and The inflow of sediment from sources located upstream. For instance, the constructing of dams can cause modifications in the deposition (aggradation) and removal (degradation) of sediment in the river. Furthermore, scour can be categorized into two types based on duration: long and short. This classification is determined by the length

of time during which the scouring process takes place. (Abdalla, January 20, 2017; Forde et al., 1999; Prendergast & Gavin, 2014).

1.3 Localized Scour

Localized scour, which occurs as a result of riverine infrastructure like bridges, can be categorized into the following divisions:

1.3.1 Contraction scour

Contraction scour is the phenomenon that occurs when the channel or river becomes narrower as a result of a constriction, such as a bridge and abutment. This constriction results in an increase of the mean velocity of the flow. Increasing the velocity of the flow leads to more erosive forces, particularly shear stresses, illustrated in Figure 1.3. As a result, these heightened shear stresses have the potential to exceed the bed-shear stress, resulting in the transportation of sediments.. This process can cause significant scouring and failure of the river banks (Hamill, 1999).

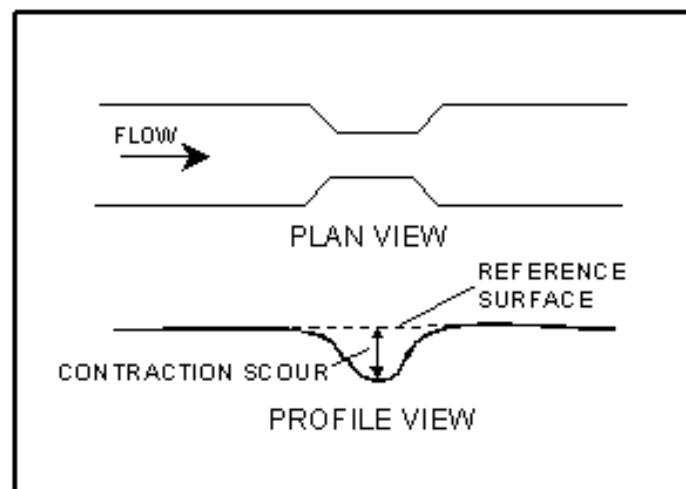


Figure 1.3 Contraction Scour (FHWA-RD-03-052, 2005).

1.3.2 Local scour

Local scour is a hydrodynamic process that takes place in streams, specifically in the close vicinity of structures such as bridge piers, abutments, and piles, where sediment is transported away from their vicinity. Subsequently, the sediment is carried downstream. Local scour is the process of erosion that takes place in near-by areas of bridge piers. It happens when the water flow slows down as it passes the piers, causing the water to come to a stop in front of the pier. This stop in the approach leads to the

formation of scour. The deceleration causes a reduction in the surface pressure on the pier. As a result, a pressure gradient is formed that acts in the opposite direction of the flow. As water drops from the river's surface to its depths, its pressure and speed lessen. This results in the downward movement of the flow along the stagnation line. As the water flows downward, it creates a horseshoe-shaped swirl. Once the pressure surpasses the resistance of the sediment particles, erosion of the sediment surrounding the piers will commence. The phenomenon of sand removal, commonly referred to as "local scour," possesses the capability to result in the prolonged deterioration of the bridge (Dheyab & Günal; Ismael et al., 2015; Liang et al., 2020; Moncada-M et al., 2009). The developed vortices around the bridge pier are shown in Figures 1.4 and 1.5.

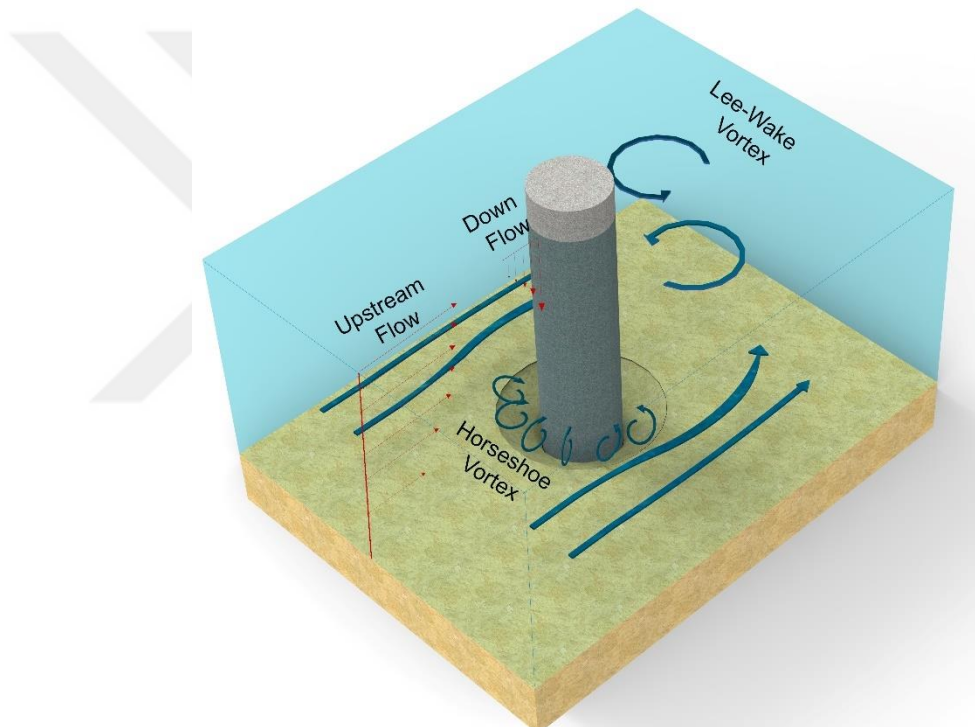


Figure 1.4 Vortexes formation around a bridge pier (Dheyab & Günal, 2023).

An further vortex is seen in Figures 1.4 and 1.5, located in the downstream area of the pier. The phenomenon being referred to is commonly known as the Wake vortex. It originates from the edges of the pier and then flows downstream. It acts like a "vacuum cleaner," efficiently capturing sediments in the stream. Primarily, the pier's form is responsible for the scouring generated downstream. A wake vortex is created by a number of variables, such as the pier's design and the average approach speed (Ismael et al., 2015; Ranjbar Zahedani et al., 2019).

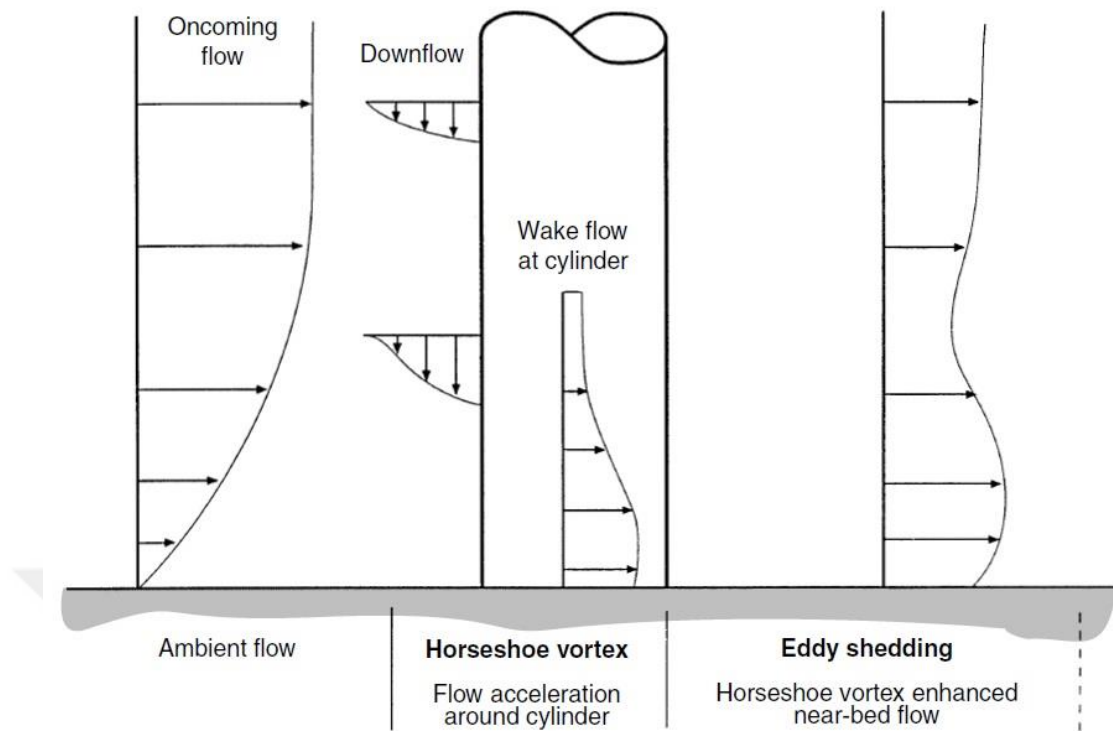


Figure 1.5 Vortex around the pier (Whitehouse, 1998).

Both live-bed scour and clear-water scour are main types of local scour. How the mean stream velocity (V) relates to the scour-critical velocity (V_c) is used to establish the categorization. (V_c) is the minimum possible speed required for transporting sediments.

Clear-water scour occurs when the average velocity (V) is less than the critical velocity (V_c), thus, particles are not moved upstream. This means that the silt in the scour hole will not be replaced by other particles. The flow approach is crucial in determining the movement of particles and the formation of the scour hole. The greatest depth of local scour is observed during the equilibrium scour phase, which is defined by the lack of sediment movement from the scoured region.

Live-bed scour takes place when the mean velocity (V) of the approach exceeds the critical velocity (V_c). This is in contrast to other types of scour. In this scenario, sediment is transported in the bed of the approach (Hamill, 1999).

The aim of this research was to study the occurrence of local scour in a bed composed of nanomaterials and sand. The experimental study was carried out at the hydraulic laboratory of Gaziantep University in Turkey. The study consisted of two phases.

In the first part, known as the control test phase, this phase aimed to establish a baseline measurement for comparison purposes in the sand bed.

In the second phase, Phase two involved adding two different kinds of nanomaterials—Nanosilica and Nano Clay—to the sand bed and measuring the local scour depth. To find out how these nanomaterials affected the scour depth.

Additionally, the research also encompassed the creation of prediction formulae and Artificial Neural Network (ANN) models. The purpose of developing these models was to enhance our comprehension of the phenomena and improve our capacity to anticipate the depth of local scour in the presence of nanomaterials. Overall, the thesis intended to investigate the behavior of local scour depth in the presence of nanomaterials and offer significant insights for future research in this subject.

1.4 Research Objective

The objective of this research is to gain a comprehensive understanding of how nano materials affect the magnitude of local scour in a sand bed. It is important to note that there is currently a lack of comprehensive research on the impact of nanomaterials on local scour. Therefore, this study plays a crucial role in advancing this field by being one of the first to investigate this topic thoroughly.

The study has the following primary objectives:

1. Conducting a thorough and comprehensive investigation is essential in assessing the effect of nanomaterials on scour phenomena. The purpose of this research is to clarify the intricate interactions between nanomaterials and the scouring processes of the sand bed through a careful and detailed series of tests.
2. Varied Parameters: Conduct tests using a wide range of parameters, such as different dimensions of cylindrical piers and varying flow depths. The study aims to gain a comprehensive understanding of how nanomaterials impact local scour in various scenarios by carefully controlling these factors.
3. Determining the Optimal Nanomaterial Ratio: Find the ideal ratio of nanomaterials that will produce the desired effect on the local scour. This research aims to determine the optimal concentration of nanomaterials that effectively reduces scour through systematic experimentation and analysis.

4. **Mechanistic Insights:** Discover the fundamental mechanisms by which nanomaterials impact the scouring mechanism. The study aims to enhance the broader understanding of fluid-sediment interactions at the nanoscale by combining empirical findings with theoretical insights.

5. **Practical Implications:** Utilize research findings to generate practical recommendations for engineering applications. This study aims to offer guidance on how to incorporate nanomaterial-enhanced solutions into structures at risk of local scour. By doing so, we aim to contribute to the development of sustainable and resilient infrastructure.

This study aims to address a knowledge gap regarding of how nanoparticles affect local scour. The study aims to address the objectives mentioned earlier, aiming to advance scientific understanding and offer practical insights for real-world engineering challenges.

1.5 Layout of Thesis

There are seven chapters in this thesis. Below are concise explanations of each chapter:

Chapter 1 Introduction:

The historical context of local scour at bridge piers is well explained in this chapter. In addition, the thesis overview and research objectives are provided.

Chapter 2 Literature Review:

This chapter provides an informative summary of previous studies conducted on the occurrence of local scour near bridge piers. The content covers subjects such as predicting the local scour depth and different factors that govern the local scour.

Chapter 3 Theoretical Study:

This chapter presents a comprehensive overview of the theoretical research by introducing the fundamental concept of dimensional analysis.

Chapter 4 Experimental Work And Equipment

This chapter presents a detailed overview of the experimental equipment, models, and methodologies employed in the investigation.

Chapter 5 Results and Discussion:

This chapter provides a detailed examination of the obtained findings is presented, along with a thorough discussion of their significance. Furthermore, the chapter explores the effects of the nano materials employed in the research.

Chapter 6 Local Scour Prediction

This chapter presents a methodology for forecasting the occurrence of local scour. in a nanomaterial-sand bed.

Chapter 7 Conclusions and Recommendations:

This chapter outlines the primary findings obtained from the study's outcomes, along with suggestions for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Local scour (Bridge scour) is a complicated and multifaceted problem involving the erosion and eradication of soil in the vicinity of a bridge pier, therefore, that issue has been studying since the earliest civilizations. As (Wang et al., 2017b), mentioned that the piers scour studies can be classified as science or engineering, as shown in Fig 2.1 which clarify the relationship between the research project about the mechanism of scouring and how to convert it to the be applicable in the engineering part.

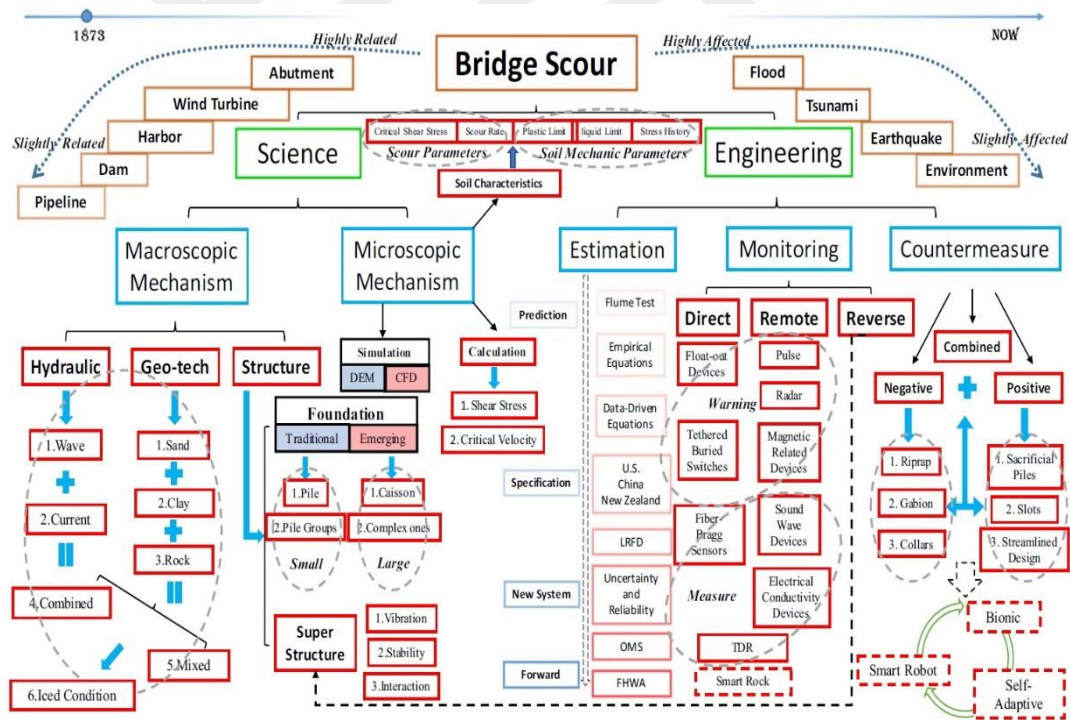


Figure 2.1 The framework of the bridge pier scouring research (Wang et al., 2017b).

This chapter presents a thorough overview of the different factors that govern the creation and intensification of local scour around bridge foundations. The chapter covers various aspects related to scouring, including the mechanism behind it, approaches to mitigate local scour, and methods for predicting and simulating scour.

2.2 Mechanism of Scouring

The occurrence of local scour near piers is primarily influenced by three main factors: hydraulic, geotechnical, and structural aspects.

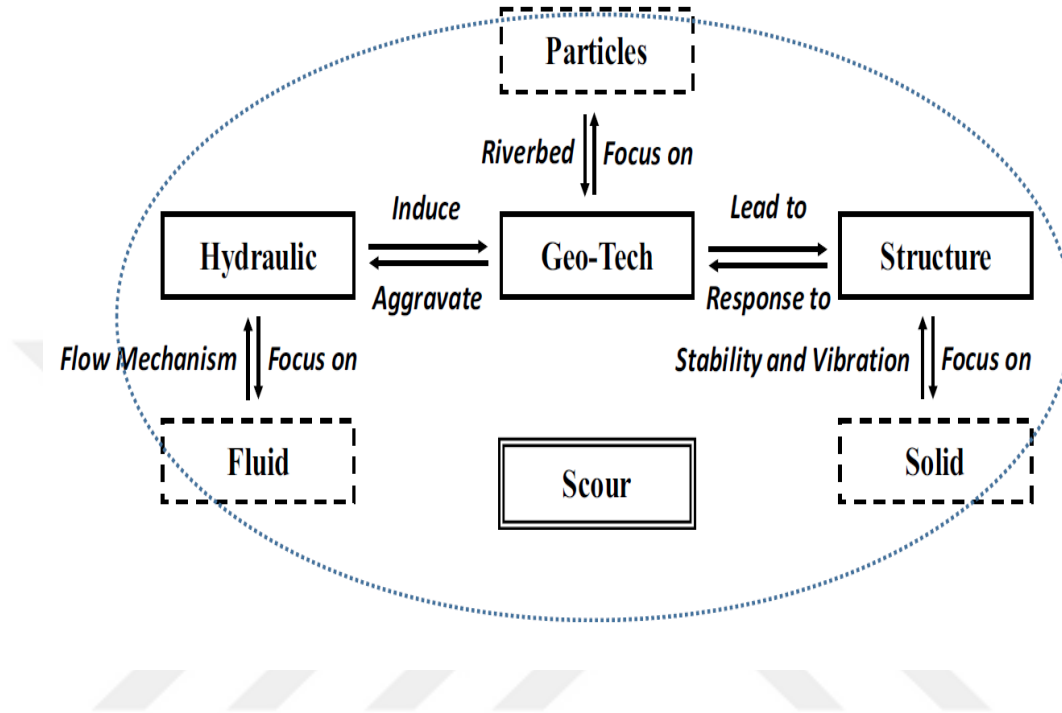


Figure 2.2 Factors of the scour bridge foundation (Wang et al., 2017b).

2.2.1 Hydraulic aspects

Hydraulic variables are crucial in the formation of scour around piers. Important parameters to consider include water depth, flow intensity, shear, mean and distribution of velocity.

2.2.1.1 Intensity of flow

Flow intensity, denoted as V/V_c , refers to the measure of the correlation between the mean velocity and the critical velocity. The critical velocity, also known as the threshold velocity, is a measure used to indicate the presence of scouring conditions. The term "approach velocity" refers to the minimum velocity needed for sediment to initiate movement (Baykal et al., 2015; Liang et al., 2020; Zhao et al., 2010).

The condition of clear live bed scour and water scour can be summarized by considering the intensity of the flow. Clear water scour occurs if $(V/V_c < 1)$. However, when the $(V/V_c > 1)$, it indicates the occurrence of live bed scour. Multiple researchers

have reached the consensus that, in situations where water is transparent and the sediment on the bed is consistent, (V/V_c) should be less than 1. This indicates that there is no transfer of sediment from the upstream flow to the scour hole. In such cases, the depth of the local scour (d_s) exhibits a near-linear and proportional relationship with the pier width (d_s/D), resulting in an increase in scour depth. Furthermore, there exists an almost linear correlation between the critical velocity and the mean velocity. This correlation ultimately results in the achievement of the peak threshold when the system reaches equilibrium, specifically when it reaches its maximum depth (d_s). Scouring in the form of live bed scour will occur if (V/V_c) is greater than 1. This indicates that as the water flows, it will carry the sediment particles, resulting in a decrease in the sediment depth (d_s) at the beginning of the flow. However, the depth will subsequently increase until it reaches a new peak live bed. The changes observed are a direct consequence of the sediment being carried by the incoming flow. As depicted in Fig 2.3. (Liang et al., 2020; MELVILLE, 2008b).

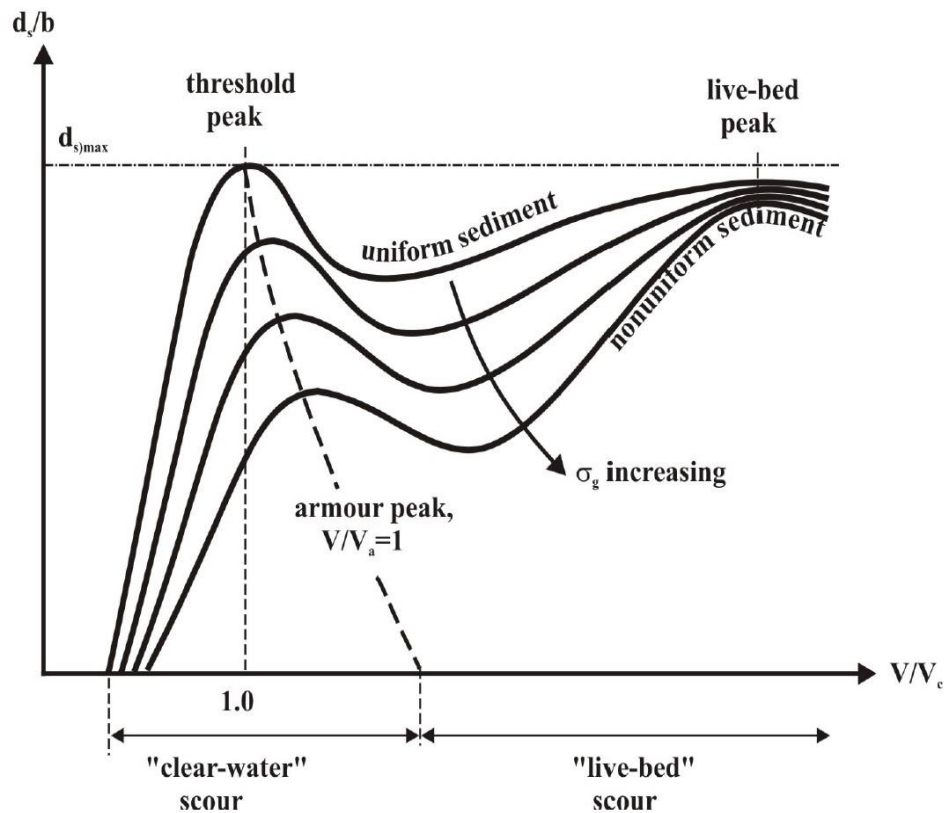


Figure 2.3 Variation in the depth of local scour with the intensity of flow. (Liang et al., 2020; MELVILLE, 2008b).

According to Arved J. Raudkivi (1983), If the sediment gradation coefficient (σ_g) is less than 2, the maximum local scour is unaffected by it.

2.2.1.2 Flow depth

Flow shallowness (h/D), which indicates the relationship between the flow level and the width of the bridge piers, is a key factor in determining the local scour. Flow velocity distribution within its depth exhibits non-uniformity, influencing sediment particles' transport. The phenomenon known as the flow shallowness effect depends upon the relationship between the average and critical velocities. Until it reaches a threshold value, the scour depth does not change (Liang et al., 2020).

Figure 2.4 shows how MELVILLE (2008b) classified experimental data based on pier width as part of his analysis. The objective was to examine how two different vortex patterns were affected by flow depth: (the horseshoe and the bow) vortex. When the flow is deep and approaches the vortex in relation to the pier width, 2.4 times the flow depth is the greatest depth of scour (d_s) that can be achieved in the narrow width category. This implies that in cases of deep flow and narrow piers, approach depth does not affect local scour depth, as there is no interaction between the horseshoe vortex and the bow vortex. On the other hand, in cases of wide piers and deep flow, there is interaction between the two vortices. However, this interaction does not allow the horseshoe vortex to effectively transport sediments, resulting in a lesser depth of local scour (d_s). In cases of intermediate , The flow depth and pier width are the two primary factors that determine the scour depth.

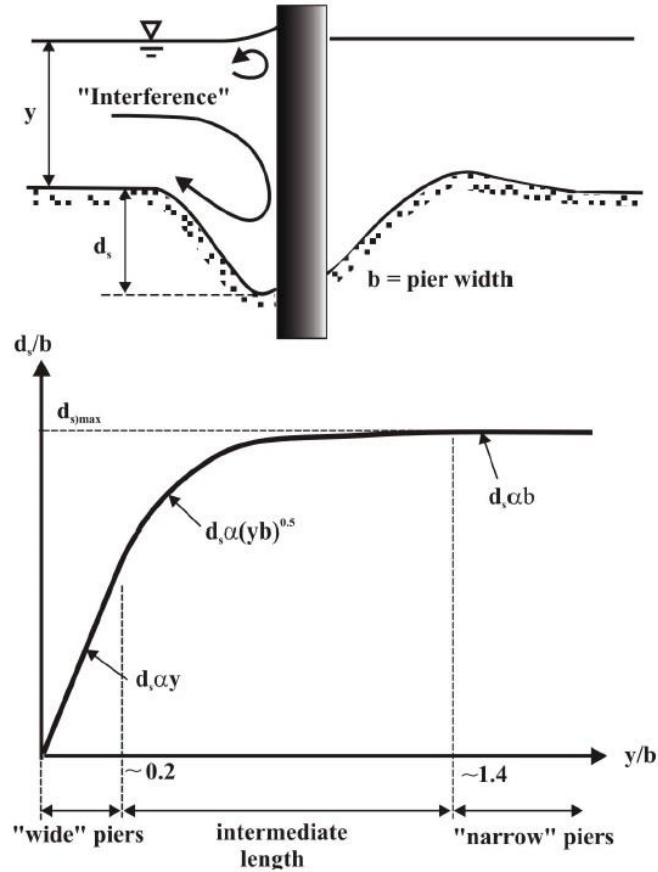


Figure 2.4 The relationship between flow depth and local scour depth (MELVILLE, 2008b).

2.2.1.3 Effect of Euler number and Reynolds number

In accordance with R. Ettema (1998), Scour close to the bridge pier may become greater as the Euler number V^2/gb is increased. Using the term $V^2/2g$ is beneficial to explain the flow energy gradients around the bridge pier. This can be interpreted as the ratio between the stagnation head and the pier width. In terms of simulation, the real pressure head flow approach and the laboratory setup for the pier both utilize the same stagnation head $V^2/2g$. However, the narrow pier's will lead to a reduced ratio of d_s/b compared to the wider pier.

Through an experimental investigation, Baker (1980) studied the turbulent horseshoe vortex. In order to visualize the vortex, smoke and oil flow were utilized. According to the results of Baker's experimental study, the vortex's location can be determined by varying the body diameter in relation to the displacement thickness (δ^*) and the

Reynolds number (Re). The range of Reynolds numbers considered in the study was $4000 < Re < 9000$.

Numerous scholars have undertaken investigations pertaining to the influence of the pier Reynolds number (Re). For instance, it was determined by Dargahi (1989) that in the cylinder bridge pier, the number of horseshoe vortices is directly related to the Reynolds number for turbulent flow. In Dargahi's study, the Reynolds number range considered was $6000 < Re < 65000$.

The Reynolds number is the main factor that influences the creation of the horseshoe vortex shape, according to Apsilidis et al. (2010). Within particular limitations, the various kinds of vortex shedding shown in Fig. 2.6 grow with the Reynolds number (which is commonly referred to as the Pier Reynolds number). Fig 2.5 illustrates the variation, as demonstrated by Robert Ettema (2006).

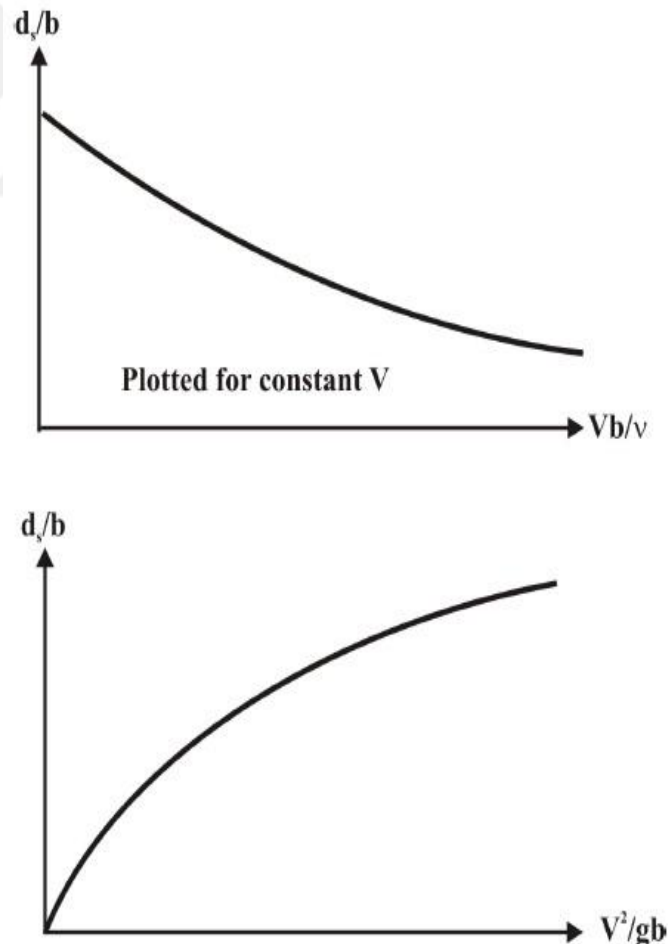


Figure 2.5 d_s/b with large-scale turbulence (Robert Ettema, 2006).

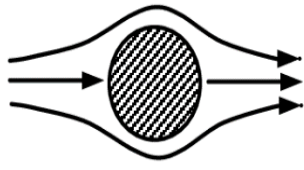
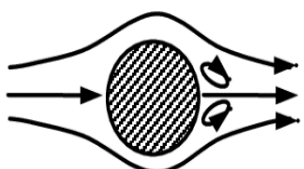
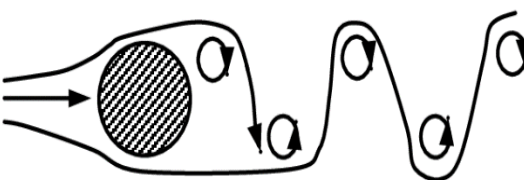
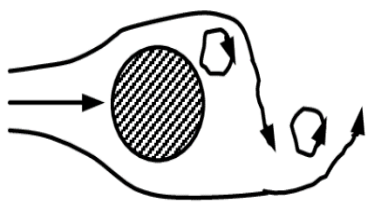
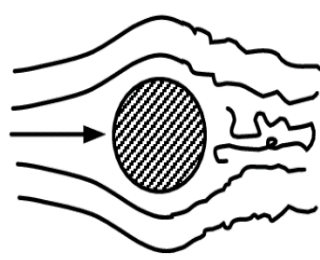
	$Re < 5$	Regime of unseparated flow
	$5 \leq Re < 40$	A fixed pair of vortices in wake
	$40 \leq Re < 90$	Vortex street is laminar
	$90 \leq Re < 150$	Vortex street is laminar
	$150 \leq Re < 300$	Transition range to turbulence in vortex
	$300 \leq Re < 3(10^5)$	Vortex street is fully turbulent
	$3(10^5) \leq Re < 3.5(10^6)$	Laminar boundary layer has undergone turbulent transition and wake is narrower and disorganized
	$3.5(10^6) \leq Re$	Reestablishment of turbulent vortex street

Figure 2.6 Vortex shedding based on the pier Reynolds number (Irvine, 2009).

2.2.2 Structural aspects

The structural characteristics of a pier encompass its shape, size, angle of inclination, orientation, and whether it stands alone or is part of a group.

2.2.2.1 Pier shape

Several researchers have conducted investigations on how the geometry of a pier affects the way local scouring occurs around bridge piers.

A thorough investigation of many experiments by Breusers et al. (1977) indicated that a circular or round-nosed pier, if well-designed, might decrease scour depth by 25%. The effectiveness of this impact is diminished when it is subjected to angles of attack greater than 10° to 15° . By comparison to a reference pier, rectangular piers have the ability to raise the depth of scour by as much as 40%. The local scour depth tends to increase as the pier edges become less defined, according to Ettema (1980) study. In their study, Melville and Coleman (2000) conducted measurements pertaining to the scour phenomenon on different designs of piers. They ensured that the projected width remained constant at 140 mm. According to what was found in the experiments, it is evident that a pier with a circular cross-section results in a small degree of scour, in contrast to a rectangular pier with sharp edges, which causes the most scour. Fig 2.7 illustrates the typical shape of a pier.

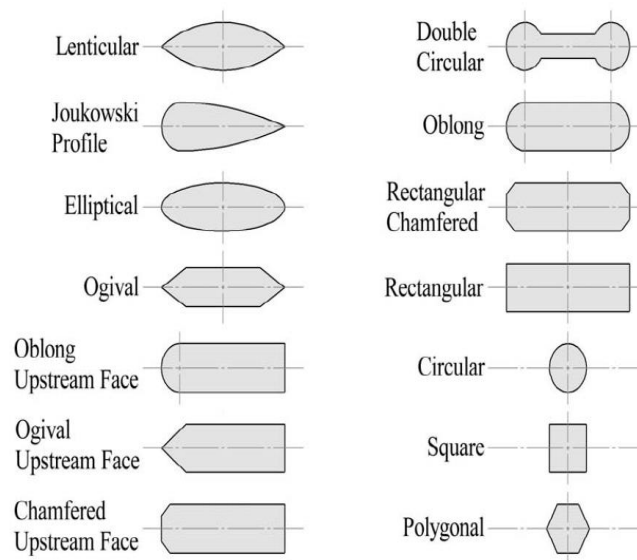


Figure 2.7 Pier shapes (Akhlaghi et al., 2020).

Because it changes the flow patterns and turbulence close to the pier, pier shape has a substantial impact on local scour. Studies have shown that rectangular piers have a tendency to create more turbulent flow patterns and stronger vortices around their corners. On the other hand, piers with circular cross-sections exhibit more streamlined flow patterns and reduced turbulence when compared to piers with rectangular cross-sections (Al-Shukur & Obeid, 2016; Dey & Raikar, 2007; Farooq & Ghumman, 2019; Vijayasree et al., 2019).

2.2.2.2 Angle of Flow Attack

An "angle of attack" is the degree to which the direction of fluid flow is perpendicular to the pier's orientation. Since the effective length of the front segment of the pier increases in direct proportion to the angle of attack, the depth of scour increases as the angle of attack is increased. Near the pier, the distribution of velocities and flow patterns are affected by the attack angle. As the front pier section becomes increasingly effective, the depth of scour increases with an increase in the attack angle. The occurrence and magnitude of flow separation are both impacted by the attack angle. Stronger vortices can form, and flow can be separated at higher angles of attack.

Additionally, Increasing the angles of attack can cause the flow velocity to increase around the outer edges or vertices of the pier. Increased flow velocity can result in higher velocities and a greater vulnerability to scouring in those areas. The available evidence suggests that the angle of attack at bridge crossings can experience substantial fluctuations during flood events in braided channels, while it may undergo gradual alterations over time in meandering channels (Akhlaghi et al., 2020).

Laursen and Toch (1956) proposed attack angle multiplication factors for various pier length-width ratios saw widespread application, which is shown in Fig 2.8.

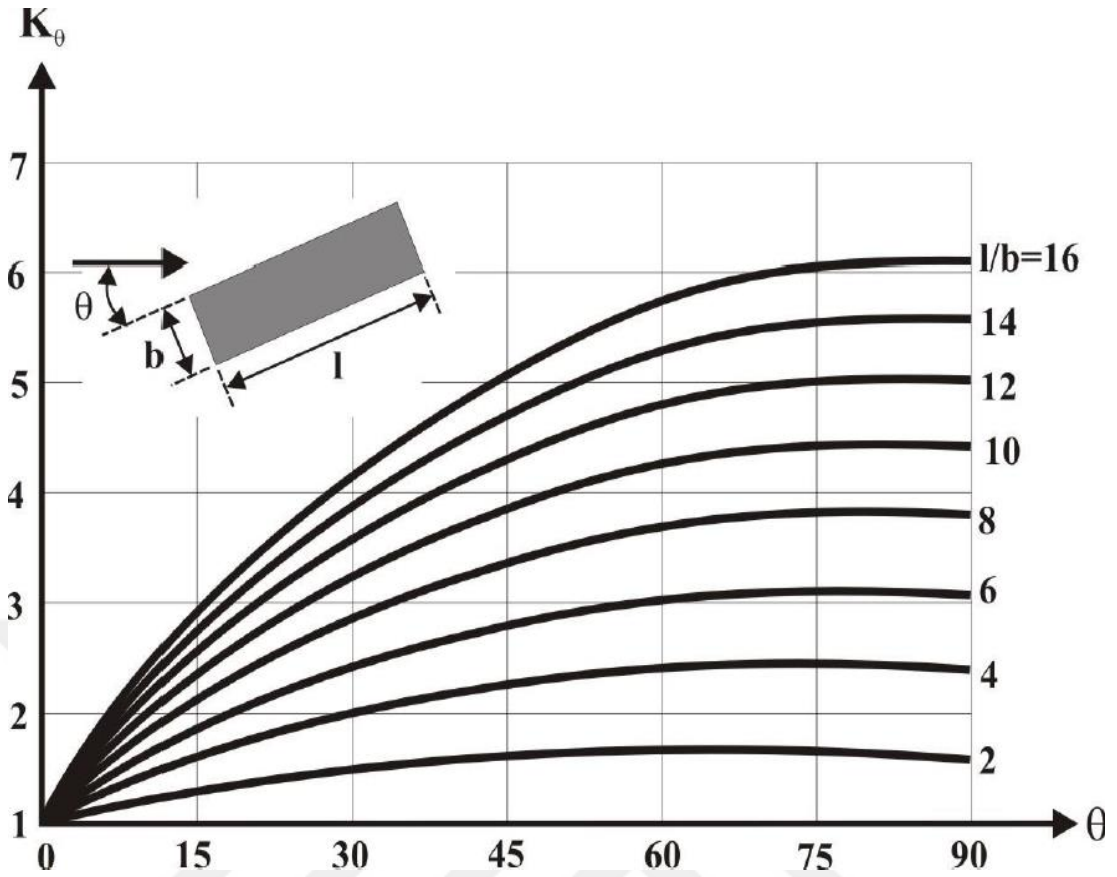


Figure 2.8 Scour depth divergence with pier orientation (Laursen & Toch, 1956).

2.2.3 Geo-tech aspects

The geological aspect is commonly known as sediments. Local scour is a phenomenon that occurs in the bed material due to the influence of various factors. However, the primary element affected by local scour is the bed material or sediments. As a consequence, the movement of these sediments around the pier can lead to its eventual collapse. The dynamic relationship between fluid and sediment results in the transportation of sediments. The two primary modes of transporting sediment are bedload transport (which includes sliding, rolling, and saltating) and suspended load (particles suspended in the stream). This classification is depicted in Figure 2.9. (Pizarro et al., 2020b).

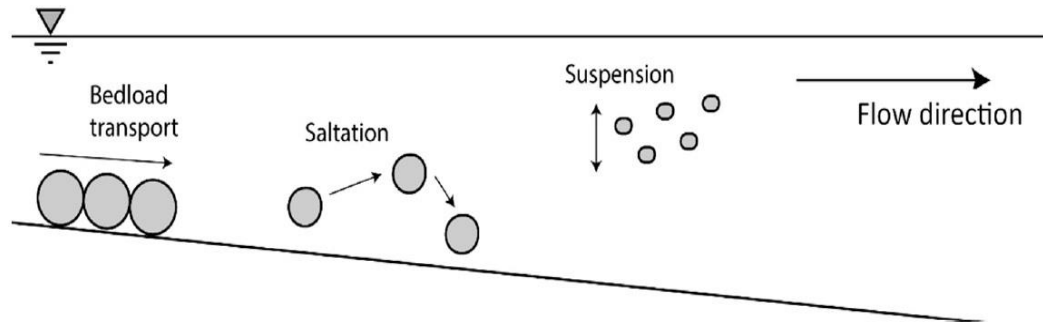


Figure 2.9 Types of sediments transport (Pizarro et al., 2020b).

Since the hydrodynamic forces acting on the sediment particles at the channel bed surfaces are increasing in magnitude as the flow velocity increases, the rate of sediment transport is increasing as well; the sediments begin to move when the hydrodynamic forces surpass their capacity (critical values), the condition of that is called *threshold* or *critical condition*, the mechanism of the sediment transport can be presented by threshold module (Dey & Papanicolaou, 2008). As illustrated in Figure 2.10, there are three forces acting on the particles of sediment throughout their transport: the downward force resulting from their submerged weight (FG), the seepage force (FS), and the hydrodynamic forces (FD and FL) (Dey & Zanke, 2004). The sediment particles' submerged weight is reduced by the seepage forces, which act as extra forces on the particles and between them (Dey & Zanke, 2004).

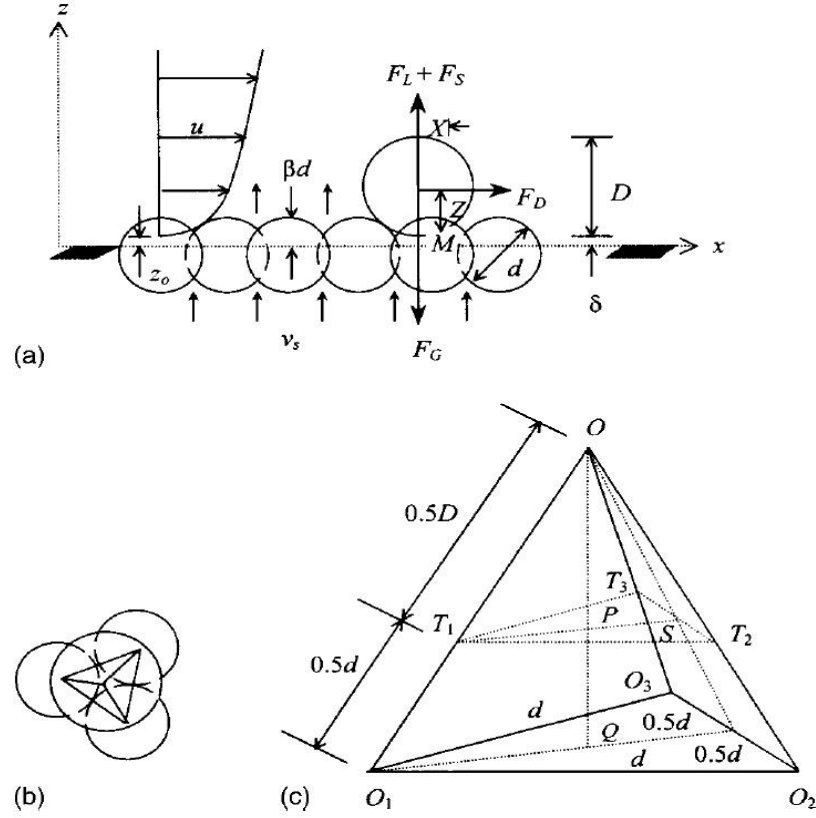


Figure 2.10 a. Acting forces on the sediment particle, b. Top view of the particles, c. tetrahedron formed (Dey & Zanke, 2004).

Yang (1973) presented the formula of the drag force FD , Eq. 2.1.

$$FD = C_D \frac{\pi}{8} D^2 \rho u_d \quad (2.1)$$

where C_D = drag coefficient and u_d = velocity at a distance D above the bed.

Morsi and Alexander (1972) provided the drag coefficient in Eq. 2.2

$$C_D = a + \frac{b}{R} + \frac{c}{R^2} \quad (2.2)$$

Where:

R = flow Reynolds number at the particle level ($u_d D/\nu$), ν the kinematic viscosity of fluid; a , b , and c coefficients dependent on R .

Saffman (1965) proposed the formula of the lift force FL , which results from the velocity gradient in a shear flow called lift due to shear effect FL_s .

$$FL_s = \alpha_L \rho D^2 u_d \left(v \frac{\partial u}{\partial z} \right)^{0.5} \quad (2.3)$$

Where α_L lift coefficient; $(\partial u)/(\partial z)$ velocity gradient; and u = flow velocity at z . The value of α_L proposed by (Chepil, 1958) is $0.85 C_D$.

Rubinow and Keller (1961) presented the lift due to the Magnus effect (FL_m).

$$FL_m = 0.5 \alpha_L \rho D^3 u_d \omega \quad (2.4)$$

Where ω : angular velocity of spinning particle, based on the Saffman (1965) the angular velocity is equal to $0.5 (\partial u)/(\partial z)$.

The formula of the total lift force:

$$FL = FL_s + FL_m \quad (2.5)$$

The seepage force is :

$$F_s = 0.5 \frac{v_s^2}{\rho_0^2} a_e \quad (2.6)$$

where v_s seepage velocity; ρ_0 porosity of sediment particles; and a_e effective area of solitary particle receiving the seepage force.

The submerged weight (FG):

$$FG = \frac{\pi}{6} D^3 (\rho_s - \rho) g \quad (2.7)$$

Where ρ_s the mass density of sediment particles; ρ mass density of fluid; and g gravitational acceleration.

The Shield diagram, as illustrated in Figure 2.11, might be regarded as the standard for sediment movement, as Shields (1936) proved. The condition of the sediment transport can be described in Eqs 2.8, 2.9, 2.10 (Dey & Papanicolaou, 2008; Pizarro et al., 2020b).

$$\phi \geq \phi_c \quad (2.8)$$

$$- \quad \tau \geq \tau_c \quad (2.9)$$

$$V \geq V_c \quad (2.10)$$

Where, The relationship between the critical Shields parameter, denoted as Θ_c , and the Reynold number Re^* is known as the Shield curve. The critical Shields parameter is dependent on the grain size (Pizarro et al., 2020b).

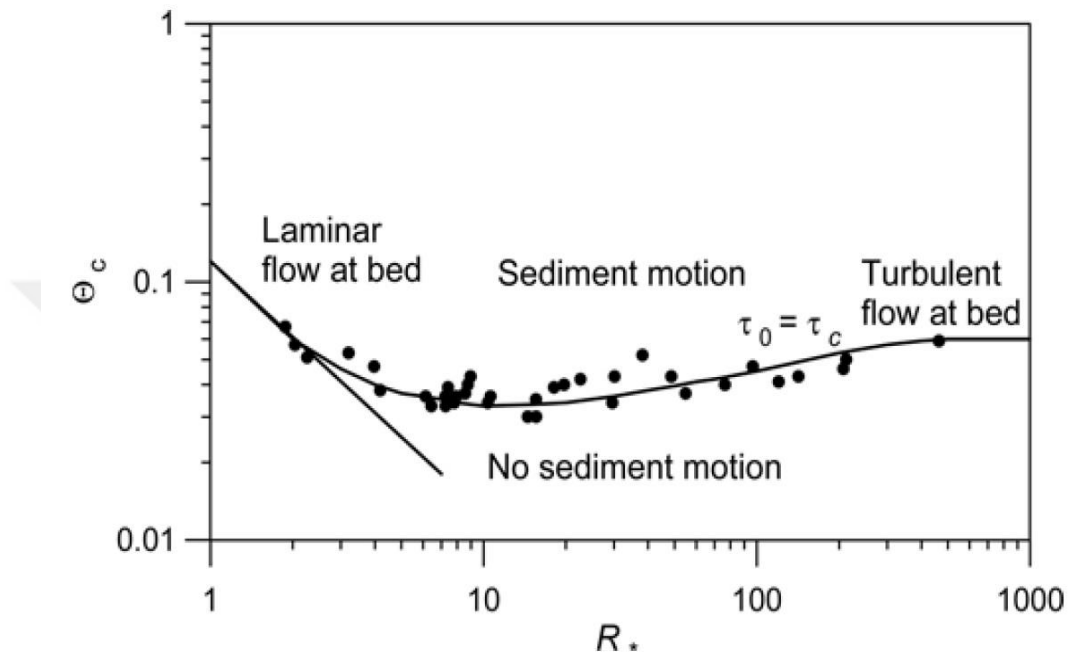


Figure 2.11 Shield diagram.

The impact of sediment characteristics on the magnitude of the local scour has been the subject of numerous studies. Prendergast and Gavin (2014) identified the key characteristics of sediments that need to be examined in order to assess their impact on local scour. These include determining the initiation of sediment particle transport, understanding the interaction between particles, and assessing the effects of sediment characteristics such as particle size, adhesion, soil composition, and degree of saturation.

During the last years, many of the equations have been developed to formulate the critical velocity as listed in Table 2.1.

Table 2.1 Critical velocity equation

Authors	Critical velocity equation		Eq.
(Mavis & Laushey, 1949)	$V_c = 0.5\rho'^{0.5}d_{50}^{\frac{4}{9}}$	d_{50} in mm Vc in ft/s ρ' is dimensionless	(2.11)
(Novak & Nalluri, 1974)	$V_c = 1.6(\rho'gd_{50})^{0.5}$	g & d_{50} in SI unit	(2.12)
(Zanke, 1977)	$V_c = \left\{ 2.8(\rho'gd_{50})^{0.5} + 14.7 \frac{\nu}{d_{50}} c \right\} \frac{\tan(3.09 \times 10^{-4} H^*) + 2.5}{3.5}$	$H^* = \left(\frac{g}{\nu^2} \right)^{\frac{1}{3}} (h - 1)$ All unit is in SI, the effect of viscosity, cohesion, and flow depth are accounted by this equation	(2.13)
(Van Rijn, 1993)	$V_c = 8.5d_{50}^{0.6} \log \left(\frac{12h}{3d_{90}} \right)$	For the sand particles between (0.05-2)mm, when $d_{90} = 2 d_{50}$	(2.14)
(E. Richardson & S. Davis, 2001)	$V_c = 6.19h^{\frac{1}{6}}d_{50}^{\frac{1}{3}}$	For the density of the sediment $\rho_s = 2650 \text{ kg/m}^3$	(2.15)
(Hager & Oliveto, 2002)	$V_c = 2.33D^{*-0.25} \left(\frac{R}{d_{50}} \right)^{\frac{1}{6}} (\rho'gd_{50})^{0.5}$ for $D^* \leq 10$	R Hydraulic Radius D^* dimensionless	(2.16)
	$V_c = 1.08D^{*\frac{1}{12}} \left(\frac{R}{d_{50}} \right)^{\frac{1}{6}} (\rho'gd_{50})^{0.5}$ for $10 < D^* < 150$	sedimentological grain size	(2.17)
	$V_c = 1.65 \left(\frac{R}{d_{50}} \right)^{\frac{1}{6}} (\rho'gd_{50})^{0.5}$ for $D^* > 150$		(2.18)

2.2.3.1 Bed sediment coarseness

The coarseness is the ratio of the median sediment size (d_{50}) to the width of the pier (D). Melville and Coleman (2000) clarified and defined the coarseness limitation (2000). If the width-to-grain-size ratio of the pier is greater than fifty ($b/d_{50} > 50$), then the depth of local scour is unaffected, as per their research. When the ratio D/d_{50} is smaller than 50, which indicates the presence of larger sediment particles, their research reveals that size of the sediment particles affects local scour. In Figure 2.12, we can see this connection graphically. Table 2.2 is the standard for presenting the soil types classification.

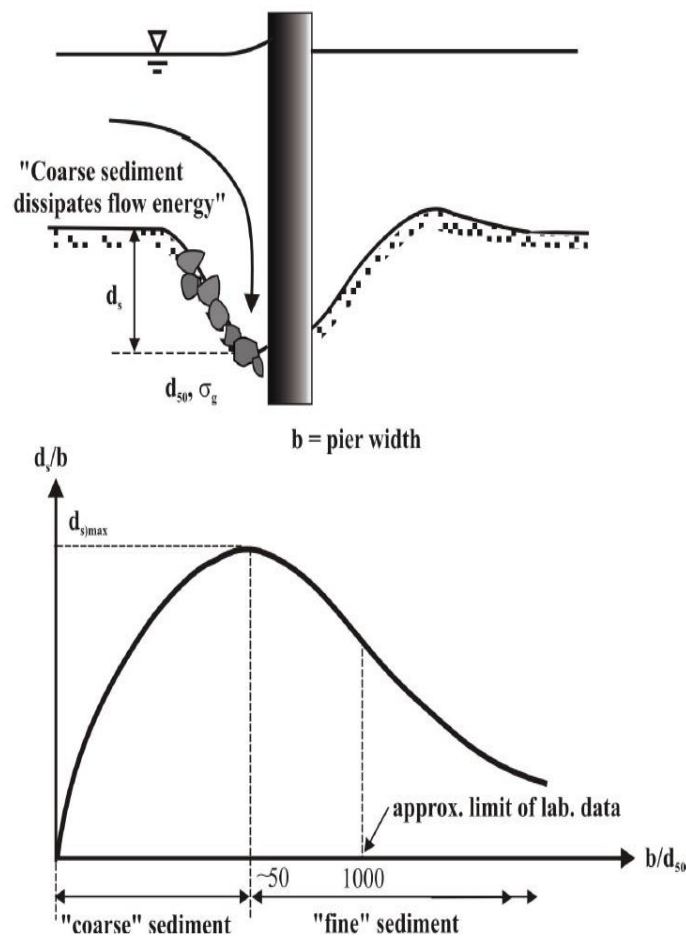


Figure 2.12 The coarseness of the sediments variation and the depth of local scour d_s (MELVILLE, 2008b).

Table 2. 2 The ISO-14688-1: 2017 standard categorizes soil classes based on their d_{50} size.

Granular fractions	Subdivisions	Particle size (mm)
Very coarse soil	Large boulder	$630 < d_{50}$
	Boulder	$200 < d_{50} \leq 630$
	Cobble	$63 < d_{50} \leq 200$
Coarse soil	Coarse gravel	$20 < d_{50} \leq 63$
	Medium gravel	$6.3 < d_{50} \leq 20$
	Fine gravel	$2 < d_{50} \leq 6.3$
	Coarse sand	$0.63 < d_{50} \leq 2$
	Medium sand	$0.2 < d_{50} \leq 0.63$
	Fine sand	$0.063 < d_{50} \leq 0.2$
Fine soil	Coarse silt	$0.02 < d_{50} \leq 0.063$
	Medium silt	$0.063 < d_{50} \leq 0.02$
	Fine silt	$0.002 < d_{50} \leq 0.063$
	Clay	$d_{50} \leq 0.002$

Additionally, Ettema (1980) , if D/d_{50} , the coarseness ratio, is smaller than 50, it means that the individual grains are larger than the excavated groove resulting from downward flow. When this occurs, the erosion is reduced because part of the energy from the downward flow is distributed by the porosity bed. Based on Sheppard et al. (2004) , as illustrated in Fig. 2.9, a high ratio of coarseness values ($D/d_{50} > 50$) may lead to a reduced the depth of local scour. The parameter D/d_{50} might be seen as a

fundamental distinction between field and experimental investigations. According to (Breusers & Raudkivi, 1991; Raudkivi, 1986).the coarseness ratio D/d_{50} does not influence the field depth of local scour.

According to MELVILLE (2008b), it was observed that when the grain size is significantly larger than the width of the pier, particularly when the coarseness ratio D/d_{50} is lower than eight., scouring is likely to occur near the pier. Additionally, it was noticed that under these conditions, the scouring depth reduces.

Lee and Sturm (2009) conducted study where they used three different pier sizes to compare experimental results obtained in the laboratory with field data. The main aim of their study was to examine the influence of sediment size on the phenomenon of local scour. The findings revealed that the coarseness ratio significantly indicates the local scour depth. Specifically, when the ratio D/d_{50} equaled 25, local scour reached its maximum depth. In contrast, a rise in the coarseness ratio resulted in a reduction in the depth of scouring.

2.2.3.2 Sediment size and uniformity

Numerous researchers have conducted studies on the impact of sediment characteristics, including type, size, and uniformity, on scour depth. In the case of cohesionless sediment, such as sand, the scouring process reaches equilibrium relatively quickly, typically within a few hours or a short in duration, depending on the intensity of the event, such as a flood, and the gradual transport of sediment particle by particle. Conversely, cohesive sediment has a scouring mechanism that takes more time to reach equilibrium. Figure 2.13 shows that particles move through the sediment in blocks. In the case of fine sediment, forces between particles can be either electromagnetic or electrostatic. Additionally, the intricate structure of clay hinders the scouring process, which can be considered a significant factor contributing to the disparity in the duration required to achieve equilibrium in local scour. The scouring rate in cohesive soil is expected to be longer in duration when compared to cohesionless soil (Prendergast & Gavin, 2014).

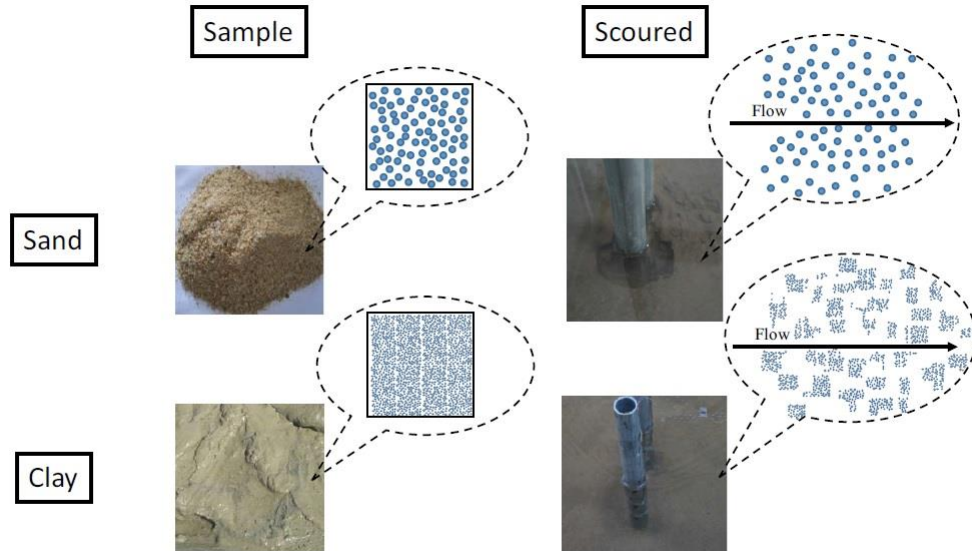


Figure 2.13 The mechanism of local scour based on the soil type (Prendergast & Gavin, 2014; Wang et al., 2017a).

a further variable that impacts the local scour depth is the gradation of sediments, which can be quantified by the geometric standard deviation of sediment grain size (σ_g). This parameter can be calculated using the approach that follows Eq. 2.19 (Liang et al., 2020).

$$\sigma_g = d_{84}/d_{50} = d_{50}/d_{16} = \sqrt{\frac{d_{84}}{d_{16}}} \quad (2.19)$$

Many researchers classified the uniformity of the sediments based on the sediment grain size σ_g as indicated in Table 2.3.

Table 2.3 Sediment classification.

Authors	σ_g Value	Classification
(Dey, 1995)	$\sigma_g < 1.4$	Uniform Sediments
	$\sigma_g > 1.4$	Non-uniform Sediments
(Hoffmans, 1997)	$\sigma_g < 1.4$	Uniform Sediments
	$\sigma_g = 1.8$ /rivers	Non-uniform Sediments

MELVILLE (2008b) summarized the accomplishments of several researchers (Baker, 1986; Chiew, 1984; Ettema, 1976; Ettema, 1980). The graph's zones were categorized according to the particles' resistance to the flow, which is shown by the threshold condition V/V_c . As the value of V/V_c increases, the effect of σ_g decreases, leading to a faster transport of sediment. So, in contrast to non-uniform sediments, uniform sediments will have a greater local scour depth.

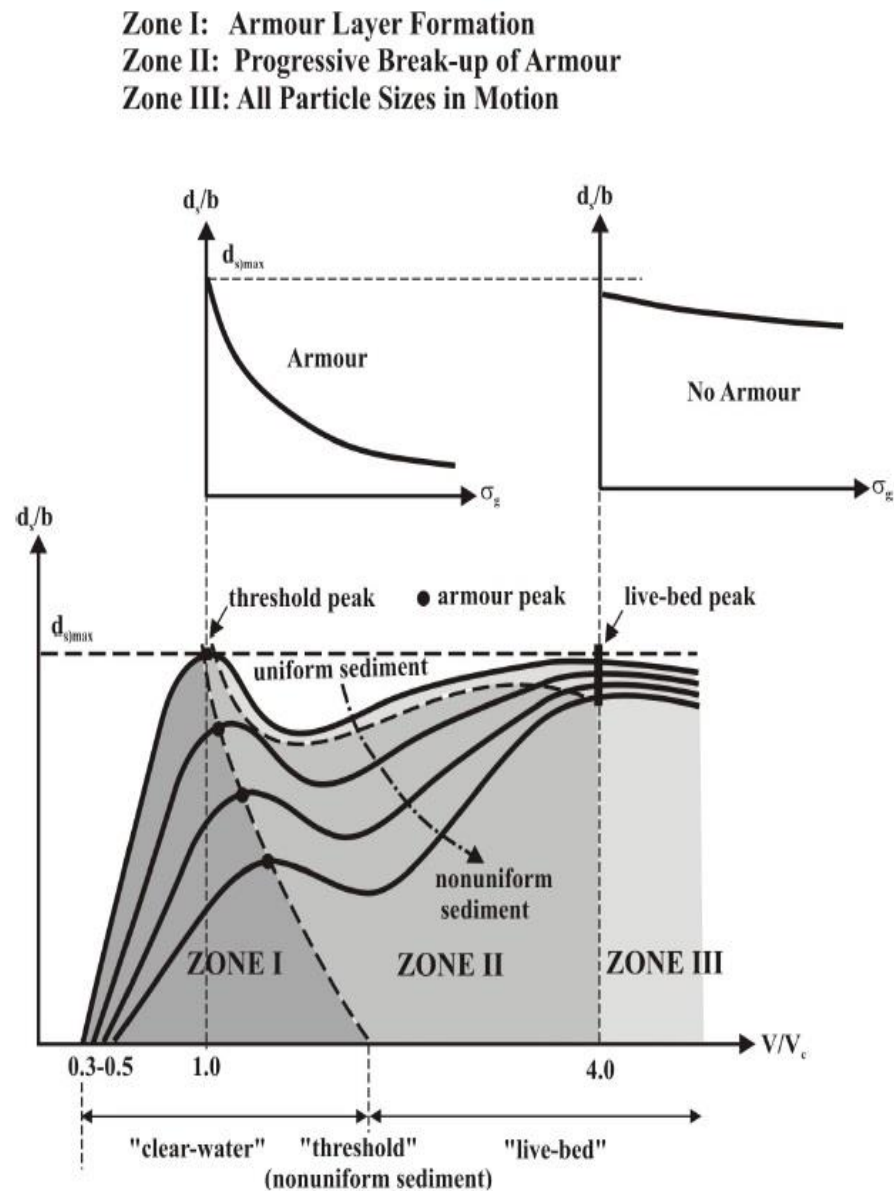


Figure 2.14 Sediment nonuniformity and local scour depth comparing (MELVILLE, 2008b).

2.2.3.3 Effect of the fine particles

Over the past few decades, several academic researchers have conducted experimental studies on local scour, with a specific focus on non-cohesive sediments like sand. Some of the notable studies in this area include those conducted by (Ettema et al., 1998; Melville, 1997; Raudkivi & Ettema, 1983). Previous studies have demonstrated that there are differences in the behavior of local scour between fine and coarse sand in sand beds. Hence, it is crucial to examine three key aspects: (1) the initiation of particle erosion, (2) the destination of particles during transportation, and (3) the interactions between particles. The characteristics of soil can vary based on several factors, including particle size, adhesion, sediment structure, soil composition, and degree of saturation (Wang et al., 2017a).

On the other hand, scour in cohesion beds is a topic of great interest to scholars.

Ruff and Abt (1980) were the ones who first investigated at the cohesive bed. In thier investigation, researchers examined the physical and chemical bonding of particles in addition to complicated (shear strength and shear stress) as mechanical phenomena. Several elements impact the scour process in this environment. These include the amount and kind of minerals, the characteristics of the clay (both microscopic and macroscopic), the amount of water present, the pH and temperature of the eroding water, the thixotropy of the clay, and its consolidation.

Fine-grained soils have particles tightly bound together due to the electromagnetic and electrostatic forces that occur between them. Because of the aforementioned factors, cohesive soil scours at a very moderate rate, and the maximum scour depth may not be achieved for quite some time after the bridge is built (Wang et al., 2017a). The scour hole's angle in cohesive soils can be extremely sharp, often nearly vertical (Molinas & Hosni, 1999; Ruff & Abt, 1980). The fine particles, which are known as cohesive sediments, can be categorized as either clay or silt and have a particle size of less than 36 μm (Debnath & Chaudhuri, 2010a).

The particles of mineral clay have a flat shape and display electronegativity on their surface. When the terminal atoms located on the edges of the lattice are not completely charge neutralized, it leads to an imbalance of charges. The presence of exchangeable

ions, mainly cations, helps to maintain their external equilibrium. The phenomenon of cation exchange holds significant importance in the fields of soil physics and soil chemistry (Molinas & Hosni, 1999).

The categorization of water in clay is determined by the intermolecular forces present between the soil and water. Three different kinds of water are found in clay: adsorbed water, double-layer water, and free water. The soil has a high capacity for retaining adsorbed water, while the double layer water refers to all the water molecules attracted to the soil. On the other hand, free water is water that does not show any attraction to the soil. In cohesive soils, the main component that controls erosion is the interaction between clay particles and water (Sonia Devi & Barbhuiya, 2017).

Debnath and Chaudhuri (2010b) presented two contrasting viewpoints on cohesive sediment movement. The first perspective suggests that cohesive sediments do not have erosion thresholds and that some particles are vulnerable to erosion regardless of the bed shear stress, as noted by (Lavelle et al., 1984; Parchure & Mehta, 1985). Nevertheless, according to the second perspective, there are erosion thresholds for cohesive sediments as supported by various studies (Amos et al., 1992; Kothiyari & Jain, 2008; Ravens & Gschwend, 1999; Tolhurst et al., 2000).

In reality, the materials used for bedding are not limited to sand or clay alone. Observations in the field indicate that the ocean floor can contain fine sand or silt particles with varying densities. Relatively large-particle cohesive soil and sand make up the bulk of the Yangtze River estuary's bed components, as shown in Figure 2.15, according to statistical data from China. Yellow River Delta bed materials, on the other hand, are mostly clay and silt (Wang et al., 2017a). Moreover, in Turkey, the Filyos River estuary consists of cohesive soil and sand (Kaya et al., 2007), as shown in Fig 2.16.

As a consequence, researchers are currently investigating the effects of adding fine particles into sand and its impact on the scour behavior. The objective of these studies is to determine how this mixture affects the rate of erosion in the area and how long it takes to reach stability.

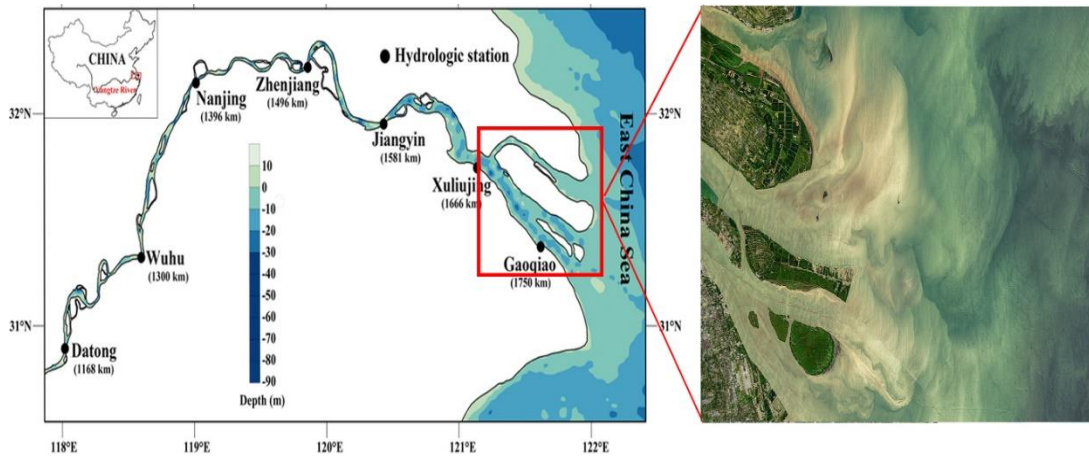


Figure 2.15 Yangtze River estuary, the source of the photos (Yu et al., 2020) and (Webmaster, 2020)

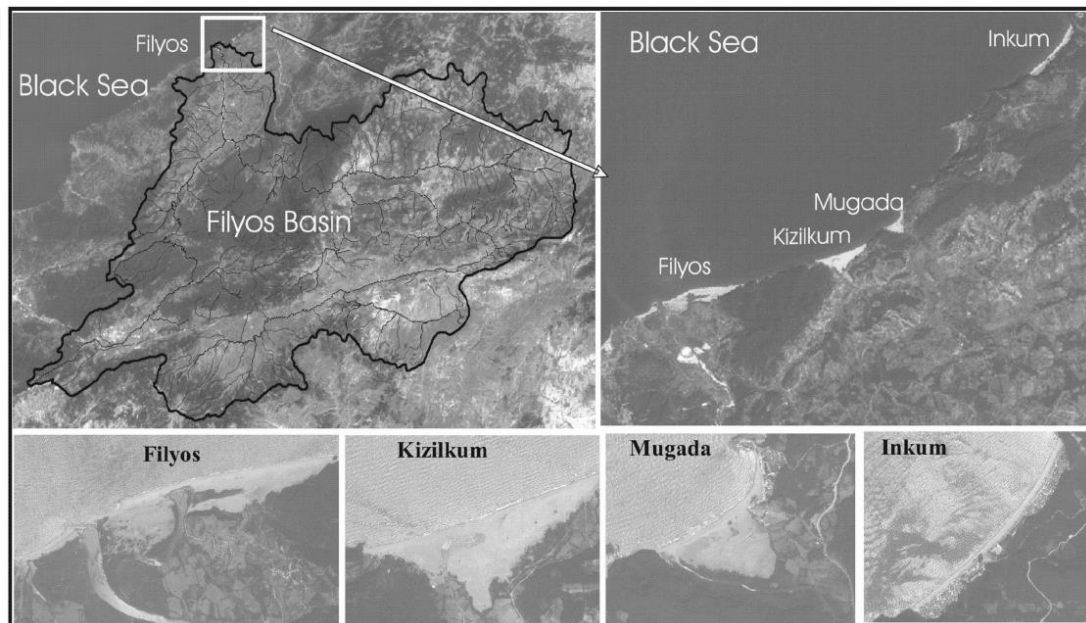


Figure 2.16 Filyos River estuary (Kaya et al., 2007).

In 1999, (Molinas & Hosni) conducted 39 experiments to examine the impact of combining sand and clay. The mixtures of clay and sand contained different amounts of C_p (Clay ratio), which ranged from 0% to 40% based on the dry weight of the mixture. The sand had a median diameter (d_{50}) of 0.55 mm.. Furthermore, the following factors were being studied in the case of the pier scour is primarily influenced by various factors related to the mixtures of clay-sand, including degree of saturation, , shear strength, compaction, initial water content, and flow conditions. Studies have shown A lower clay fraction or percentage clay (C_p) is associated with a

higher maximum scour depth (d_s), based to the studies. The duration required to reach d_s (t) expands in direct proportion to the value of C_p .

Furthermore, Ansari et al. (2002) conducted a study on the occurrence of local scour around a pier in a clay-sand mixture. They conducted several experimental runs with varying clay ratios (C_p) and water ratios, and compared their findings to the findings of a cohesionless bed under the same conditions. A significant correlation was found between the water concentration prior to scouring and the position of the deepest scour in cohesive sediments. During the experiments, it was observed that scouring began at the sides of the pier and moved upstream towards the pier nose for a range of $0.05 < C_p < 0.1$. Similar behaviour was observed for C_p values between 0.2 and 0.4, whereas for C_p of 0.5, the behaviour differed.

Debnath and Chaudhuri (2010a) and Debnath and Chaudhuri (2010b) conducted an experiment to examine the impact of a mixture of clay and sand on the erosion of the surrounding area. The study investigated at how several variables including clay fraction, water concentration, and size of sand affected scouring process, scouring shape at equilibrium, scouring depth at equilibrium, scouring process duration, and scour fluctuation over time. According to the results, the scouring process, the scour hole form, and the maximum depth of scour equilibrium are primarily influenced by the clay and water content. Various methods for removing sediment from the scour hole were noted; these included utilizing large amounts of aggregate, removing aggregates separately, and removing particles one by one. Using finer sand in clay-sand beds resulted in a deeper scour than using coarser sand. Nevertheless, the observed disparities did not reach statistical significance. Figure 2.17 displays the testing conditions and the measured local scour.

Debnath and Chaudhuri (2012) examined how the local scour level in mixed beds varied depending on the pier's shape. According to the findings, round-nosed piers have a lower maximum equilibrium scour depth, d_s , compared to square and rectangular piers with the same bed material properties. In contrast, d_s values were greater for square and rectangular piers than for circular piers. Shape factors varied between certain ranges. And the correction factors are not constant values. Some findings are shown in Fig 2.18.

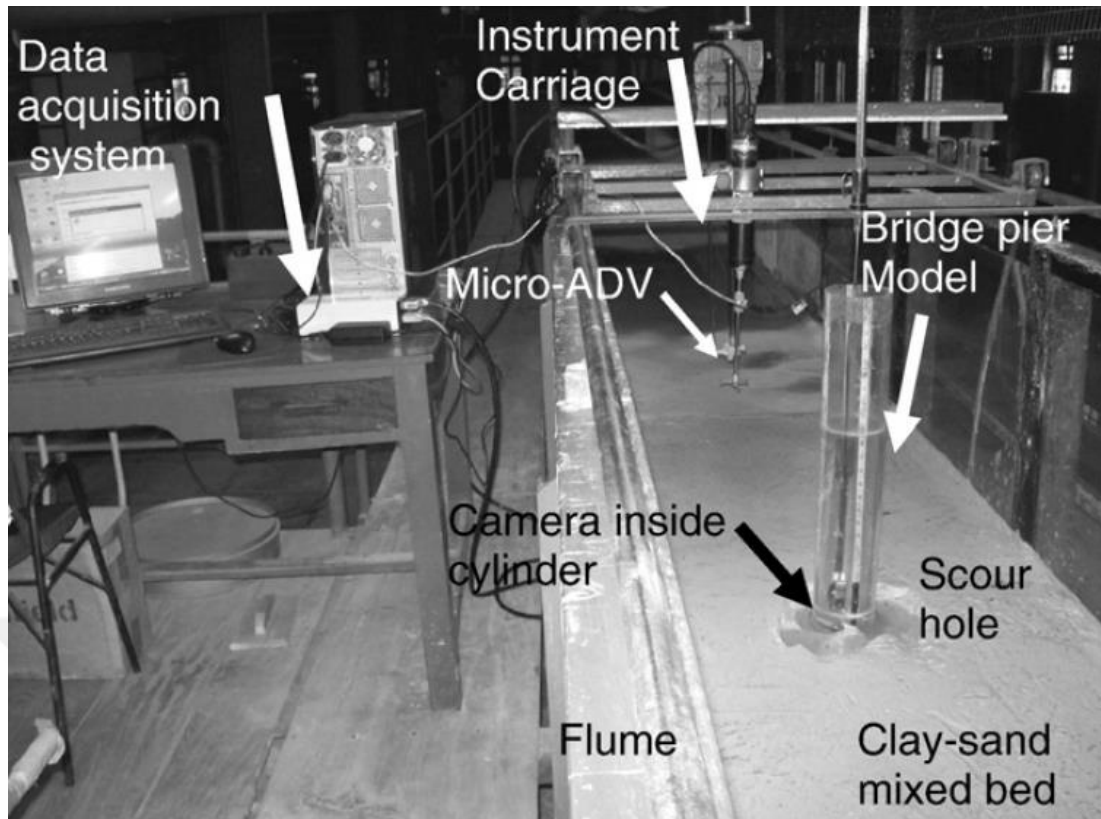


Figure 2.17 The experimental setting and observed scour (Debnath & Chaudhuri, 2010a).

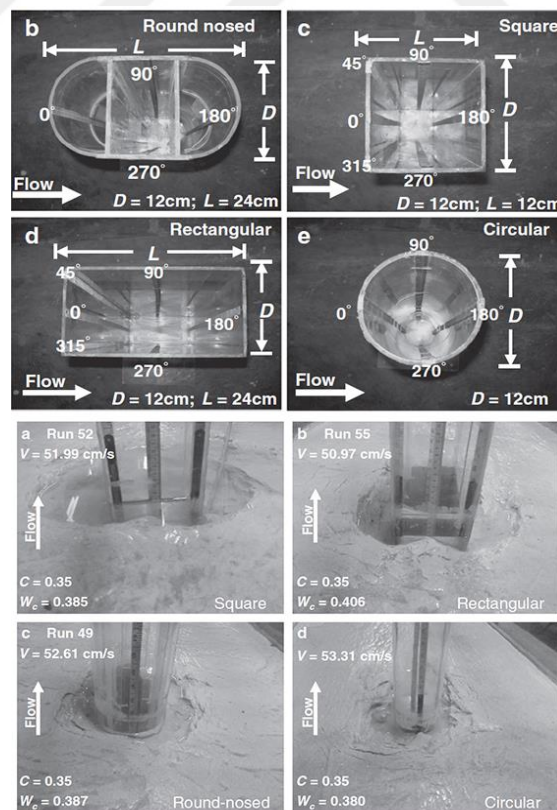


Figure 2.18 Scour around different shapes of the pier in the clay-sand bed (Debnath & Chaudhuri, 2012).

(Chaudhuri & Debnath, 2013) carried out a study on the impact of mixing clay with sand in various pier shapes under different hydraulic conditions and varying clay percentages. Under identical bed and hydraulic conditions, according to the research, the local scour depth was lower for the circular pier compared to the square pier type. It was found the deepest local scour on the round pier's sides and the square pier's front corners. Researchers discovered that a higher clay ratio resulted in less local scour. The local scour increases as the ratio is further raised, as shown in Figure 2.19, after reaching a 0.5 fraction of clay.

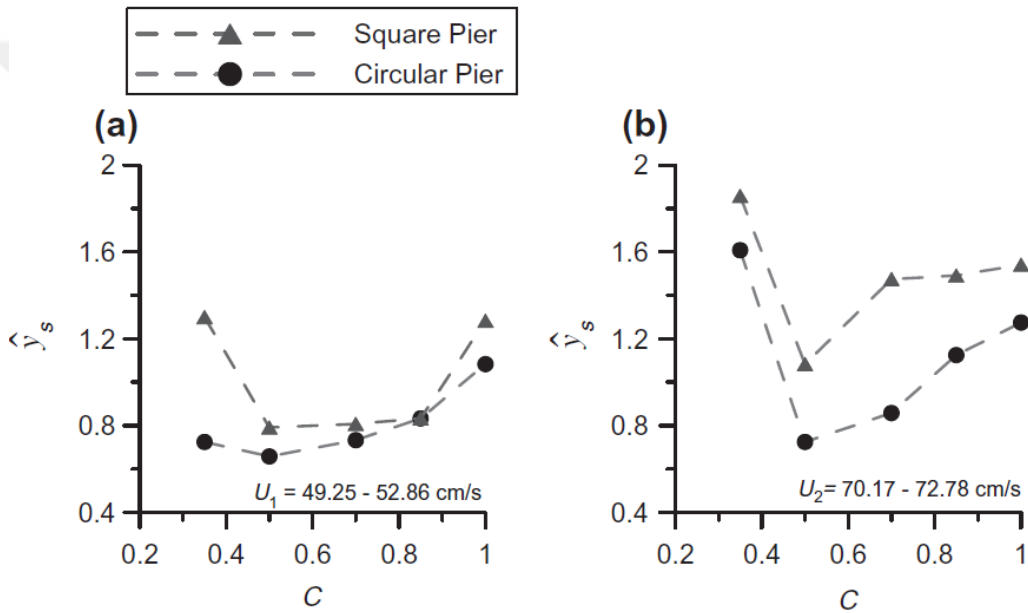


Figure 2.19 Local scour depth based on the clay ratio (Chaudhuri & Debnath, 2013).

Das et al. (2022) examined local scour in mildly cohesive silt mixed with fine sand, under varying pier shapes (circular and square). According to the results, the local scour depth was highest when a square pier was used and greater with increasing water velocity. Additionally, ripples with different crystal patterns, ranging from sinusoidal to languid, lunate, catenary, and straight crested parallel, were observed with varying concentrations.

An research was conducted by Chaudhuri et al. (2022) to investigate the effect on the local scour hole volume of varying percentages of clay mixed with fine sand and medium sand.. The results demonstrated that the local scour hole may be more

effectively reduced by combining clay with medium sand particles, in contrast to the mixture of clay and fine sand.

2.2.3.4 Effect of particle densimetric Froude number

The particle densimetric Froude number Fr_0 is a dimensionless parameter that is utilized in fluid dynamics to describe the motion of sediment-laden flows, particularly in rivers and coastal regions. This equation describes the relationship between the inertial forces of a fluid and the gravitational forces acting on sediment particles that are suspended within the flow. The initial motion of sediments, as suggested by several researchers. It has been established that Fr_0 is an effective indicator of sediment transport, as noted by Aguirre-Pe et al. (2003). Furthermore, Fr_0 is the interplay between the inertial force exerted on individual particles and their specific weight while submerged is a crucial factor, it is one of the main factors of the local scour and governing the bridge pier scour depth (Hager & Oliveto, 2002; Williams et al., 2016). The calculation of the particle densimetric Froude number Fr_0 can be done by utilising Eq. 2.20.

$$Fr_0 = \frac{V}{\sqrt{(S_s - 1)gd_{50}}} \quad 2.20$$

When V : mean flow velocity, S_s : The specific gravity of sediment = $(\rho_s)/\rho$, g : Gravitation acceleration, d_{50} = The median particle size.

The densimetric Froude number has an influence on the deepest level of scour that can be anticipated. Deeper scour depths are typically associated with higher Froude numbers. The reason for this is that when the Froude number is higher, it indicates that gravitational forces are relatively stronger compared to inertial forces. As a result, the flow has greater erosive power.

2.2.4 Time

It is crucial to determine the duration required to achieve the final stage of local scour, known as the equilibrium phase. This duration depends on several parameters that have been previously discussed and affect local scour.

In this section, we will discuss the local scour time according to the type of bed sediments. The different types we will consider are non-cohesive sediments, cohesive sediments, and sand-clay/silt mixtures.

Predicting the exact time of local scour is a complex duty that relies on various factors. Empirical formulas and mathematical models are commonly employed to estimate scour depth and predict the rate at which scour develops over time. However, it is crucial to acknowledge that these models are usually developed based on typical conditions and may not accurately capture the intricate dynamics of scour.

The scouring process has an asymptotic pattern in non-cohesive instances. The depth of scour reaches a point of equilibrium under situations of clear water scour. With a live-bed circumstances, it may reach to the equilibrium depth faster. However, the scour depth then fluctuates as a result of the movement of bed features passing by the pier or abutment; experimentally, the clear water may take more than one day to reach the equilibrium phase (Melville, 2008a).

Fig 2.20 depicts the summary and conclusion of experimental studies conducted by Chiew and Melville (1996); (Melville & Chiew, 1999) under clear-water conditions. The figure clearly shows that as the ratio between the mean and critical velocities decreases, the time taken to reach equilibrium also decreases.

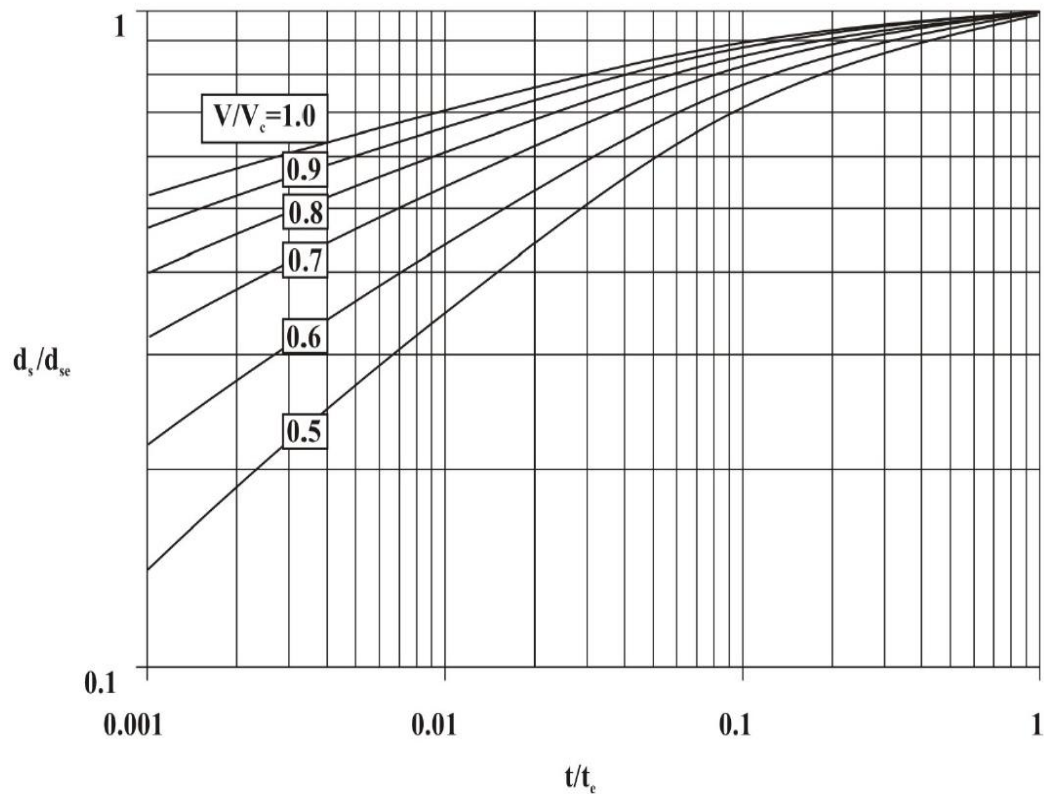


Figure 2. 20 Developing the local scour with time in clear-water conditions (Melville, 2008a).

The time of local scour increases as the flow becomes shallower, indicated by the h/D ratio. Conversely, the impact of this effect is reduced in deeper flows. The relationship between sediment coarseness and time is such that as the D/d_{50} ratio increases, the coarseness of the sediments increases and the time decreases. In other words, when the sediments are coarser, the time required is less compared to when the sediments are fine (Melville, 1997). Figure 2.21 demonstrates the impact of both factors and the relationship between them.

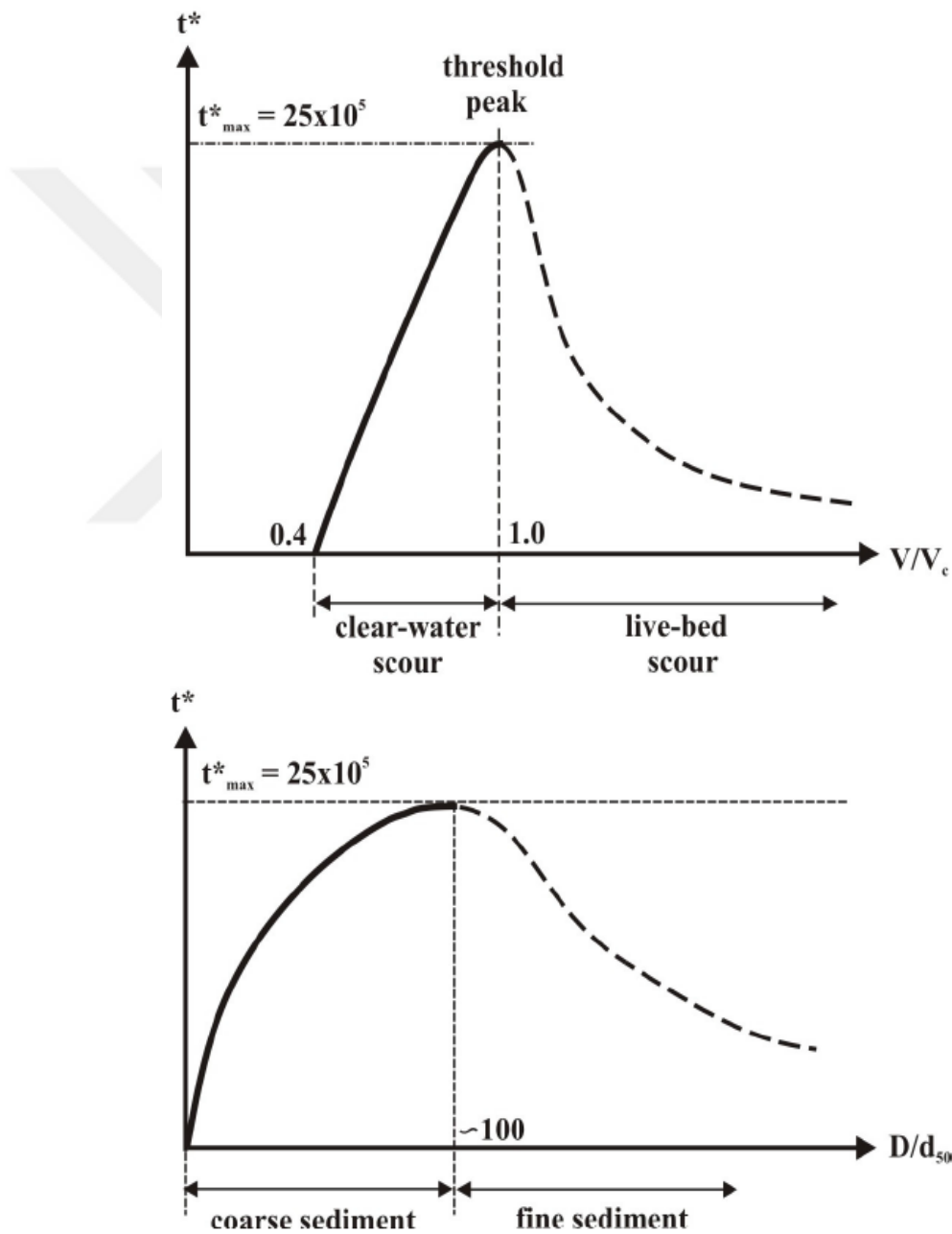


Figure 2. 21 Effect of the time and flow shallowness, sediment coarseness (Melville, 2008a).

In the context of cohesive sediments, numerous investigations have shown that clay exhibits less scour than sand. In addition, the equilibrium scour depth occurs at longer intervals for larger piers, resulting in a more significant scour phenomenon. Conversely, smaller piers exhibit a reduced interval to achieve the equilibrium scour depth. Furthermore, it has been observed that the system reaches a state of equilibrium more quickly at lower flow velocities in comparison to higher flow velocities. Additionally, it has been observed that higher flow velocities lead to more pronounced scour phenomena (Rambabu et al., 2003; Sonia Devi & Barbhuiya, 2017; Ting et al., 2001).

In the case of a sand-clay bed, it will take more time to reach equilibrium local scour compared to a sand bed. This is due to the change in the mode of the local scour. According to Debnath and Chaudhuri (2010a), the time increases as the clay fraction increases. The most severe rate occurs in the initial stage of time, typically within the first hour.

2.3 Local Scour Prediction

Local scour prediction involves estimating or calculating the extent and pattern of erosion, that can occur near bridge piers. The occurrence of scour can pose a threat to the stability of these structures, highlighting the importance of accurately predicting and understanding scour for engineering design and maintenance purposes. Here are some commonly used techniques for predicting local scour:

2.3.1 Empirical equations

Empirical equations are derived from observations and measurements obtained through field studies and laboratory experiments. The equations establish a relationship between scour depth and different hydraulic and geometric factors, including flow velocity, sediment characteristics, and structure dimensions. As well as, laboratory scour studies employ physical scale models. Scour behavior can be studied by scientists through the development of a scaled-down hydraulic structure, which is then observed under controlled settings. Scale models can be used to verify empirical equations or establish prediction correlations. Several of these equations are given in Table 2.4.

Table 2.4 Formulas for local scour.

Reference	Equations	Eq. No.
Eq. 3 of (Raeisi & Ghomeshi, 2020)	$\frac{d_s}{D} = 0.8 Fr_0^{0.5} - 0.5$	2.21
Eq. 8 of (Raeisi & Ghomeshi, 2020)	$\frac{d_s}{D} = 1.25 Fr_0^{0.4} - 1.3$	2.22
HEC- 18/Jones Equation (E. V. Richardson & S. R. Davis, 2001)	$d_s = 2hK_1K_2K_3K_4 \left(\frac{h}{D}\right)^{0.65} Fr^{0.43}$	2.23
HEC- 18/Mueller Equation (Mueller, 1996)	$d_s = 2hK_1K_2K_3K_4 \left(\frac{h}{D}\right)^{0.65} Fr^{0.43}$ With modified K_4	2.24
Clay- Sand bed/(Debnath & Chaudhuri, 2010a)	$ds = 8.2Fr_p^{0.79}C_p^{-0.28}W_c^{0.15}\tau_s^{-0.38}$	2.25
Clay- Sand bed/(Molinas et al., 1999)	$\frac{d_s}{D} = 18.92 \left[\frac{Fr^{2.08}}{(1 + C_p)^{1.88}} \right]$	2.26
Clay- Sand bed/(Kho et al., 2004)	$d_s = 0.0044 Re_p^{1.0234}(1 + C_p)^{0.5}$	2.27

* K_1 represents the factor of correction for the shape of the pier, K_2 represents the factor of correction for the flow direction, K_3 for the coarse bed's armoring factor of correction (Mueller, 1996; E. V. Richardson & S. R. Davis, 2001). C_p is Clay ratio, W_c Water content, Fr_p Pier Froude Number, Re_p Pier Reynolds number.

2.3.3 Artificial Intelligence and Machine Learning:

Artificial Intelligence (AI) and Machine Learning (ML) methods can potentially improve the accuracy of local scour prediction. By analyzing large datasets that include scour measurements and related parameters, artificial intelligence (AI) and machine learning (ML) algorithms can identify patterns and correlations that may not be easily detectable using traditional methods. These techniques can potentially improve the accuracy and reliability of predictions, especially in scenarios that involve complex or non-linear scour phenomena. Numerous researchers have employed various methodologies in the field of machine learning, such as Artificial Neural Networks (ANN) (Choi & Cheong, 2006; Dheyab & GÜNAL, 2024c), Adaptive Neuro-Fuzzy Inference Systems (ANFIS) (Choi et al., 2017; Daneshfaraz et al., 2022; Muzzammil, 2010), Support Vector Machines (SVM) (Choi & Choi, 2022; Najafzadeh et al., 2016; Nassar et al., 2009), (Firat & Gungor, 2009) the Generalized Regression Neural Networks (GRNN).

Pizarro et al. (2020a) stated that machine learning algorithms have not been widely utilized in engineering practice, despite their potential for producing promising results. This is primarily due to the significant amount of data that is necessary for training and validation purposes. The high cost of computation and the challenges associated with accurately simulating real-world situations have limited the widespread use of numerical methods in engineering practice.

According to the proof as a whole, methods of machine learning display significant predictive capacities for the local scour depth. Nevertheless, careful thought must still be given to certain aspects, such as data collection methods, data standardization or dimensionality reduction techniques, and the selection of variables.

2.3.2 Numerical modeling

Numerical modeling, specifically Computational Fluid Dynamics (CFD) models, are utilized more frequently to simulate intricate flow patterns around hydraulic structures and predict scour. The simulations currently use numerical methods to solve fluid flow and sediment transport governing equations. CFD models necessitate comprehensive data regarding the aftermentioned variables of the local scour, hydraulic, structural, and hydraulic conditions (Alasta et al., 2022; Dheyab & GÜNAL, 2024a; Gaydarov et

al., 2014; Jalal & Hassan, 2020; Richardson & Panchang, 1998; Salaheldin et al., 2004), Fig 2.22 shows an example of the CFD local scour model. There is another methodology used by another group of researchers Yang et al. (2018) that combines CFD and the Discrete Element Method (DEM). Combining these approaches, especially for sediment transport, improves scour simulation. DEM's particle-scale scour mechanism analysis is its strength. It effectively captures the interconnected force chains between particles and their motion. The linked fluid-particle model simulates the continuum fluid phase using FEM. DEM effectively represents the discrete solid phase in this model (Bierawski & Maeno, 2006; Wang et al., 2017a).

Modeling using particles can be challenging. Calibration may be necessary for simulations. Simulations depend on theoretical assumptions, which are often subject to questioning and criticism when employed to estimate scour depth. Improvements in numerical simulation are necessary to accurately predict local scour (Wang et al., 2017a)

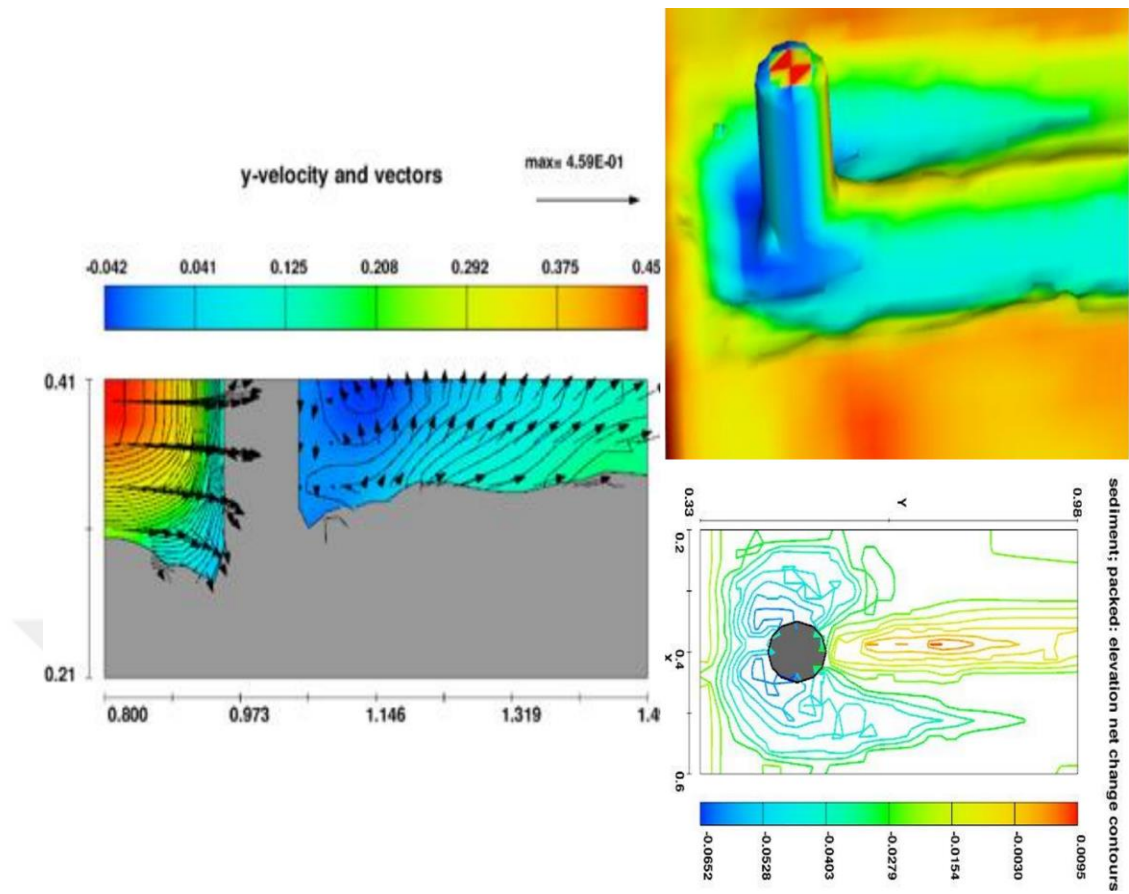


Figure 2. 22 Example of the CFD local scour model (Alasta et al., 2022)

2.4 Nano Materials

Nanomaterials possess unique properties and behaviors that differ from those observed in larger-scale materials. Nanomaterials have the unique ability to be intentionally designed and controlled to display specific properties. This makes them highly versatile and valuable in various fields. A wide variety of nano materials are used in many engineering fields, such as construction materials, electronics and optics, energy storage, and environmental engineering (Norhasri et al., 2017).

There are many kinds of nanomaterials, which include nanoparticles, nanotubes, nanowires, nanocomposites, and nanofilms.

2.4.1 Nano clay

Nano clay refers to nanoparticles that are comprised of layered mineral silicates. Nanoclays can be categorized into many classes, such as montmorillonite, bentonite, kaolinite, hectorite, and halloysite, according to their chemical composition and nanoparticle form. And it is inexpensive materials, Nanoclay, specifically montmorillonite, is a type of deposit that stands out due to its unique structural morphology, which is characterized by platelets. The deposits mentioned above have an average thickness of 1 nanometer and a width that ranges from 70 to 150 nanometers. Montmorillonite clay possesses a unique composition that showcases several characteristics, making it an excellent substrate for manipulation in the field of nanotechnology. The attributes mentioned above include stability, the existence of an interlayer space, a significant ability to absorb water and expand, and an increased level of chemical reactivity (Norhasri et al., 2017). Figure 2.23 illustrates the structure of montmorillonite. The composition of this material includes layers of silicate that surround a layer of aluminum oxide/hydroxide ($\text{Al}_2(\text{OH})_4$). The unique composition of montmorillonite clay possesses various characteristics that render it an ideal substrate for manipulation in the field of nanomaterials. The material's stability, interlayer space, high hydration and swelling capacity, and strong chemical reactivity were among the notable features identified by Norhasri et al. (2017). It serves as an additive in paints and rubbers, a substance that increases flexibility in molding sands, a component of drilling muds, and a material that provides resistance to electricity, heat, and acid in porcelain (Uddin, 2008).

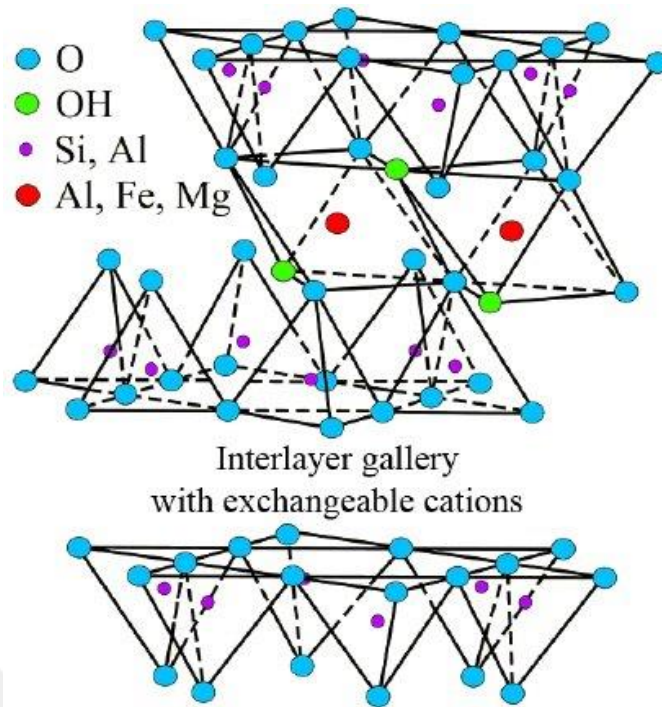


Figure 2.23 The montmorillonite structure (Steinmetz, 2007).

2.4.2 Nano Silica

Nano silica is a type of nanomaterial that stands out due to its extremely small particle size, which is typically measured in nanometers. This attribute gives the material unique properties. The production process entails reducing the particle size of silica fume or micro silica from a micro-scale to a nanoscale. Reducing the size of particles results in a significant increase in surface area. This increase in surface area allows for the effective adsorption and immobilization of harmful ions, particularly chloride ions. As a result, this improves the ability to resist corrosion. The product offers improved durability and increased resistance to corrosion (Norhasri et al., 2017).

2.4.3 Application of nanomaterials

Nanomaterials are frequently used in a variety of ways to improve the qualities of soil, grout, and building materials. Their use in hydraulic operations is, however, very limited (Dheyab & Günal, 2024b).

Ghasemi et al. (2018) conducted a study to demonstrate the promising potential of using nano-clay in floor sediments. The aim was to effectively reduce scour depth around bridge piers. The valuable insights gained from observing significant

reductions in both steady and unsteady flow conditions provide useful information for integrating nano-clay into hydraulic engineering applications. Further research can be carried out to explore the optimal concentration and application techniques for maximizing the benefits of nano-clay in mitigating scour phenomena. The trials also determined the minimum reduction in scour depth that could be achieved, which was 41.6% for steady flow and 56% for unstable flow. The findings highlight that nano-clay consistently reduces scour depth regardless of the flow regime. In this investigation, we utilized nano clay with a micro size ($d_{50} > 6\mu\text{m}$). The mixing method employed was a dry method based on volume.

Tabarsa et al. (2018) conducted a study to explore the possible application of nano clay, an engineered nanomaterial, for efficiently stabilizing loess soil. The study involved conducting a series of laboratory and field experiments at the irrigation channel of Gonbad dam.

In the laboratory, various amounts of nano clay were added to natural loess soil, ranging from 0.2% to 3% by mass. The study's objective was to evaluate the effects of nano clay stabilization. Various tests were conducted on representative samples, including Atterberg limits, standard Proctor compaction, unconfined compressive strength, unconsolidated undrained triaxial compression, wetting-induced collapse, and pinhole dispersivity.

The experimental findings showed that the specimens underwent significant plasticity, strength, and stiffness changes when mixed with nano clay. In addition, the presence of nano clay affected the dispersal properties and behavior of natural loess soil when subjected to wetting-induced collapse.

A field study examined the effectiveness of nanoclay in enhancing the properties of loess soil at a specific location along the irrigation channel. The initial pilot study showed significant improvements in stabilizing loess soils by adding 2% nano clay. The results obtained from both the lab and the field showed a strong level of consistency and agreement.

Tabarsa et al. (2018)'s research offers valuable insights into the potential use of nano clay for stabilizing loess soil effectively. The apparent improvements are evident in both controlled experiments and real-life situations.

By conducting a series of small-scale laboratory investigations, Ibrahim et al. (2022) examined the efficacy of adding varying volumes of silica fume nanomaterial to non-cohesive (alluvial) bed soil. The objective was to establish a distinctive composition of bed material that might efficiently mitigate the development of local scouring resulting from high-velocity jets downstream of a sluice gate. The studies encompassed 9 different jet Froude values, spanning a range from 1.88 to 2.81. The Froude numbers were paired with three distinct gate opening heights and three distinct tailwater depths.

The bed material was composed of five different weight percentages of Silica fume. Two mixing methods were used: one with water and one without water. A total of 99 experiments were conducted, which included 9 cases where fine sand was used as the bed material for comparison purposes. Graphical visualizations were employed to highlight the furthest depths of scouring and silting under varying hydraulic circumstances and Materials for the bed. The findings of study showed that scouring was significantly affected by choosing between dry and wet-mix procedures, even when the flow conditions and Silica fume proportion were kept constant. As the concentration of silica fume in the dry mixture increased the depths of scour also increased. In contrast, when the amount of Silica fume increased, the scouring depths decreased in wet-mix circumstances. The results demonstrated that wet-mixing considerably decreased settling volumes by 89.52% and 33.35%, as well as local scour volumes by 83.15%. The extent of these reductions depended on the fraction of Silica fume used. It is worth mentioning that when a bed containing 8% Silica fume in the wet approach was used, there was a significant reduction in scouring volume by 83.05% and silting volume by 89.42% compared to using pure sand as the bed with fine size. The proposed bed material composition can be a practical and cost-effective alternative to a smooth apron. It could end up shortening the smooth apron's length or even replacing it altogether. This reduction in length would result in lower construction costs. The research findings introduce a unique method for safeguarding hydraulic structures from local scour downstream.

Leone et al. (2021) conducted a set of controlled studies in a laboratory to assess the reliability of a new, eco-friendly solution made of colloidal silica for stabilizing coastal sand dunes. The research aimed to assess the efficacy of nanosilica in two specific settings: a flat ocean floor and a beach-dune profile that mimics natural formations. A

comprehensive assessment of wave properties was carried out to gather data, and the observed topography of the seabed and beach-dune formations were meticulously examined under different wave situations. The experiments were carried out in two separate sets. At first, the models were built using natural sand in order to faithfully replicate the historical conditions. The study then investigated the impacts of injecting a grout consisting of mineral colloidal silica.

The findings indicated that the inclusion of mineral colloidal silica enhances the structural integrity of non-cohesive sediments. Consequently, the amount of erosion that occurs on the dunes is decreased, ultimately improving the ability of the beach-dune system to withstand damage and last for a longer period of time.

In conclusion, the study provides evidence that nanosilica is a promising solution for the preservation of coastal sand dunes. The laboratory experiments offer valuable insights into the potential application of a non-toxic colloidal silica-based solution in real-world scenarios. This research contributes to the advancement of coastal engineering practices.

CHAPTER 3

THEORETICAL STUDY

3.1 Introduction

This chapter provides an overview of the theoretical research on the highest possible scour depths around bridge piers in mixed beds nanomaterials - sand (specifically, non-uniform, medium-sized sand). Dimensional analysis was employed to determine the maximum relative scour depths at the cylindrical-singular pier. Additionally, dimensionless relations for the scour boundaries surrounding the pier were derived.

3.2 Dimensional Analysis

Local scour is a complex problem due to the numerous factors that influence this phenomenon. The factors can generally be stated as follows:

$$ds = f \left(\begin{array}{l} \text{Flow} (h, V, Re_p, g, \rho, \mu), \text{Sediments} (d_{50}, \tau_c, \rho_s, \sigma_g, S_s, C_p, V_c), \\ \text{Pier geometry} (D, \alpha, \beta) \end{array} \right) \quad 3.1$$

Where flow depth h , velocity V , critical velocity V_c , Pier Reynolds number Re_p , gravitation acceleration g , pier diameter D , flow direction α , correction factors for pier shape β , bed shear strength τ_c , a standard deviation of particle size σ_g , clay fraction C_p , median particle size d_{50} , water density ρ , sediment density ρ_s , a specific gravity of sediment S_s , and dynamic viscosity of water μ .

This study utilized the Buckingham approach to find out the variables that have a significant impact on the depth of local scour at a bridge pier located on a non-cohesive sediment bed. The most significant variables have been identified as follows:

$$d_s = f(D, h, V, g, d_{50}, \sigma_g, \rho_s, \rho_w, \mu, M_s, M_n) \quad 3.2$$

Where: d_s = local scour depth (cm), d_{50} = Median particle size (mm), M_s = Mass of sand (Kg), h = Flow depth (cm), ρ = Water density (Kg/m³), μ = Dynamic viscosity of water (K/m.sec), σ_g = The standard deviation of particle size, ρ_s = Sediment density (Kg/m³), D = Pier diameter (cm), M_n = Mass of Nano clay (Kg), g = Gravitation acceleration (m/sec²), V = Mean Velocity (m/sec).

The following equation 3.3 is reached after solving equation 3.2 using the Buckingham method:

$$f\left(\frac{d_s}{D}, \frac{h}{D}, \frac{\rho_s}{\rho}, \frac{d_{50}}{D}, \sigma_g, \frac{gD}{V^2}, \frac{\mu}{DV\rho}, \frac{M_s}{D^3\rho}, \frac{M_n}{D^3\rho}\right) = 0 \quad 3.3$$

Rearranging eq.2 by Substitute Froud Number $Fr = V/(gh)^{0.5}$, Reynolds number $Re = DV\rho/\mu$, S_s is the specific gravity of sediment = $(\rho_s)/\rho$. By combining some terms, we can obtain that, firstly, the mass of sand with the mass of nanomaterials $(\frac{M_s}{D^3\rho}, \frac{M_n}{D^3\rho})$ and the parameters of the mixture can be expressed in this way $Mr = \frac{M_n}{D^3\rho} / \frac{M_s}{D^3\rho}$. Secondly, recombining and rearranging the specific gravity of sediment S_s , and the flow Froude number Fr can be expressed as a sediment densimetric Froude number.

The densimetric properties of the sediment The Froude number Fr_0 is the ratio of the inertial force exerted on a particle to the particle's specific weight when it is submerged (Hodi, 2009). According to research by (Hager & Oliveto, 2002; Williams et al., 2016) Fr_0 can be utilized as a threshold for forecasting the beginning movement of sediments. Aguirre-Pe et al. (2003) identified Fr_0 as an accurate indicator of sediment transport. Hence, the sediment densimetric Froude number Fr_0 was considered as the main factor influencing the depth of local scour. Fr_0 number can be calculated by using

$Fr_0 = \frac{V}{\sqrt{(S_s - 1)gd_{50}}}$. Eq. 3.5 is the final equation.

$$\frac{d_s}{D} = f\left(\frac{h}{D}, \frac{d_{50}}{D}, Re, Mr, \sigma_g, Fr_0\right) \dots \dots \dots 3.5$$

CHAPTER 4

EXPERIMENTAL WORK AND EQUIPMENT

4.1 Experiments Setting

In this investigation, numbers of the test were conducted in an experimental flume in Gaziantep University. The flume dimensions are 0.9 m in depth, 0.8 m in width, and 9 m in length. The shape of the cross-section is rectangular without a slope, the glass-walled flume was constructed on a solid steel base. The distance from the inlet to the 1.5-meter-long testing part was three meters. In the very last section of the flume was the tailgate, which was used to regulate the water level throughout the trials. In this investigation, one pier was used, and it was placed exactly in the middle of the experimental area. An electromagnetic flowmeter was used to accurately measure the rate of flow. Figures 4.1 and 4.2 show the experimental setup.

Laser meters were utilized for measuring the elevation of the bed and the extent of scour gaps. The magnetic flow meters and laser meters underwent calibration as part of the fabrication process. Therefore, there is no need to calibrate the two instruments. The instrument is connected to a carriage that is manually propelled and moves smoothly along rails on the upper part of the flume wall. The accuracy of the test depended on the leveling of the surface, hence a laser meter was used to randomly measure the initial bed levels.

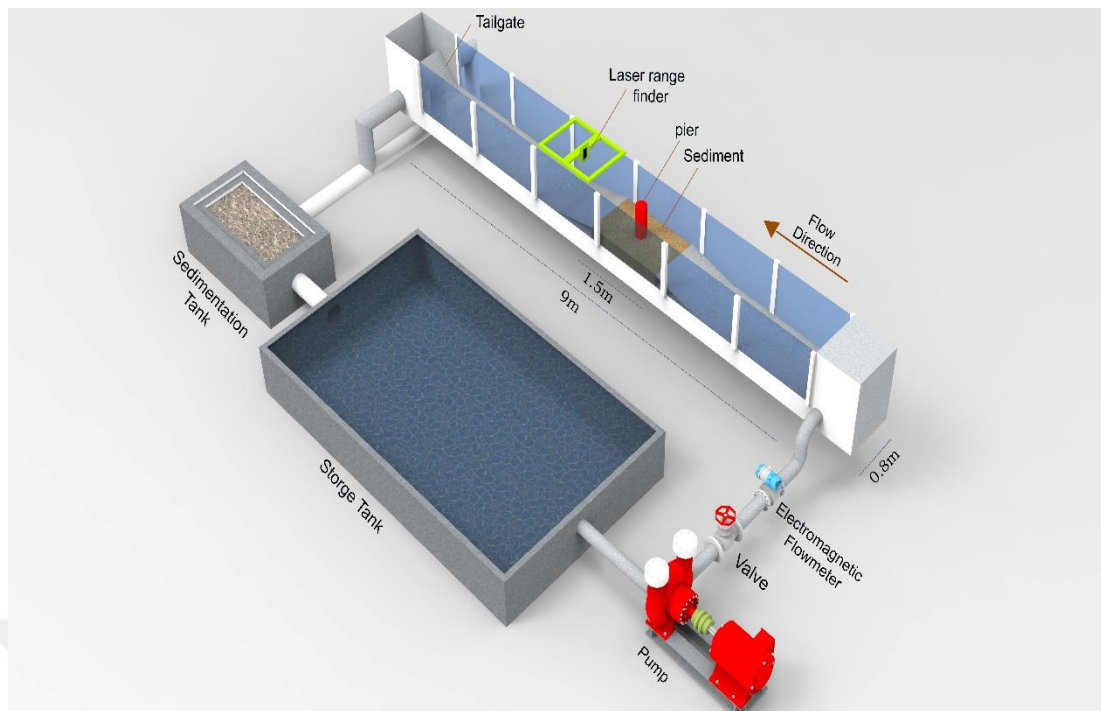


Figure 4.1 Schematic layout of the flume



Figure 4.2 Experiment Setting during the run.

4.2 Pier Models

The pier modeling was done based on the criteria provided by (Chiew & Melville, 1987). To prevent the channel wall from affecting the scouring process, the ratio of the channel width to the pier diameter must be greater than 10 ($B/D > 10$). Therefore, single cylindrical piers with diameters of 3, 5, and 7.5 cm were utilized in this investigation. Figure 4.3 illustrates the piers that have been previously mentioned.



Figure 4.3 The pier models with 3 cm, 5 cm, and 7.5 cm.

4.3 Sand Properties

The sand characterization was determined by conducting a mechanical sieve analysis according to the ASTM (C136-01, 2001) and a specific gravity test. The mean particle size, as indicated in Figure 3, is 1.4 mm. According to Dey et al. (1995), sediments can be classified as non-uniform if the geometric standard deviation (σ_g) is greater than 1.4. In this study, the geometric standard deviation of particles is calculated to be $\sigma_g = 2.99$. (σ_g) can be determined using this equation: $\sigma_g = d_{84}/d_{50} = d_{50}/d_{16}$. According to Raudkivi and Ettema (1983), the sediments are categorized as non-ripple-forming sediments due to their d_{50} value being equal to or greater than 0.7 mm. All the properties of sand is listed in Table 4.1. The sand consists of 6.2% coarse sand, 93.4% sand, and 0.4 % Fine particlaes.

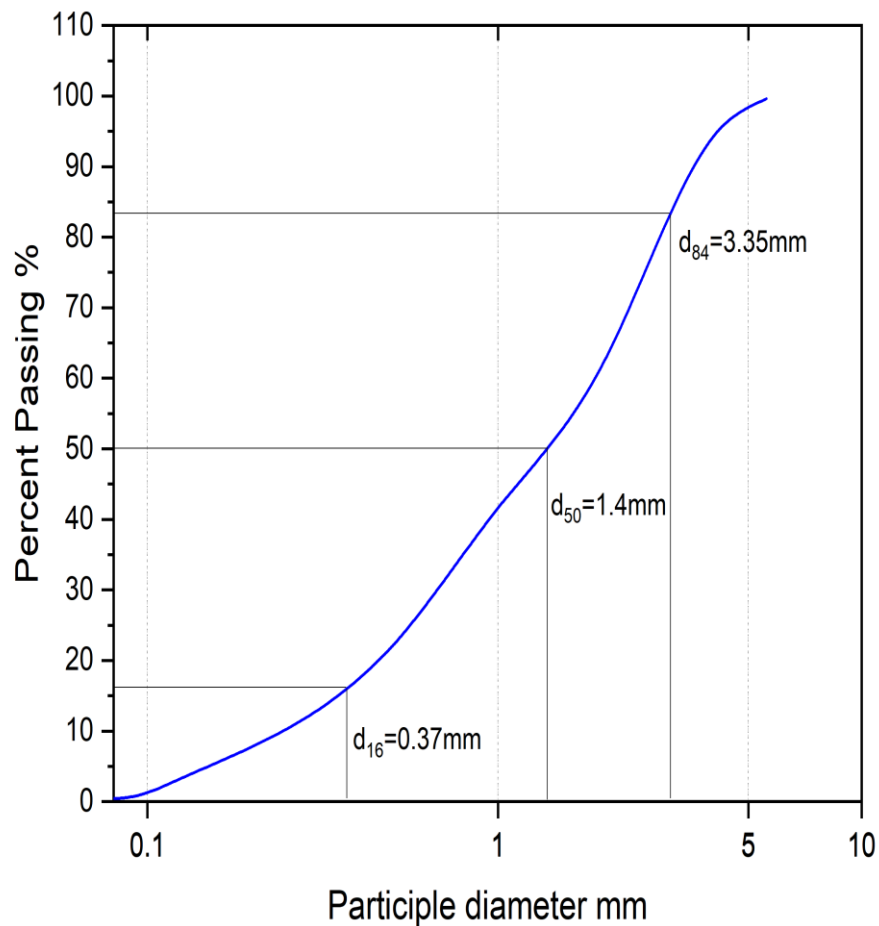


Figure 4.4 Sieve analysis of sand.

4.4 Nano Materials Properties

The aim of the current research was to examine the efficiency of nanoparticles in mitigating piers scour. The research focused on identifying changes in scour behavior after the mixing of nanoparticles to the sand. The use of two different nanomaterials, specifically nano-clay and nano-silica, is illustrated in Figure 4.5. Table 4.1 provides a comprehensive description of the properties of these materials.



Figure 4.5 (a) Nano clay powder. (b) Nano silica powder.

Table 4.1 The properties of the bed materials

Materials	Parameters	Value
Sand	Bulk Density	1660 kg/m ³
	The median size d ₅₀	1.4 mm
	Specific Gravity G _s	2.65
	Standard deviation	2.39
Nano Clay (Montmorillonite)	Form	Powder
	Purity	99%
	Color	White
	Particle Size	800 nm
	Density	2.7 g/cm ³
	Specific Gravity G _n	2.6
Nano Silica	Form	Powder
	Purity	99%
	Color	White
	Average Particle Size	15-35 nm
	Bulk Density	<0.1 g/cm ³
	Specific Gravity G _n	1.03

4.5 Flow Conditions

The impact of mixing nanomaterials with sand at velocities that are near the threshold velocities for the sand is one of the main aims of this study. The very first step was to undertake some preliminary study to identify the features of the initial movement in the sand bed at the channel's base. The experiments were designed with a specific purpose: to study the movement of sand along the sediment bed of the river when there are no obstacles present. After conducting the runs, the tests showed that the bed material started moving at a discharge rate of 0.032 m³/s, or when the flow depth fell below 9.4 cm.

The following Table summarizes the experiment conditions,

Table 4.2 Experiment parameters

Parameters									
Discharge (m ³ /s)	0.032								
Flow depth (cm)	5.7			7.55			9.1		
Mean Velocity (m/s)	0.701			0.529			0.439		
Reynolds number Re	3341.34			3267.65			3164.38		
Froude number Fr	0.9374			0.6146			0.4646		
Pier Reynolds number Re _p (*10 ⁵)	20.4	34	51.1	15.4	25.7	38.5	12.8	21.3	32
V / V _c	1.816			1.308			1.059		
The thickness of the sediments (cm)	20								

Froude number (Fr) values between 0.4646 and 0.9374 have been consistently found in all the investigated circumstances. Based on the given range, we can infer that the flow upstream, before reaching the pier, is classified as sub-critical. This is indicated by a Fr value of less than 1. Now, let's redirect our attention to the flow regime that occurs when fluid passes around a cylindrical pier, which is commonly referred to as vortex shedding. This specific flow regime can be categorized into two separate stages. The first phase involves a laminar boundary layer that undergoes turbulent transition within Reynolds number (Rep) range of 3×10^5 to 3.5×10^6 . Once the Reynolds number exceeds 3.5×10^6 , the flow undergoes a transition into a turbulent vortex street, resulting in an unsteady flow.

The Reynolds number (Rep) could be used to mathematically represent vortex shedding in a pier. Reynolds number, denoted as Rep, is defined by the equation $Rep = VD/\mu$. This formulation was developed based on research conducted by Schlichting and Kestin in 1961, Lienhard in 1966, and Chandrasekaran in 2020. E. V. Richardson

and S. R. Davis (2001) formula was employed for computing the critical shear velocity (V_c).

$$V_c = \sqrt{\frac{\tau_c h^{0.33}}{\rho g n^2}} \quad 4.1$$

g = acceleration due to gravity, h = flow depth, n = Manning' s coefficient, ρ = water density, τ_c = critical shear stress.

4.6 Experimental Procedure

4.6.1 Experimental steps

The study comprised 81 experiments focused on investigating the impact and behavior of adding nanomaterials (nano clay and nano-silica) into the sand.

- Control tests: The first 9 runs served as control tests for comparison purposes.
- Experimental setup: The investigations were carried out utilizing a specified technique, which included the following procedures:
 1. Preparing the sand bed, the test part was 80 cm wide, 20 cm deep, and 150 cm long.
 2. Pier installation: In order to reduce the impact of any possible slope-induced factors on the vortex, a pier was placed in the exact middle of the testing area.
 3. Verticality check: The verticality of the pier was verified to ensure accuracy during the experiment.
 4. Sand filling: The test section was filled with sand.
 5. Sand bed leveling: Leveling the sand bed: A scraper was utilized for this purpose.
 6. Measurement: The bed's measurements were measured using a laser range finder.

- Flow initiation: The experiments began with a very slow flow to attain the desired flow depth and ensure complete saturation of sediments by allowing air bubbles to escape.
- Flow depth control: A tailgate system was used to regulate the flow depth..
- Discharge pumping: The required discharge was pumped into the test section.
- Flow monitoring: An electromagnetic flowmeter was utilized to monitor the discharge flow rate.
- Flow control: The flow rate was regulated using a valve.
- Equilibrium achievement: Careful drainage of water was applied to prevent variations in bed topography after local scour equilibrium had been reached.
- Final measurement: The bed's contour profile was measured utilizing a laser finder once equilibrium was achieved.



Figure 4.6 Test section and Pier installation.



Figure 4.7 Sand-bed leveling.



Figure 4.8 Leveled bed and ready for run.

4.6.2 Preparing the Nanomaterials-Sand beds

In this investigation, the mixing of nanomaterials (Nano clay and Nano Silica) into sand at various proportions was examined. Extensive research was conducted to identify the most suitable method for introducing nanomaterials (Nano clay and Nano Silica) into the sand. Consequently, Ibrahim et al. (2022) proposed the optimal approach for mixing Nano Silica with sand after investigating various techniques to minimize scour depth downstream of a sluice gate. It was found that the wet method proved to be the most effective way to blend Nano Silica with sand, a deeper local scour was noted as a result of the dry method.

The wet method was used to mix nanomaterials (Nano-clay and Nano-Silica) with sand in this study, using the absolute volume method. The wet technique is based on the assumption that the overall volume of the mixture is equal to the combined volumes of its individual components, which include Sand, nanomaterials (Nano clay and Nano Silica), and Water. Below is the mixing equation:

$$V_{abs} = \frac{Ms}{Gs} + \frac{Mn}{Gn} + \frac{Mw}{1} = 1000 \text{ liter} \quad 4.2$$

Here, Ms , Mn , and Mw represent the masses of sand, nanomaterials (Nano clay / Nano Silica), and water, respectively, while Gs and Gn are the Specific Gravity of sand and nanomaterials, respectively. The mixing ratios tested were 0.25%, 0.5%, 0.75%, and 1%.

The mixing process for nanomaterials and sand involved the following steps:

1. Determination of the quantities of sand, nanoparticles (Nano clay / Nano Silica), and water through the utilization of equation 5.
2. Preparation a solution of the nanomaterials (Nano clay or Nano Silica) by dissolving them in water and then mixing them rapidly.
3. Gradual addition of the nanomaterials (Nano clay / Nano Silica) solution to the sand while mechanically mixing thirty minutes in order to achieve a uniform hue in the mixture.

4. The combination should be left undisturbed for a full day to ensure that the components are equally distributed. The mixture should be covered to prevent any more water, as recommended by Debnath et al. (2007).
5. Fill the test section by layering the mixture in four equal parts, with each layer having a depth of 5cm. Afterwards, a steel trowel was employed to bind the layers without applying pressure.

4.7 The structure of the study

This research consists of four distinct experimental phases. It commences with the initial control tests, conducted on a sand bed. Subsequently, the results obtained are verified by comparing them to calculated outcomes derived from equations established in previous studies conducted under identical conditions.

The second phase involves an investigation into the influence of nano clay, specifically examining its effects in a nano clay-sand bed setting. The third phase focuses on exploring the impact of nano-silica within a nano silica-sand bed environment. During both the second and third phases, the efficacy of these nano-materials is assessed, and the optimal ratio of their use is determined.

Finally, the fourth phase involves the prediction of local scour. Fig 4.10 illustrates the flowchart outlining the progression of this study.

1. Prepare the quantity of nanomaterials



2. Prepare the nanomaterials solution



3. Mixing the nanomaterials solution to the sand



4. Filling the mixture in the test section and cover it



Figure 4.9 Flowchart the mixing steps.

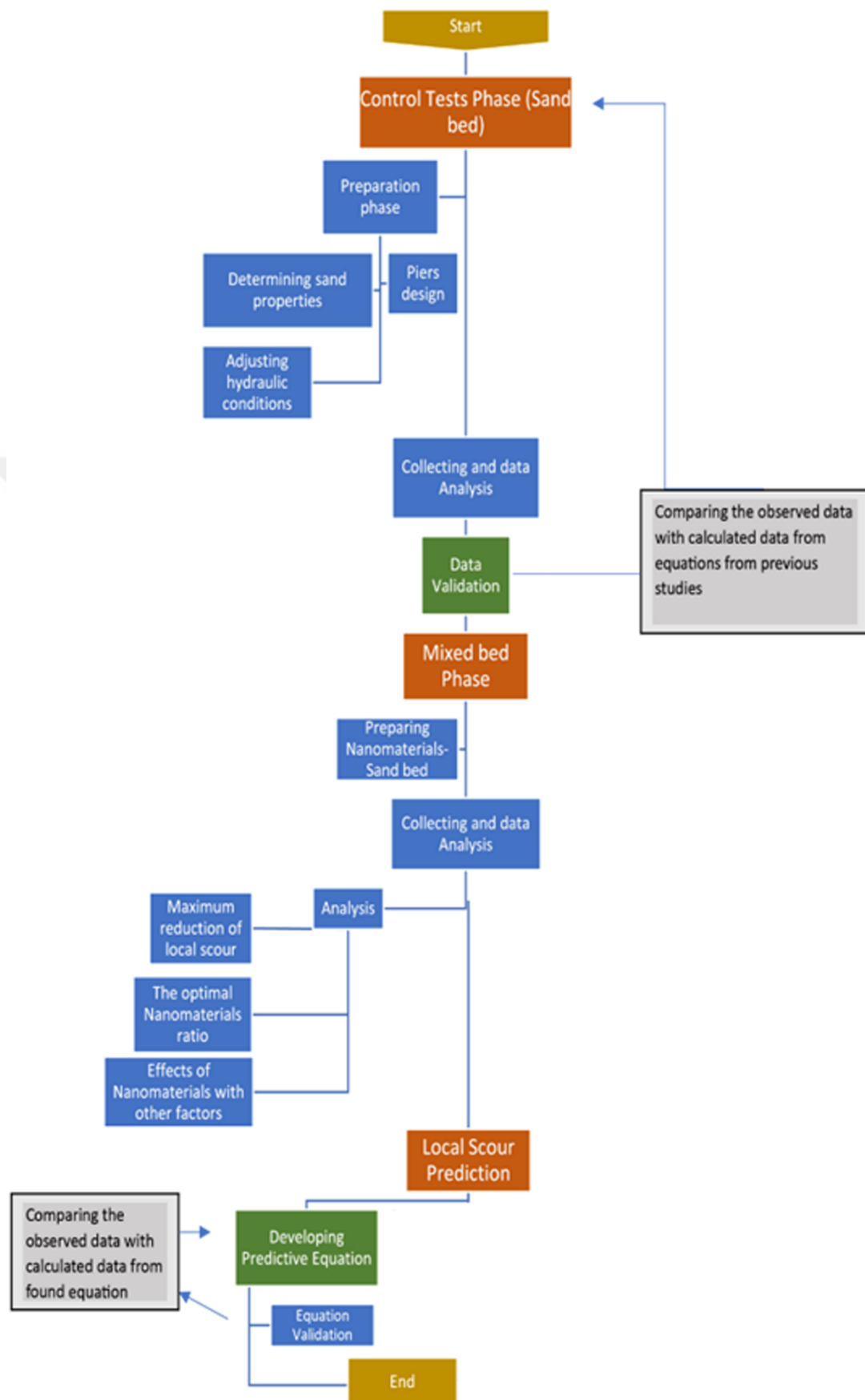


Figure 4.10 Flow chart of the study.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

This chapter presents an in-depth examination of the main findings obtained from the experimental investigations. Numerous experiments were carried out to evaluate the impact of nanomaterials on reducing the scour depth near a bridge pier. In addition, a study has utilized various hydraulic conditions to determine the ideal ratio of nanomaterials to sand in the mixing process. The findings are presented alongside relevant tables, figures, charts, and statistical analyses, which enhance the clarity and understanding of the results.

Additionally, this chapter offers the chance to perform a comparative analysis of its outcomes in relation to prior research and the current body of literature. Our goal in this endeavor is to verify the results, identify similarities or differences, and explore possible explanations for any observed deviations. Including this discussion within the broader context of existing knowledge helps determine the scholarly or practical importance of this research.

5.2 Control Tests

The experimental series began with a phase known as the control test phase. This designation was assigned because, during this phase, the sediment bed consisted entirely of sand. Chapter 4 covers a thorough explanation of the properties of the sand, with particular focus on Section 4.3. The (river- nonuniform-medium) sand was used in this study. The hydraulic conditions were discharge $0.032 \text{ m}^3/\text{sec}$, Three depth of flow, 5.7 cm, 7.55 cm, and 9.1 cm. Three singular-cylindrical pire, 3 cm, 5 cm, and 7.5 cm. In Table 5.1, all the findings in this phase are listed.

Table 5.1 The summary of the control test results.

Run	D (cm)	h (cm)	V (m/s)	ds (cm)
CD3H1	3	5.7	0.701	4.5
CD3H2		7.55	0.529	3.4
CD3H3		9.1	0.439	1.83
CD5H1	5	5.7	0.701	8.35
CD5H2		7.55	0.529	5.35
CD5H3		9.1	0.439	3.07
CD7H1	7.5	5.7	0.701	11.24
CD7H2		7.55	0.529	8.78
CD7H3		9.1	0.439	6.61

5.2.1 Experimental Measurements Calibration

The study began by conducting reference tests, which are also referred to as control tests. The tests included implementing specific conditions such as using a sand sediment bed, three different pier diameters, and three varying flow depths. These conditions were maintained at a consistent discharge rate. Table 5.1 presents the documented findings regarding the extent of local scour. The runs are named as follows: CD3H1, CD3H2, CD3H3, CD5H1, CD5H2, CD5H3, CD7H1, CD7H2, and CD7H3.

Table 5.2 details the four established formulas that were used to compare the actual and computed scour depth in the sand bed scenario. All parameters that were investigated were carefully chosen to be included in the equations. Figure 5.1 presents

a scatter plot that compares the calculated data with the measured data. It visually represents the data points and shows the optimal linear fit between the observed and calculated data. The scatter plot includes an error band that represents an estimated margin of error of approximately 30%. After considering the circumstances, the control test data has been determined to be acceptable and has been validated by comparing it with equation data.

Table 5.2 Formulas for local scour.

Reference	Equations
Eq. 3 of Raeisi and Ghomeshi (2020)	$\frac{d_s}{D} = 0.8 Fr_0^{0.5} - 0.5$
Eq. 8 of Raeisi and Ghomeshi (2020)	$\frac{d_s}{D} = 1.25 Fr_0^{0.4} - 1.3$
HEC-18/Jones Equation (E. V. Richardson & S. R. Davis, 2001)	$d_s = 2hK_1K_2K_3K_4 \left(\frac{h}{D}\right)^{0.65} Fr^{0.43}$
HEC-18/Mueller Equation (Mueller, 1996)	$d_s = 2hK_1K_2K_3K_4 \left(\frac{h}{D}\right)^{0.65} Fr^{0.43} \text{ With modified } K_4$

* K1 represents the correction factor for the shape of the pier, K2 represents the correction factor for the flow direction, K3 represents the correction factor for the bed, and K4 represents the correction factor for the armoring of the coarse bed (Mueller, 1996; E. V. Richardson & S. R. Davis, 2001).

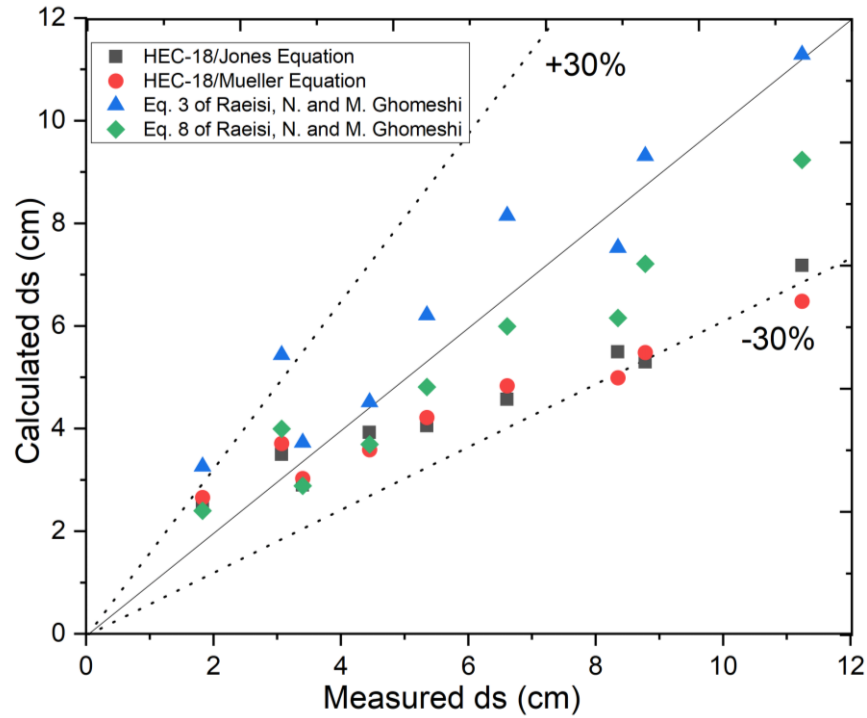


Figure 5.1 Experimental measurements calibration

5.2.2 Effect of Main Parameters

This section includes a comprehensive analysis of the primary factors that contribute to local scour. Additionally, examine how these factors affect local scour depth during the control test phase. It is crucial to recognize that when concentrating on the influence of a particular parameter, it is essential to maintain consistent experimental conditions that allow to understand the isolated effect of that parameter clearly. In this section, the impact of each factor is presented in relation to the dimensionless factor (ds/D). And the main factor, as determined in the dimensional analysis, are the shallowness ratio (h/D), coarseness ratio (d_{50}/D), Pier Reynold number (Rep), and The sediment densimetric Froude number (Fr_0). Figure 5.2 displays all the obtained data regarding on the variables and how the variables act on the local scour phenomena.

Furthermore, statistical analysis was applied to evaluate the correlation; Pearson correlations were calculated among the four dimensionless variables. The correlation coefficient, which quantifies the strength of the relationship between variables, is measured on a scale that ranges from -1 to 1. The scale presented here corresponds to the respective P value. The findings displayed in Figure 5.3 stated a statistically significant correlation between the ds/D value and shallowness ratio (h/D), coarseness ratio (d_{50}/D), Pier Reynold number (Rep), and The sediment densimetric Froude

number (Fr_0). When the significance value (P) is less than or equal to 0.01, it is important to take into account the criteria for conducting meaningful statistical analysis.

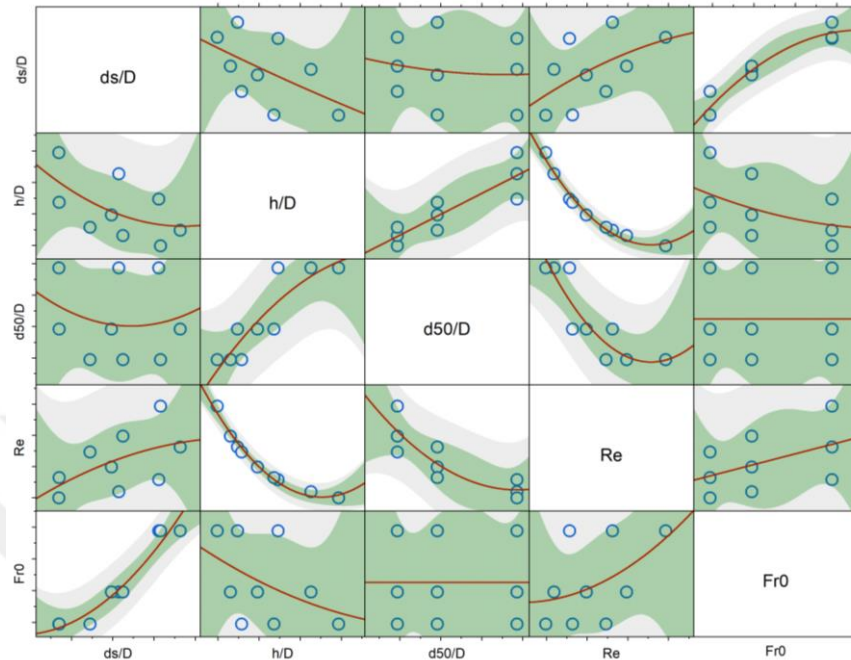


Figure 5.2 The relation between the variables.

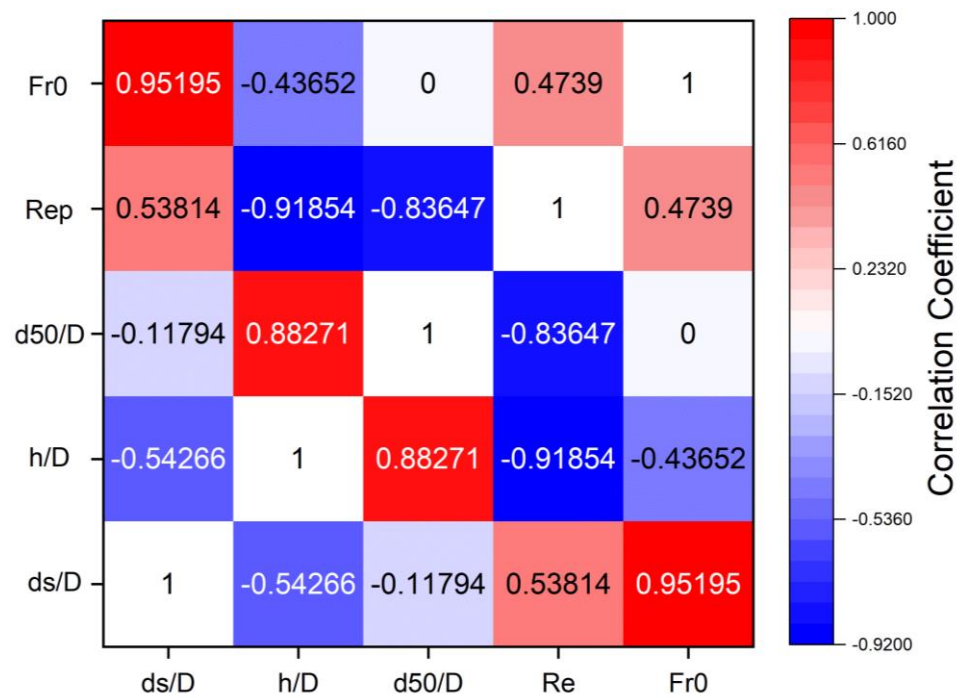


Figure 5.3 Correlations coefficient of variables.

5.2.2.1 Shallowness ratio (h/D)

This section presents the impact of the shallowness ratio (h/D) in relation to the ds/D . The findings demonstrated an inverse relationship between the rise in flow depth and the local scour depth. This is clearly illustrated in Figures 5.2 and 5.4. Furthermore, the statistical analysis revealed an inverse correlation of the variables ds/D and h/D , with a correlation coefficient of -0.54. This is due to the fact that two factors influence the development of the horseshoe vortex: the pier's diameter and the water's depth. As the pier diameter increases, the horseshoe vortex becomes more pronounced. Conversely, the horseshoe vortex becomes more significant in causing local scour when the depth of the flow minimizes.

In their study, Melville and Coleman (2000) categorized the shallowness of flow into three groups narrow width, intermediate, and wide. All scenarios where a 5 cm or 3 cm pier diameter was used fall into the first category, narrow width, except for the case where the flow depth is 5.7 cm. All of the aforementioned situations are categorized according to the requirement (h/D) is below 1.4. Furthermore, the pier diameter can be categorized as having intermediate widths for the experiments that were carried out conducted with diameters of 5 cm, and flow depth 5.7 cm, and all scenarios with 7.5 cm pier. This classification is based on the h/D values falling within the range of 0.2 to 1.4.

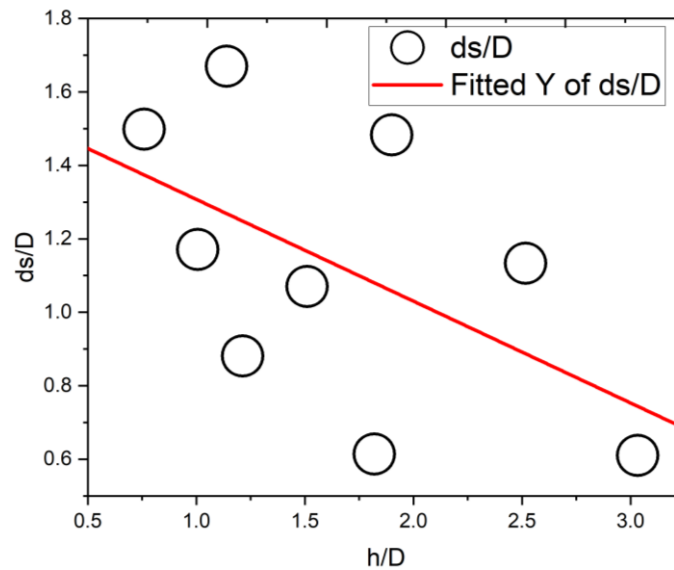


Figure 5.4 Relation between the ds/D and shallowness.

5.2.2.2 The coarseness of the sediments d_{50}/D

The sediment coarseness, denoted by the D/d_{50} ratio, is assessed by comparing the pier's diameter to the median particle size (d_{50}). This coarseness significantly influences the scour depth. In this research, the D/d_{50} values for pier diameters of 3 cm, 5 cm, and 7.5 cm are 21.74, 35.71, and 53.2, respectively.

According to Ettema (1980), the scenarios in which the ratio of D/d_{50} is less than 50 for piers with diameters of 3 cm and 5 cm indicate the presence of coarse sediments. The coarse surface causes more energy to be dropped in the downward flow because of the larger particles and the gaps between them. This in turn, helps to prevent erosion. However, it is important to note that as D/d_{50} approaches 50, the local scour depth increases significantly. This phenomenon was noted in the trails of the D 7.5 cm.

Based on the statistical analysis, it can be indicated that an inverse correlation of the factors ds/D and d_{50}/D , with a correlation coefficient of -0.117. This is clearly shown in Figures 5.2 and 5.3.

5.2.2.3 Pier Reynold number (Re_p)

The Pier Reynolds number is the primary indicator for determining the shape of the horseshoe vortex. This will result in significant changes to the extent and depth of local scour, as well as effectively managing the accumulation of sediments downstream. Reynolds number and ds/D were shown to be significantly correlated in this study. The correlation coefficient for this relationship is 0.538, as shown in Figures 5.2 and 5.3. In addition, this relationship is connected to both the mean velocity and the flow level. A rise in the Reynolds number of the pier can be an indication of a deeper local scour.

In this research, There are two types of the pier's vortex shedding. First, A laminar boundary layer that went through a turbulent transition is defined as having a Reynolds number (Re_p) ranging from 3×10^5 and 3.5×10^6 . Second, a turbulent vortex street unstable flow when $Re_p > 3.5 \times 10^6$. The phenomenon of vortex shedding from a pier can be determined by utilizing the mathematical equation $Re_p = VD/\mu$, where μ is the dynamic viscosity, D is the characteristic dimension, and V is the velocity (Chandrasekaran, 2020; Lienhard, 1966; Schlichting & Kestin, 1961).

5.2.2.4 The densimetric Froude number Fr_0

This study focused mainly on the densimetric Froude number, Fr_0 , instead of the critical velocity. The statistical analysis reveals a clear and substantial positive correlation between Fr_0 and the variables ds/D . This correlation is supported by a high coefficient of 0.95, as clearly illustrated in Figures 5.2 and 5.3. The depth of local scour (ds/D) increases in a direct relationship to the densimetric Froude number (Fr_0).

5.2.3 Local scour Time And Bed Topography

Throughout all experiments, it was determined that the time needed for the local scour to reach equilibrium was 245 minutes. Figure 5.5 illustrates the vibration pattern of the local scour for each scenario during the control test phase. Generally, 90% of the equilibrium state was achieved within the initial 20 minutes. The transportation of sediments can be defined as occurring on a particle-by-particle basis. In the first 5 minutes, the scouring was particularly intense, leading to the removal of a significant amount of fine particles downstream. Subsequently, between 5 to 20 minutes, rolling of coarse sand took place. After this phase, the scour hole contained fine sand along the inner edge, while coarse sand accumulated around the pier and downstream. The figures 5.6-5.14 illustrate the bed topography by using Computer software called Surfer.

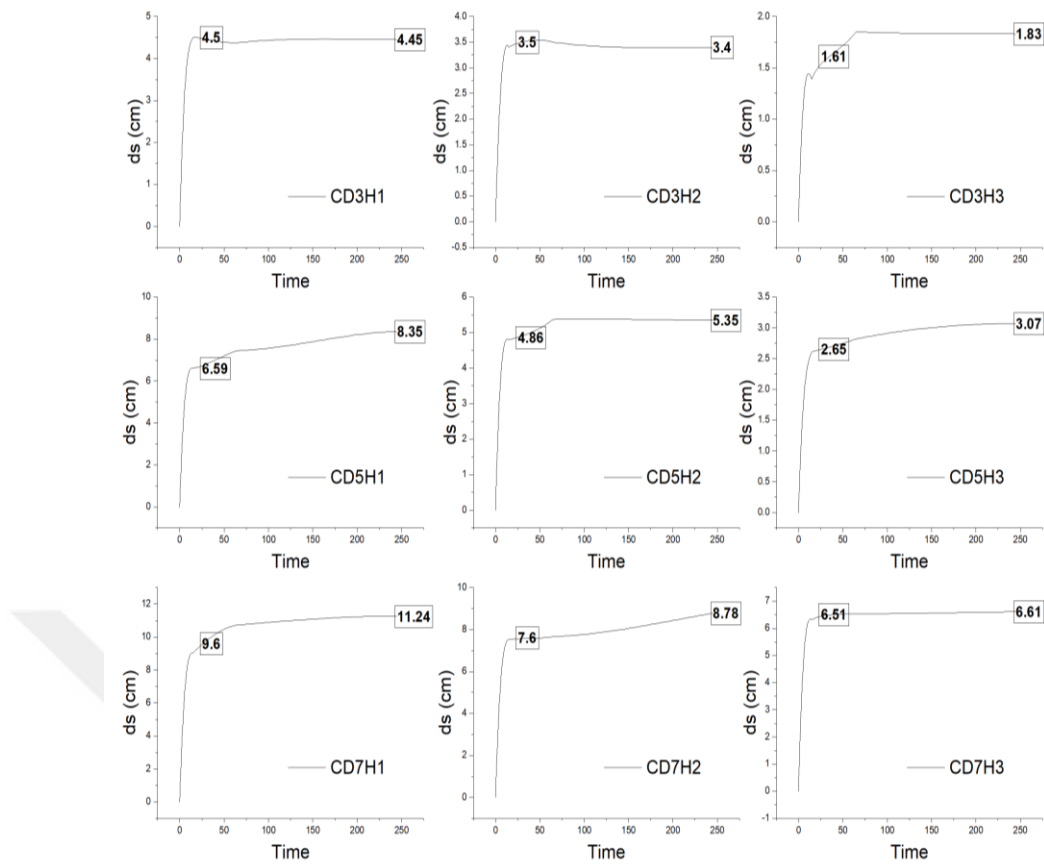


Figure 5.5 Local scour depth through the time of the experiments.

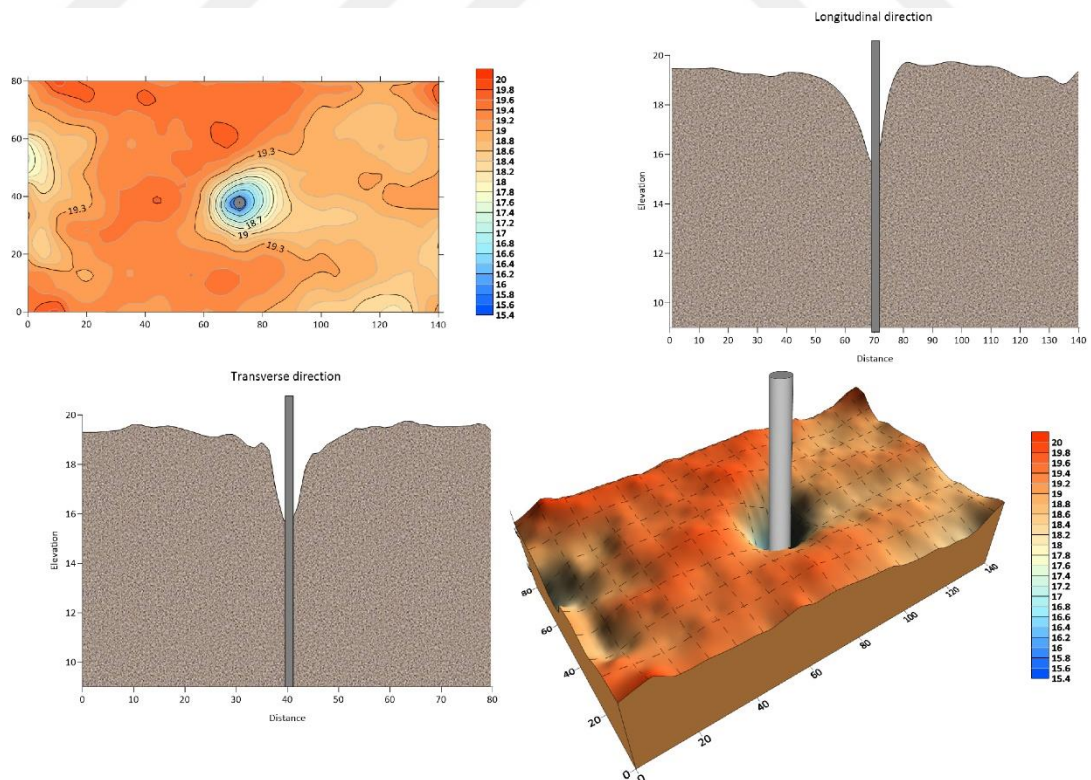


Figure 5.6 Scour pattern for scenario CD3H1

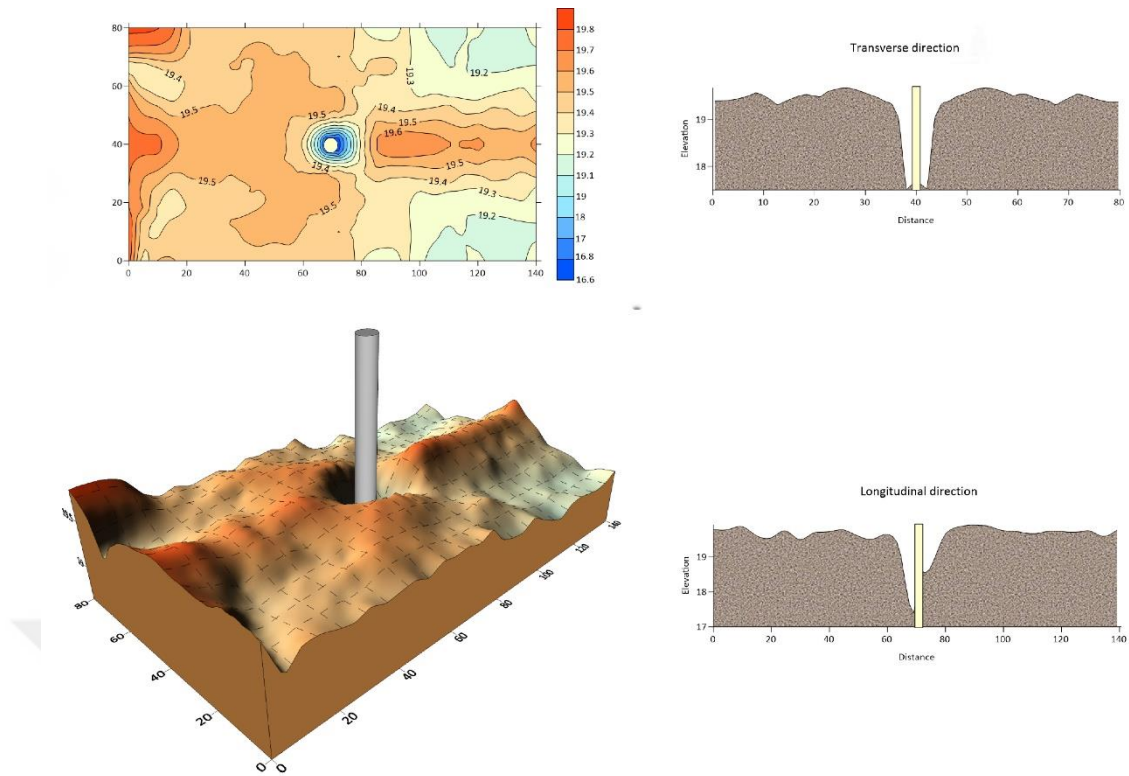


Figure 5.7 Scour pattern for scenario CD3H2

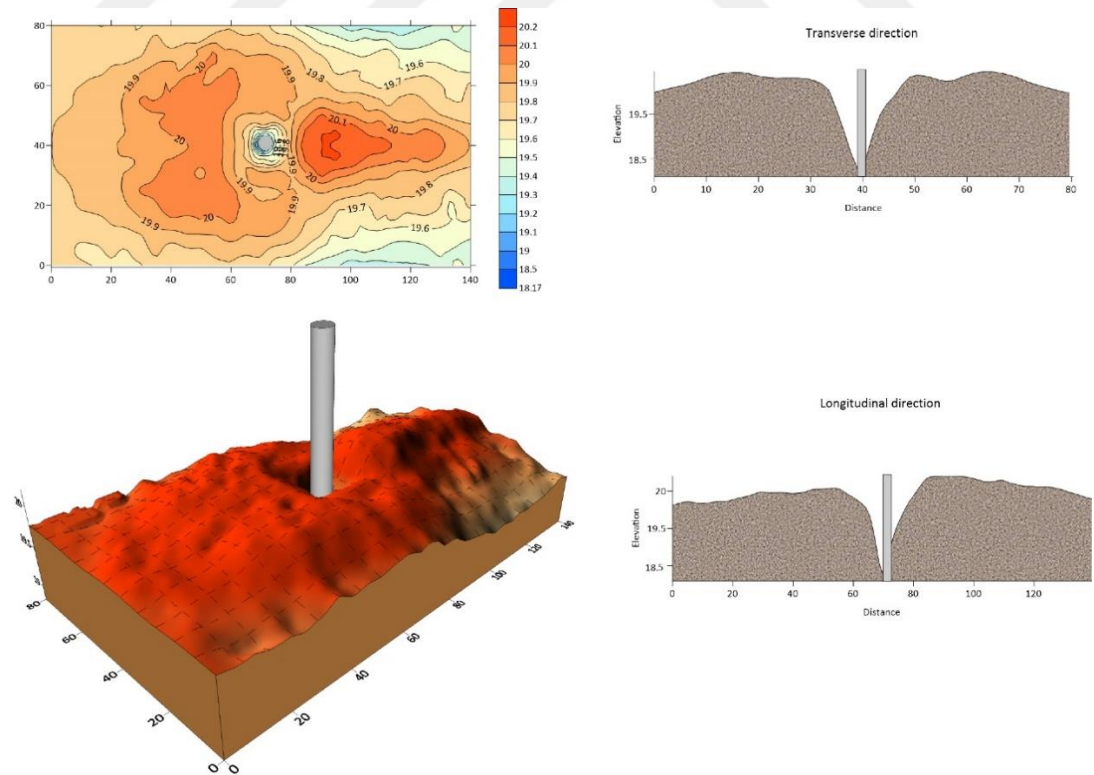


Figure 5.8 Scour pattern for scenario CD3H3

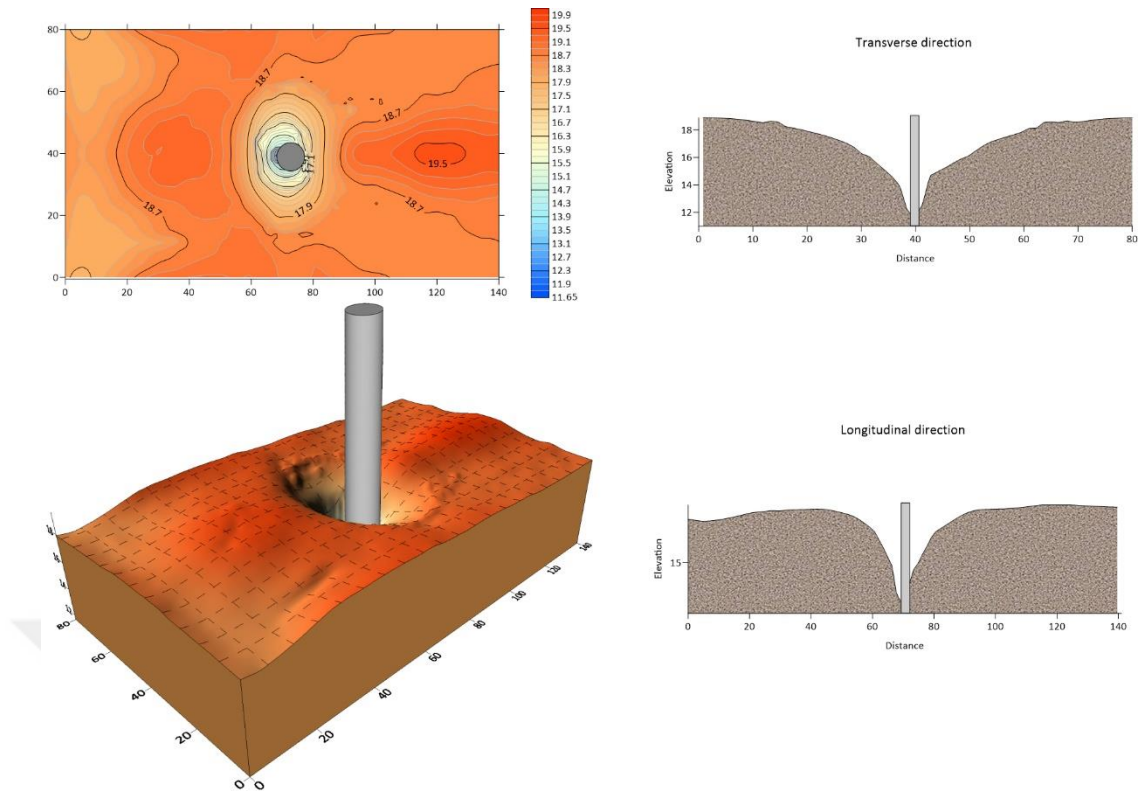


Figure 5.9 Scour pattern for scenario CD5H1

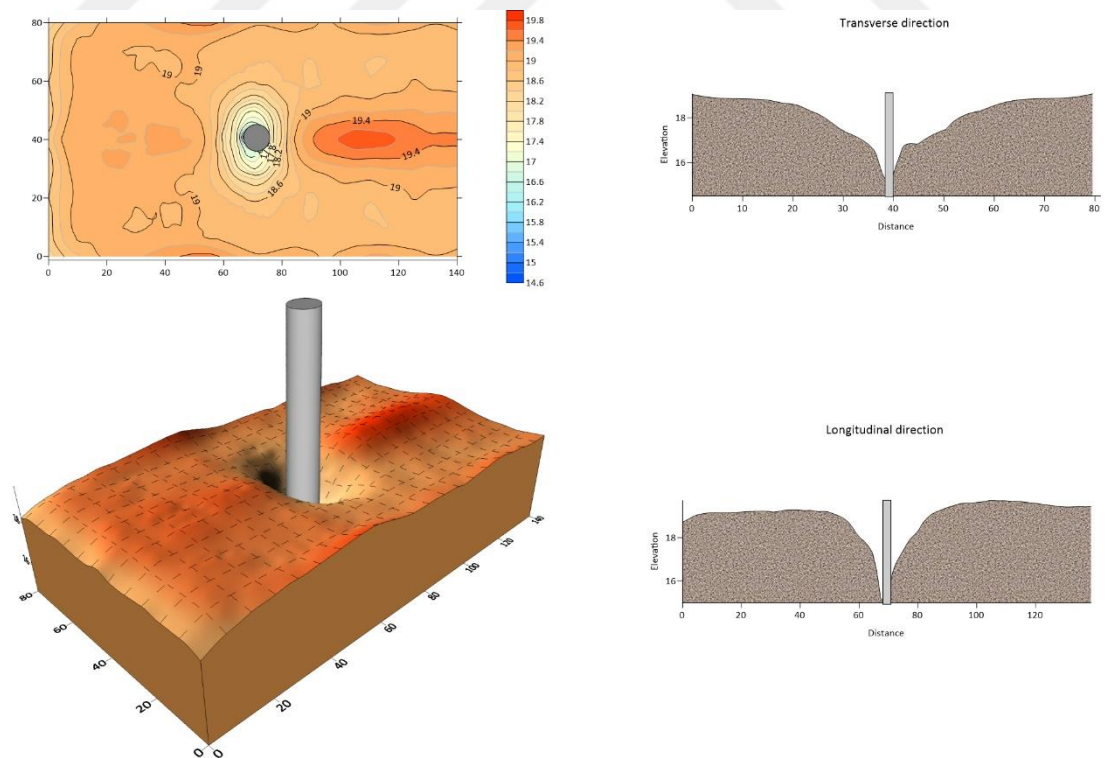


Figure 5.10 Scour pattern for scenario CD5H2

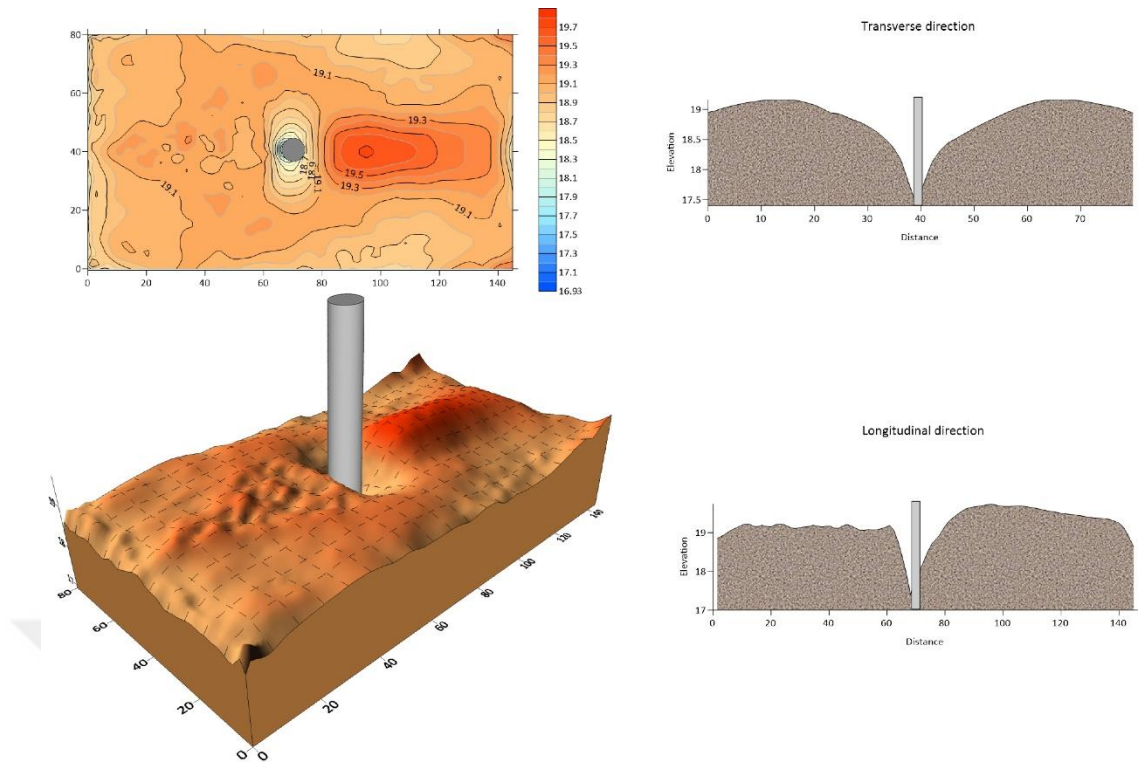


Figure 5.11 Scour pattern for scenario CD5H3

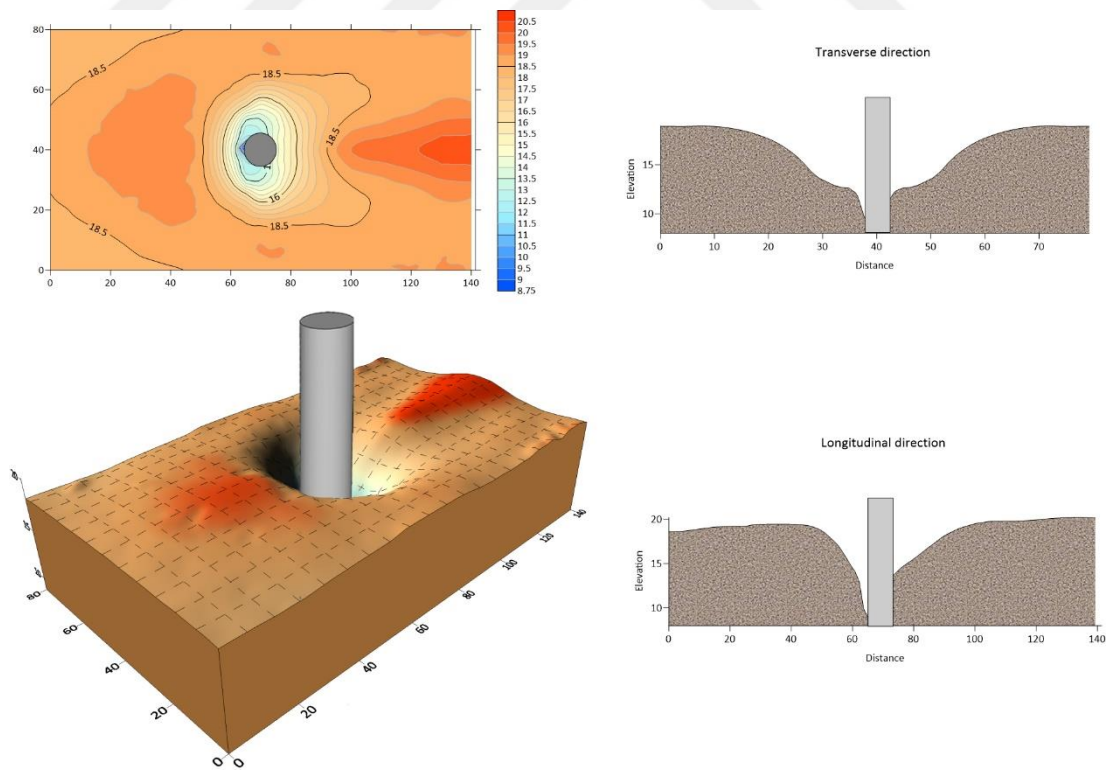


Figure 5.12 Scour pattern for scenario CD7H1

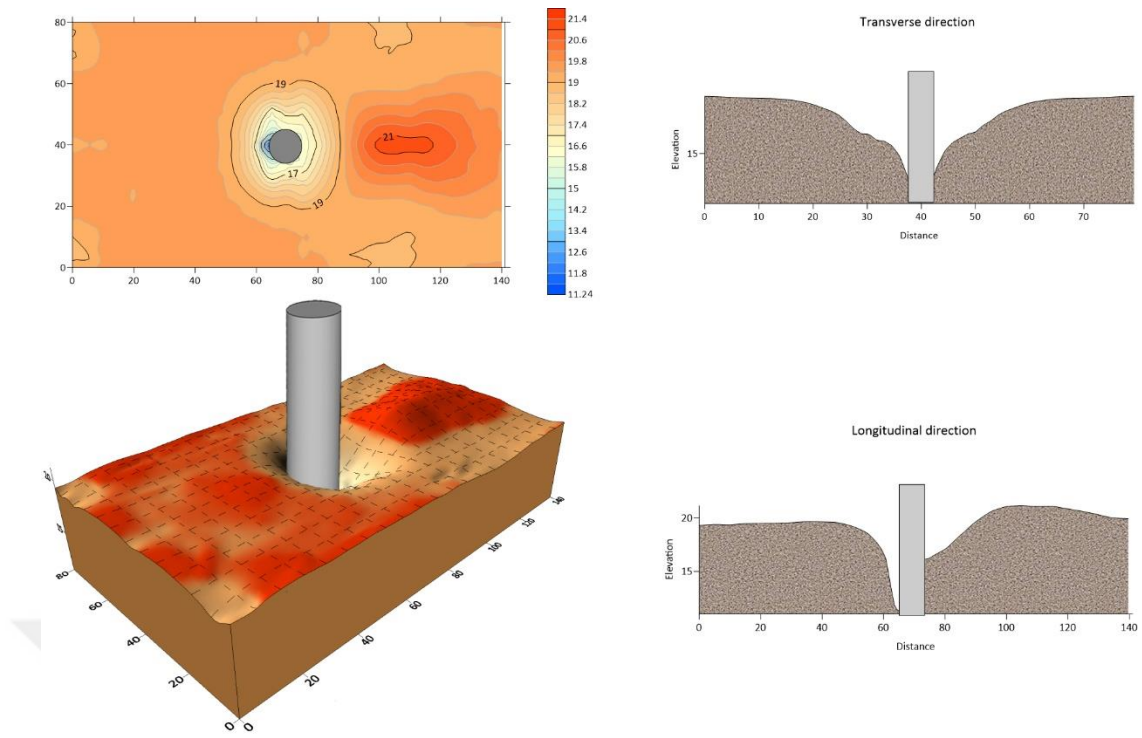


Figure 5.13 Scour pattern for scenario CD7H2

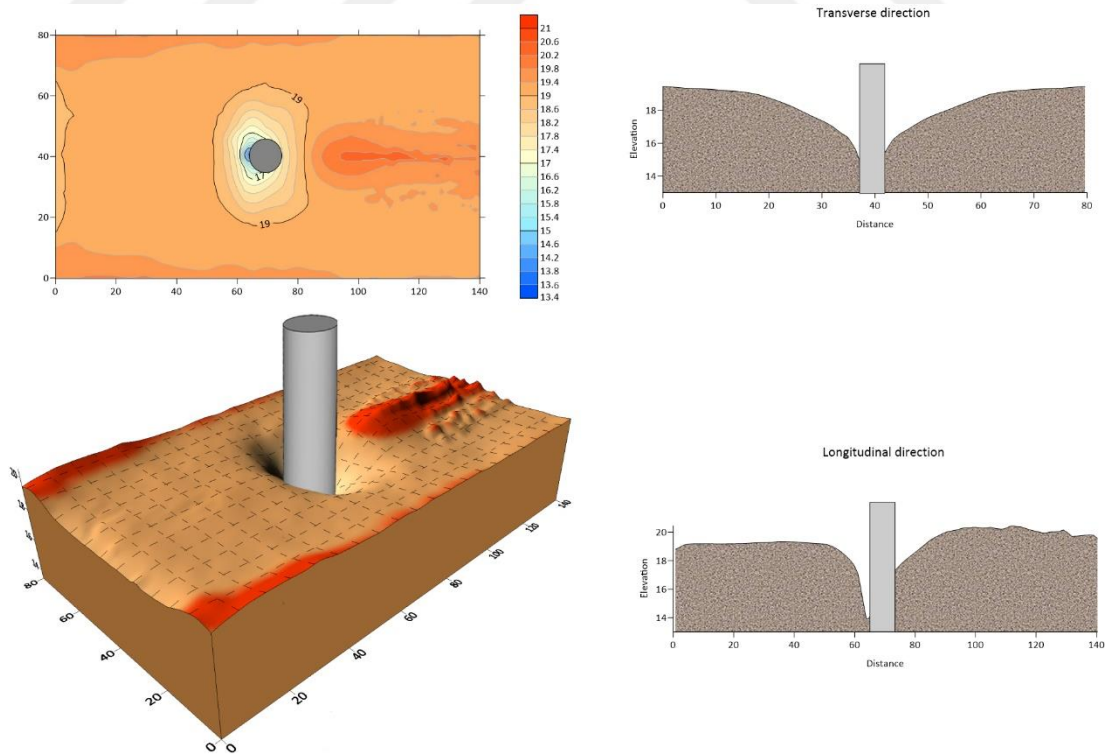


Figure 5.14 Scour pattern for scenario CD7H3

5.3 Nano Clay - Sand Bed

The primary aim of this phase is to examine the influence of nano clay on the local scour phenomenon. Several tests were conducted to investigate the effects of different hydraulic conditions on different mixes of nano clay and non-uniform sand, with the aim of achieving the desired objective. The experiments entailed the utilization of three distinct pier diameters. The findings from this phase of the investigation are provided in Table 5.3 and graphically shown in Figures 5.15-5.20, where they are compared to the results of the control experiments. The objective of this research was to examine the impact of different proportions of nanoclay. The mixing percentage is ranging from 0% to 1% with increments of 0.25%.

Table 5.3 Results summary of the mixing nano clay with sand.

Run	D (cm)	h (cm)	Nano clay (%)	V (m/s)	ds (cm)	Reduction (%)
CD3H1	3	5.7	0	0.701	4.45	0%
NC1D3H1			0.25		1.60	64%
NC2D3H1			0.5		2.39	47%
NC3D3H1			0.75		2.67	41%
NC4D3H1			1		2.94	35%
CD3H2		7.55	0	0.529	3.4	0%
NC1D3H2			0.25		1.14	66%
NC2D3H2			0.5		1.64	52%
NC3D3H2			0.75		1.78	48%
NC4D3H2			1		2.05	40%
CD3H3		9.1	0	0.439	1.83	0%
NC1D3H3			0.25		0.58	68%
NC2D3H3			0.5		0.84	54%
NC3D3H3			0.75		0.89	51%

NC4D3H3			1		0.95	48%
CD5H1	5	5.7	0	0.701	8.35	0%
NC1D5H1			0.25		4.93	41%
NC2D5H1			0.5		5.61	33%
NC3D5H1			0.75		6.19	26%
NC4D5H1			1		6.24	25%
CD5H2		7.55	0	0.529	5.35	0%
NC1D5H2			0.25		3.03	43%
NC2D5H2	5	7.55	0.5	0.529	3.55	34%
NC3D5H2			0.75		3.95	26%
NC4D5H2			1		4.03	25%
CD5H3		9.1	0	0.439	3.07	0%
NC1D5H3			0.25		1.60	47.9%
NC2D5H3			0.5		1.97	36%
NC3D5H3			0.75		2.31	25%
NC4D5H3			1		2.46	20%
CD7H1	7.5	5.7	0	0.701	11.24	0%
NC1D7H1			0.25		10.13	9.88%
NC2D7H1			0.5		8.63	23%
NC3D7H1			0.75		9.94	12%
NC4D7H1			1		11.22	-0.2%
CD7H2		7.55	0	0.529	8.78	0%
NC1D7H2			0.25		7.4	16%
NC2D7H2			0.5		6.49	26.1%
NC3D7H2			0.75		6.72	23.5%

NC4D7H2			1		8.76	-0.2%
CD7H3			0		6.61	0%
NC1D7H3			0.25		5.135	22%
NC2D7H3		9.1	0.5	0.439	4.76	28%
NC3D7H3			0.75		4.95	25%
NC4D7H3			1		6.6	0.2%

During this phase, a total of 36 runs were conducted, which commenced immediately after the control tests. Developing a suitable method for determining the ideal nano clay-to-sand mixing ratio posed a significant challenge. Once the runs had been carefully planned and initiated, the absolute volume method was implemented in accordance with the guidelines outlined in Chapter 4, section 4.6.2. Determining the optimal mixing ratio was a key objective of this study. In order to accomplish this, different amounts of nano clay were added to the used sand to establish the ideal ratio for mixing nano clay with sand to find the optimal percentage.

Figures 5.15-5.20 demonstrate that the lowest scour depth remained constant for all flow depths when the pier diameter was 3cm. This was particularly evident at a 0.25% of fraction nano clay, as shown in Fig 5.15. The scour depth reduction, in comparison to the control test, was noted to be 68%, 66%, and 64% for flow depths of 9.1cm, 7.55cm, and 5.7cm, respectively, as shown in Figure 5.16. Nevertheless, it was observed that elevating the nano clay ratio beyond 0.25% resulted in deeper local scour. Similarly, it was found that widening the diameter of the pier to 5cm resulted in the lowest measured scour depth, as seen in Figure 5.17. The decrease values of 48%, 43%, and 41% for flow depths of 9.1cm, 7.55cm, and 5.7cm, respectively, were reached by adding 0.25% nano clay, as seen in Figure 5.18. Adding nano clay considerably decreases the scour depth; a concentration of 0.25 percent yielded the most reduction. In addition to this particular concentration, the efficacy of nano clay exhibited a decline, leading to a decrease of 25% to 20% when the nano clay concentration reached 1%.

Based on the utilization of a pier diameter measuring 7.5cm, it was determined that the ideal proportion of nano clay is 0.5%, as shown in Figure 5.19. Figure 5.20 shows that for flow depths of 9.1 cm, 7.55 cm, and 5.7 cm, respectively, 28%, 26.1%, and 23.2% of local scour was reduced as a result of this ratio's implementation. As the nano clay ratio was raised to 0.25 percent, local scour reduction improved gradually until it reached the ideal ratio. However, it should be noted that beyond this threshold, the reduction ratio experienced a substantial decrease, leading to scour depths in the affected areas that were similar to those noticed in control experiments that were conducted without nano clay.

During this phase of the investigation, it was noted that large particles had a major impact on the local scour process by acting as a protective layer against erosion. Additionally, these particles are responsible for dissipating the energy of vortexes. However, the changes in the spaces between the particles have a considerable influence on the behavior of the local scour phenomena. Hence, the utilization of nano clay results in an enhanced internal resistance of the bed, particularly when combined with coarse sand compared to fine sand. Consequently, it can be inferred that the optimal ratios for this study predominantly revolved around the fine sediments present in the sand. According to the results of the sieve analysis, the fine particle fraction makes up 0.4% of the overall mass of the sand sample. The optimal ratios of the nano clay ranged from 0.25% to 0.5%. Finally, the time frame for the scour equilibrium stage was determined to be same as that of the control test, as seen in Figures 5.21-5.29.

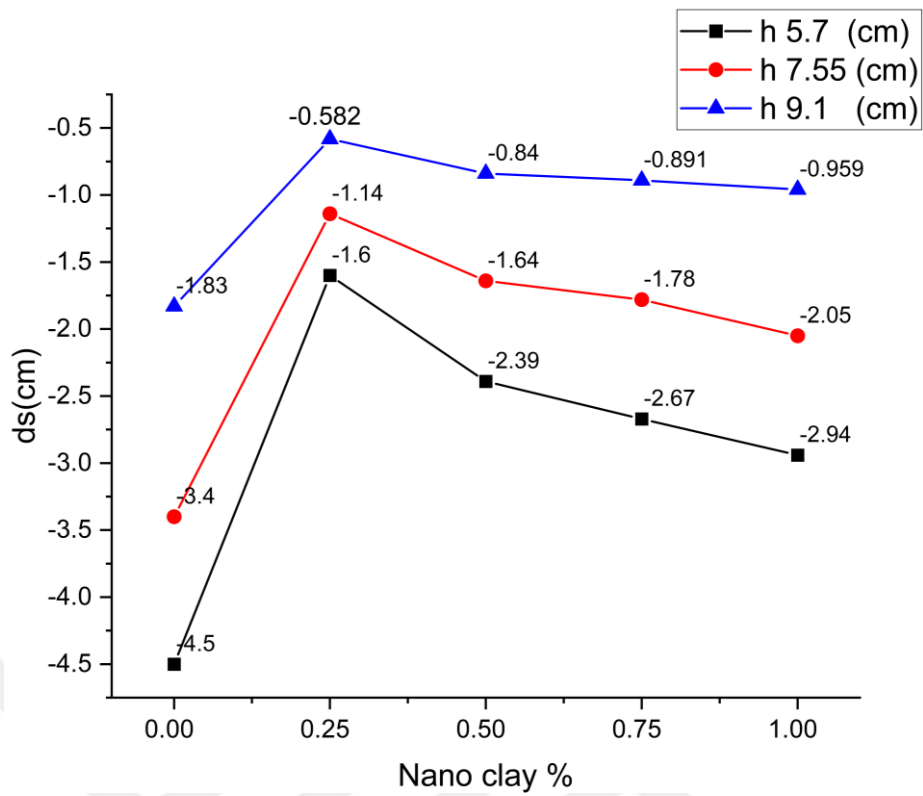


Figure 5.15 Correlation between scour depth and nano clay fraction based on flow depth, for 3 cm pier diameter cases.

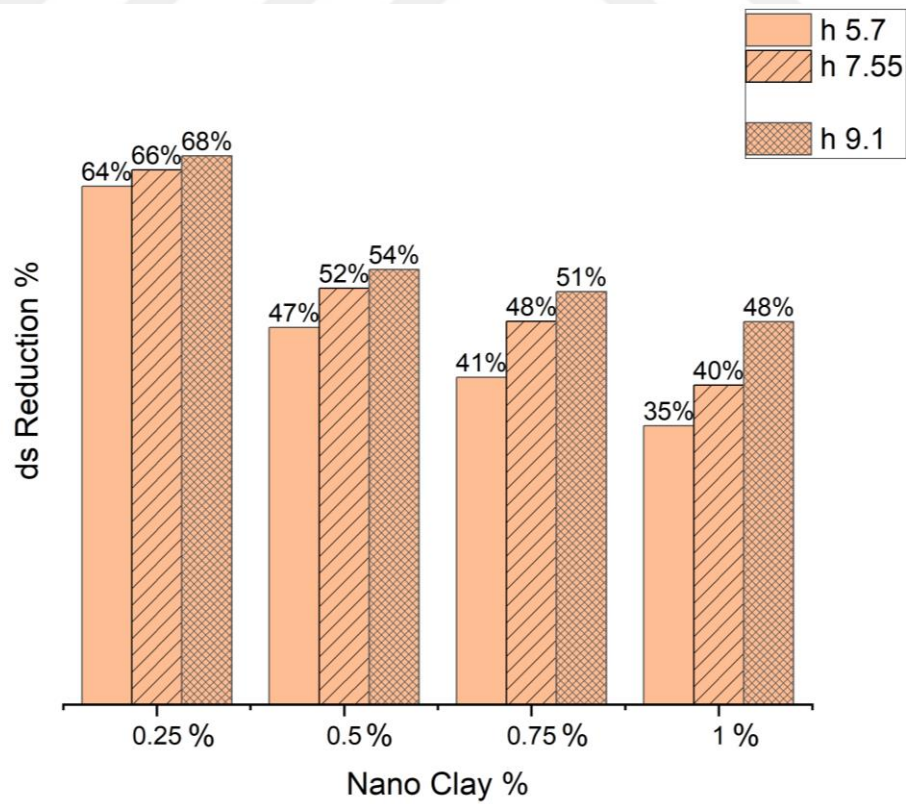


Figure 5.16 The ratio of ds reduction for 3 cm pier.

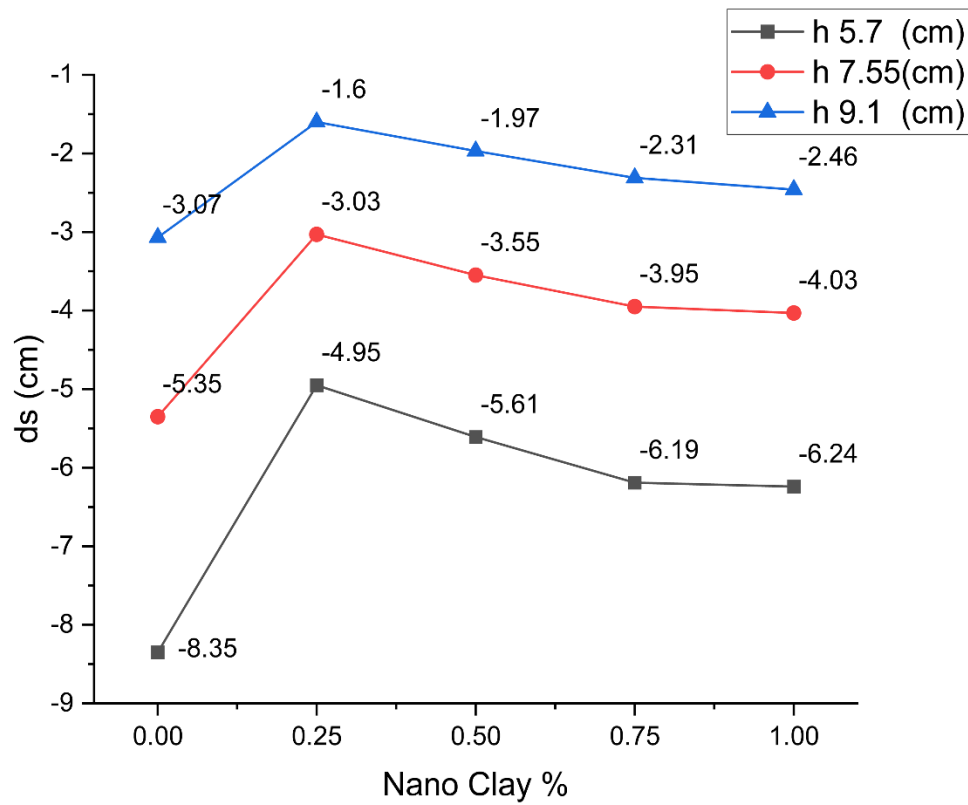


Figure 5. 17 Correlation between scour depth and nano clay fraction based on flow depth, for 5 cm pier diameter cases.

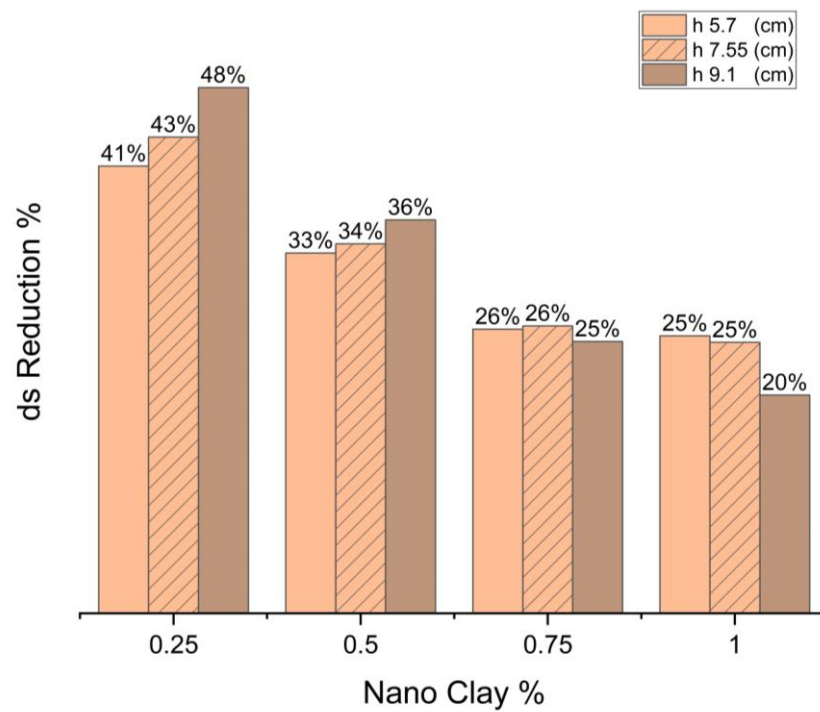


Figure 5.18 The ratio of ds reduction for 5 cm pier.

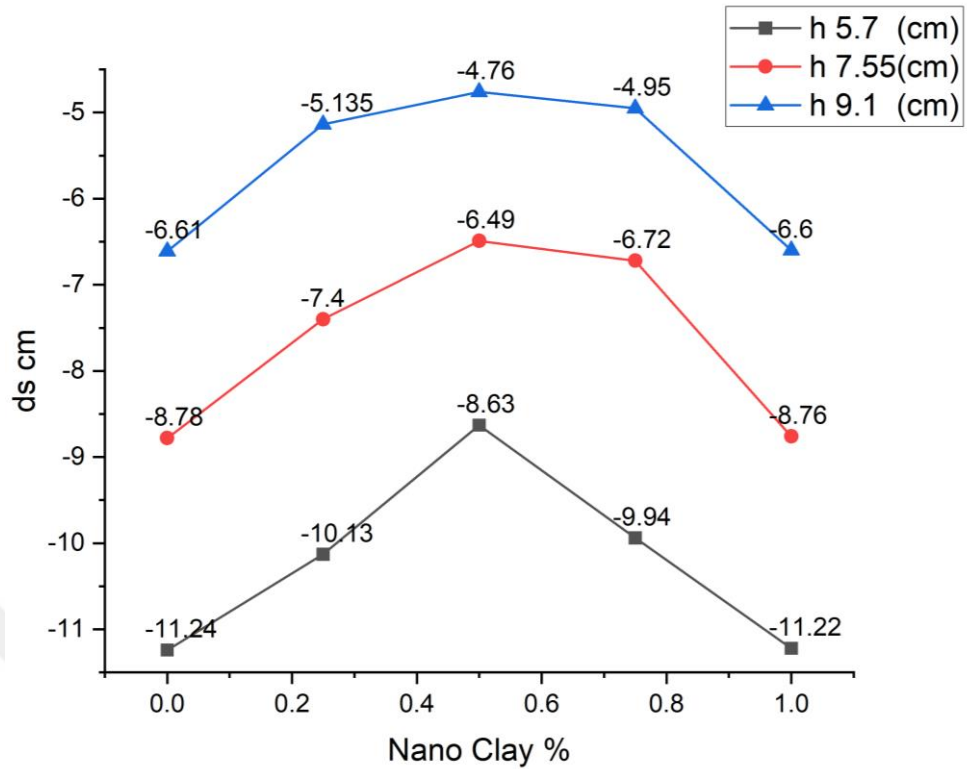


Figure 5.19 Correlation between scour depth and nano clay fraction based on flow depth, for 7.5 cm pier diameter cases.

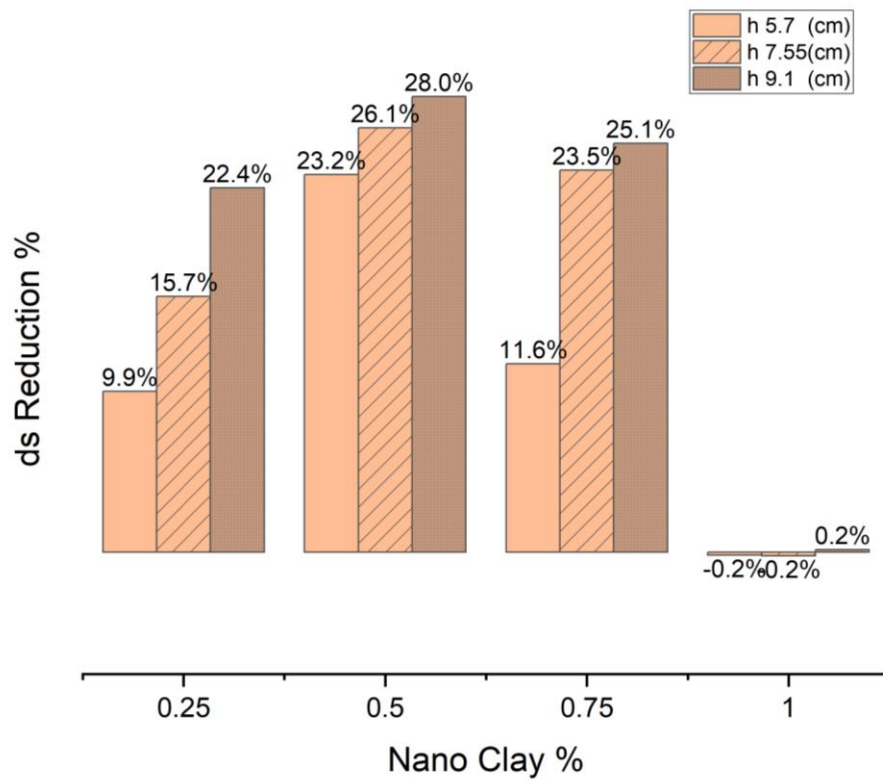


Figure 5.20 The ratio of ds reduction for 7.5 cm pier.

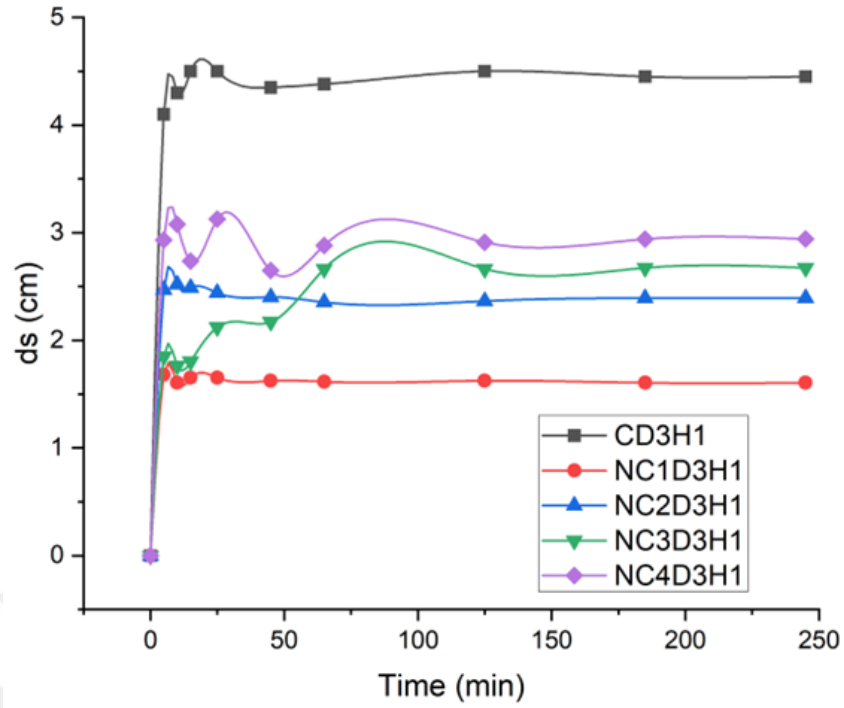


Figure 5.21 Changes in scour depth (ds) in the scenarios of a D 3 cm with h 5.7 cm (Nano clay- sand bed) over time.

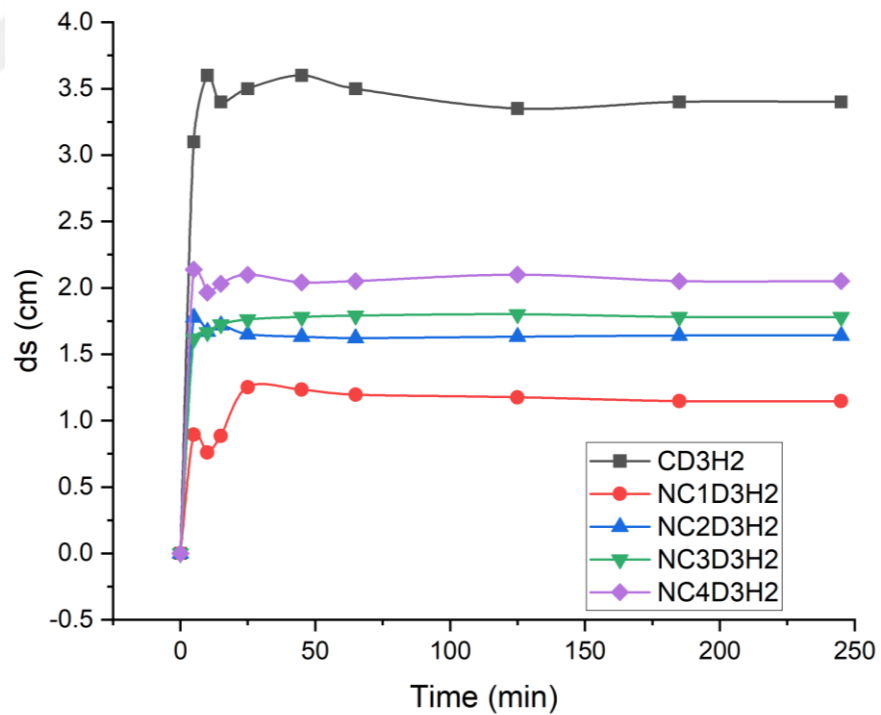


Figure 5.22 Changes in scour depth (ds) in the scenarios of a D 3 cm with h 7.55 cm (Nano clay- sand bed) over time.

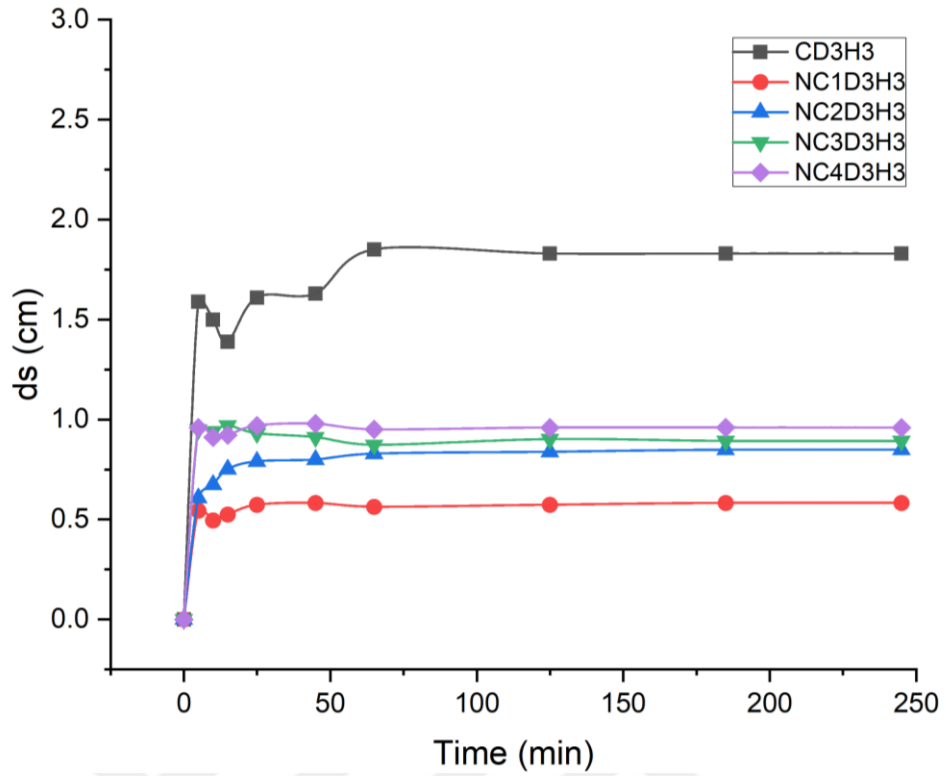


Figure 5.23 Changes in scour depth (ds) in the scenarios of a D 3 cm with h 9.1 cm (Nano clay- sand bed) over time.

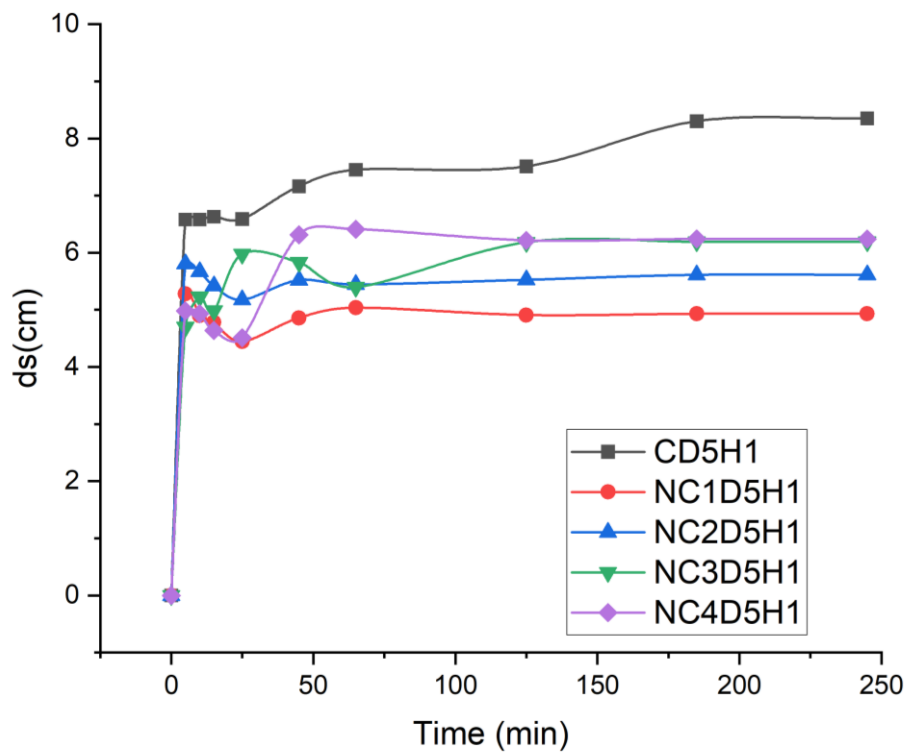


Figure 5.24 Changes in scour depth (ds) in the scenarios of a D 5 cm with h 5.7 cm (Nano clay- sand bed) over time.

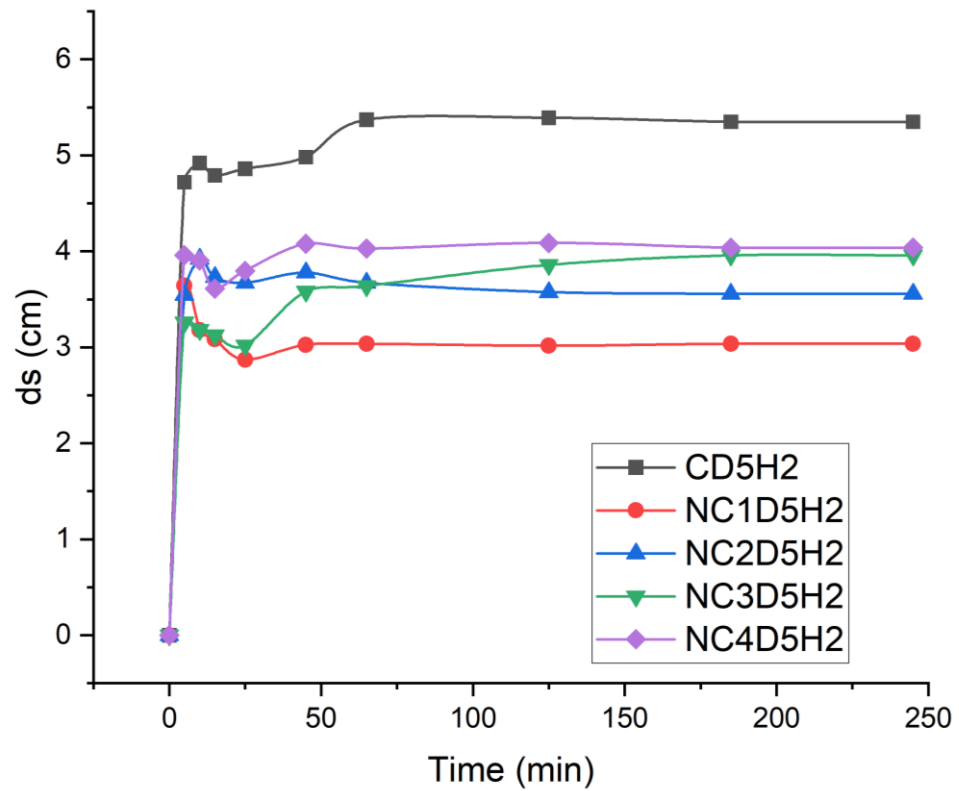


Figure 5.25 Changes in scour depth (ds) in the scenarios of a D 5 cm with h 7.55 cm (Nano clay- sand bed) over time.

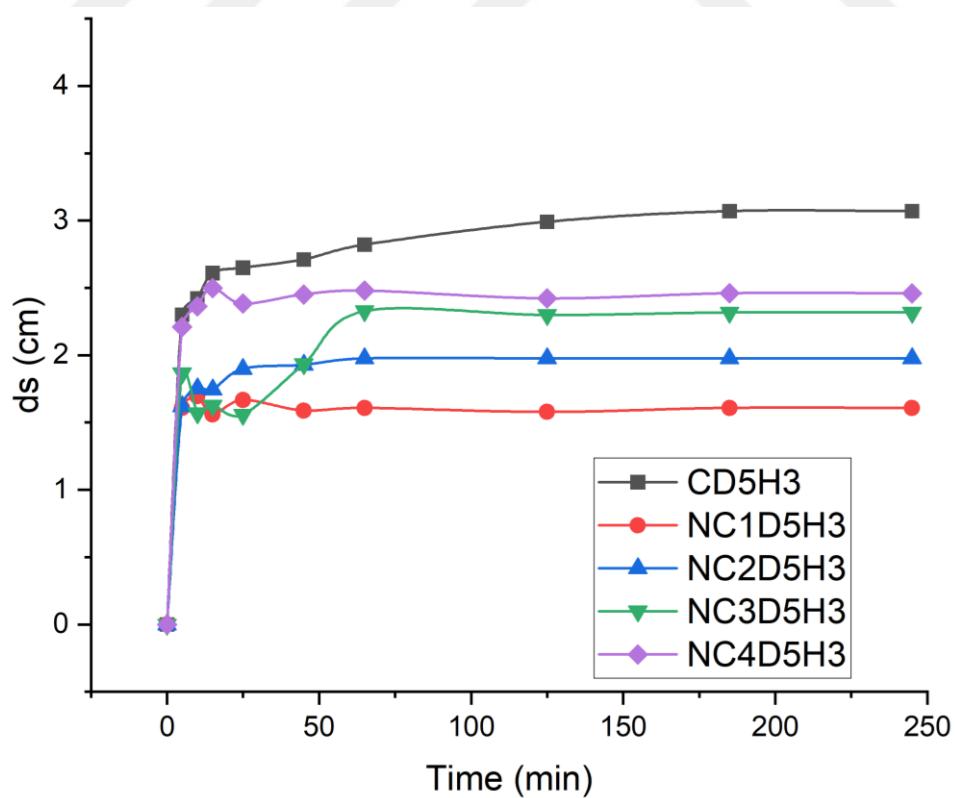


Figure 5.26 Changes in scour depth (ds) in the scenarios of a D 5 cm with h 9.1 cm (Nano clay- sand bed) over time.

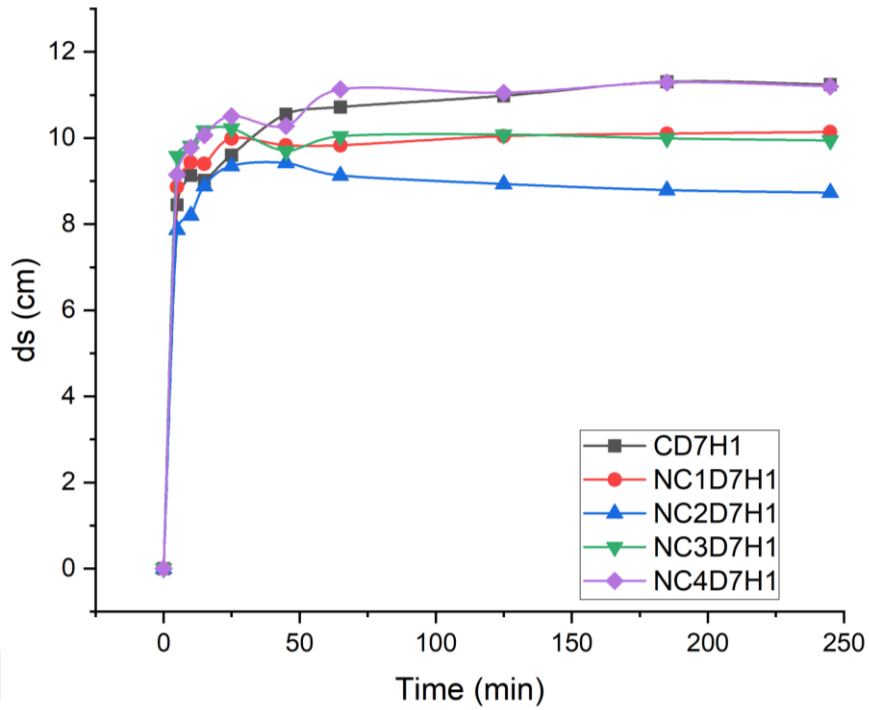


Figure 5.27 Changes in scour depth (ds) in the scenarios of a D 7.5 cm with h 5.7 cm (Nano clay- sand bed) over time.

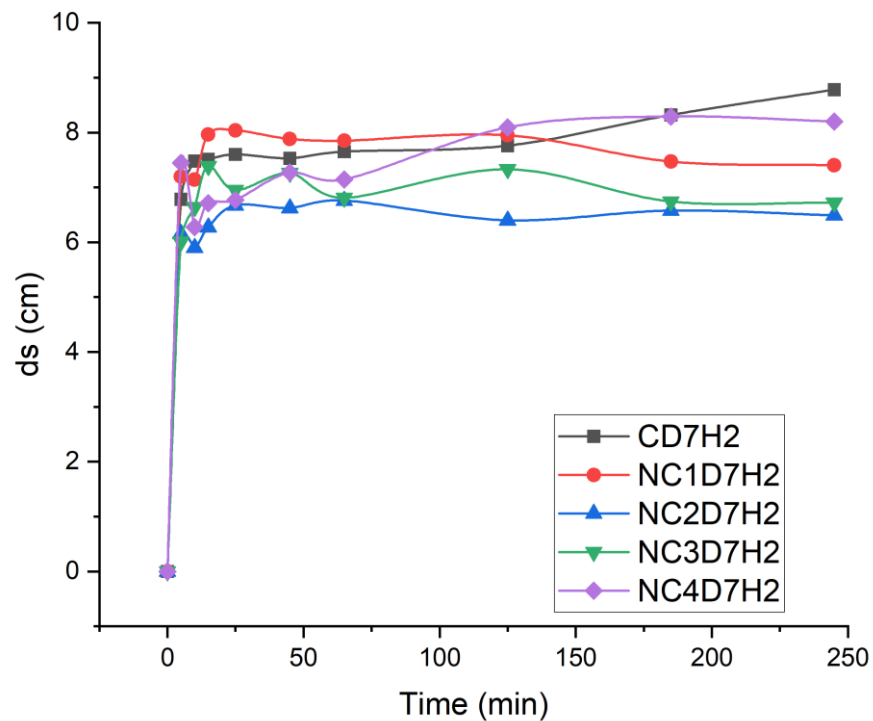


Figure 5.28 Changes in scour depth (ds) in the scenarios of a D 7.5 cm with h 7.55 cm (Nano clay- sand bed) over time.

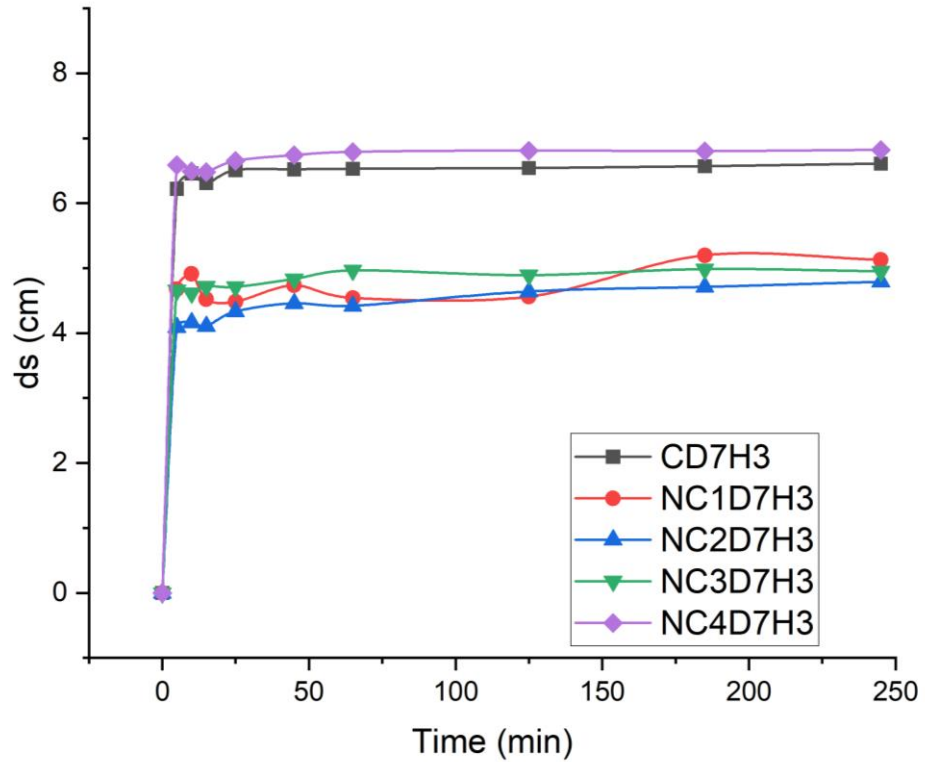


Figure 5.29 Changes in scour depth (ds) in the scenarios of a D 7.5 cm with h 9.1 cm (Nano clay- sand bed) over time.

Furthermore, this section presents the other factors' effect on the nano clay-sand bed. The relationship between the densimetric Froude number (Fr_0) and the (ds) to the characteristic diameter (D) is depicted in Figures 5.30-5.32. The nature of their relationship can be described as a direct proportionality, as demonstrated by the observed correlation between the variable Fr_0 and its corresponding increase. The observation above was also achieved by Williams et al. (2016). The Figures 5.33-5.35 illustrate the local scour hole for the optimal scenarios.

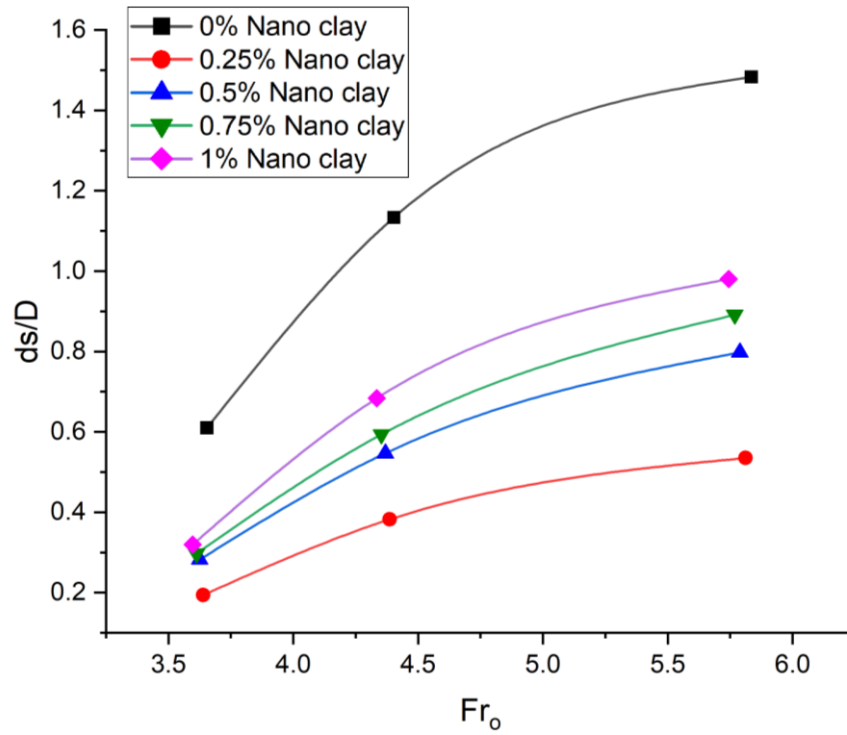


Figure 5.30 Correlation of ds/D Ratio and Fr_0 as a function of Nano Clay fraction for a D 3 cm.

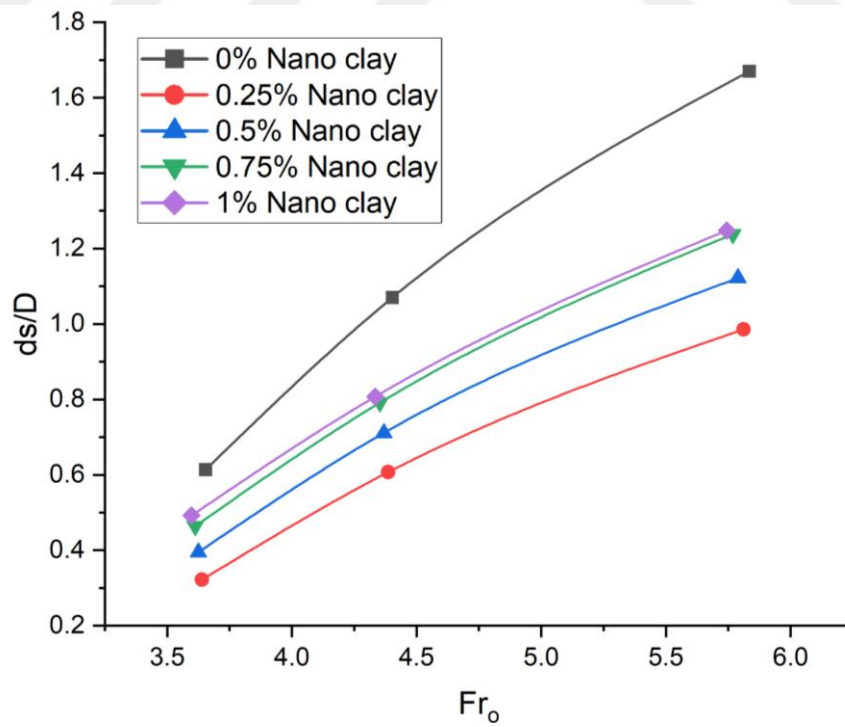


Figure 5.31 Correlation of ds/D Ratio and Fr_0 as a function of Nano Clay fraction for a D 5 cm.

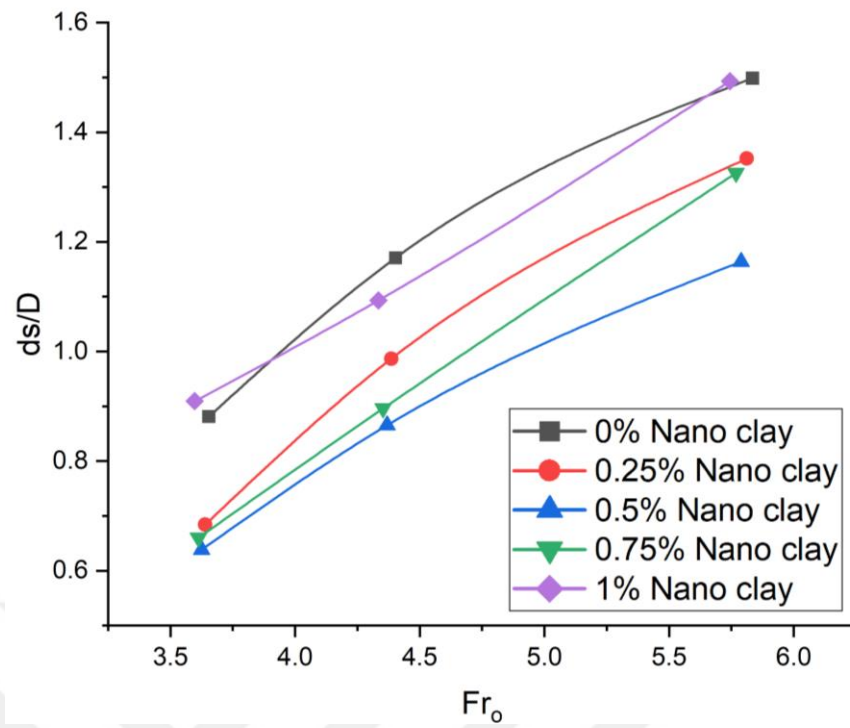


Figure 5.32 Correlation of ds/D ratio and Fr_0 as a function of Nano Clay fraction for a D 7.55 cm.

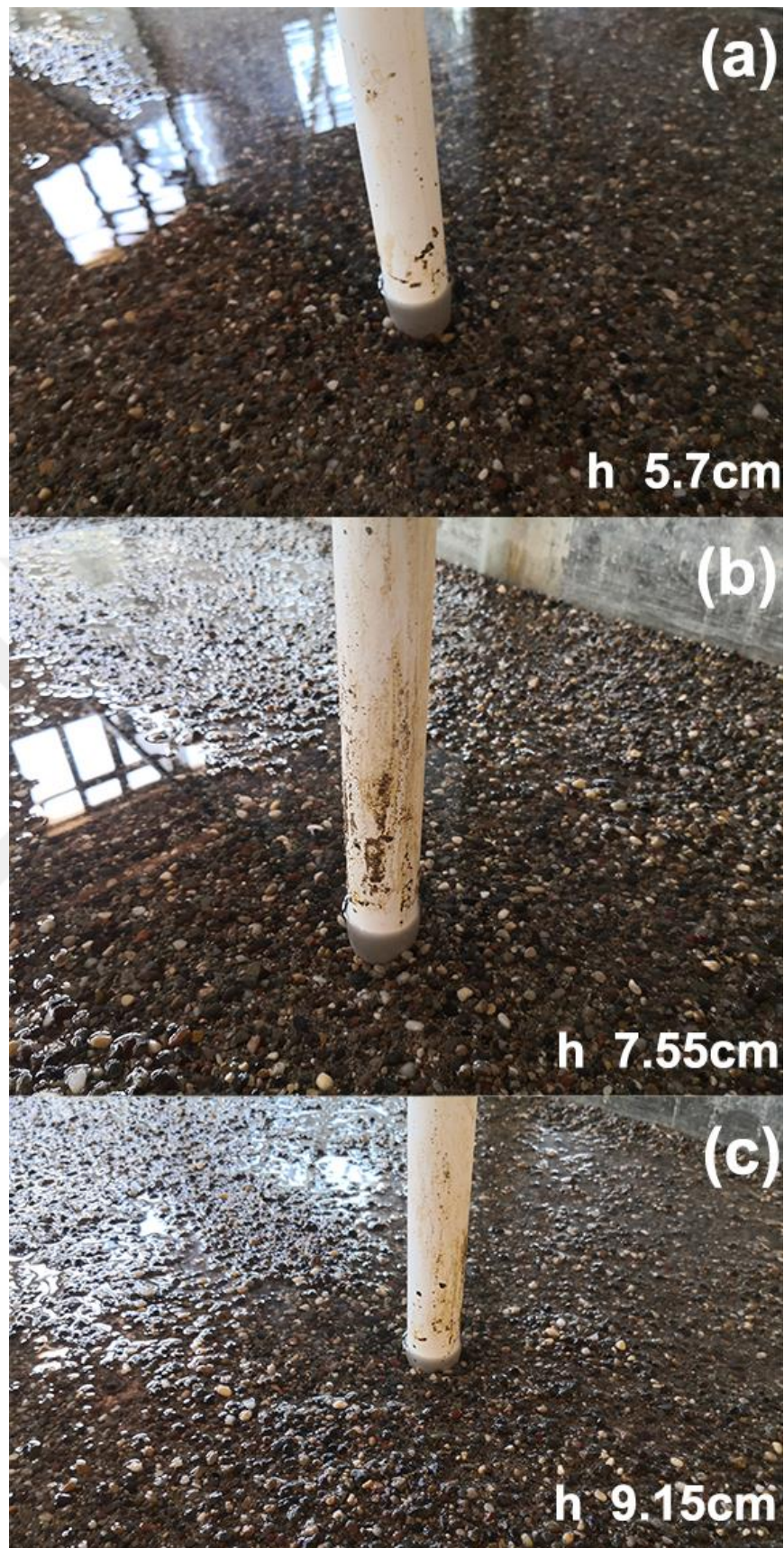


Figure 5.33 Local Scour for Scenarios: NC1D3H1, NC1D3H2, NC1D3H3.

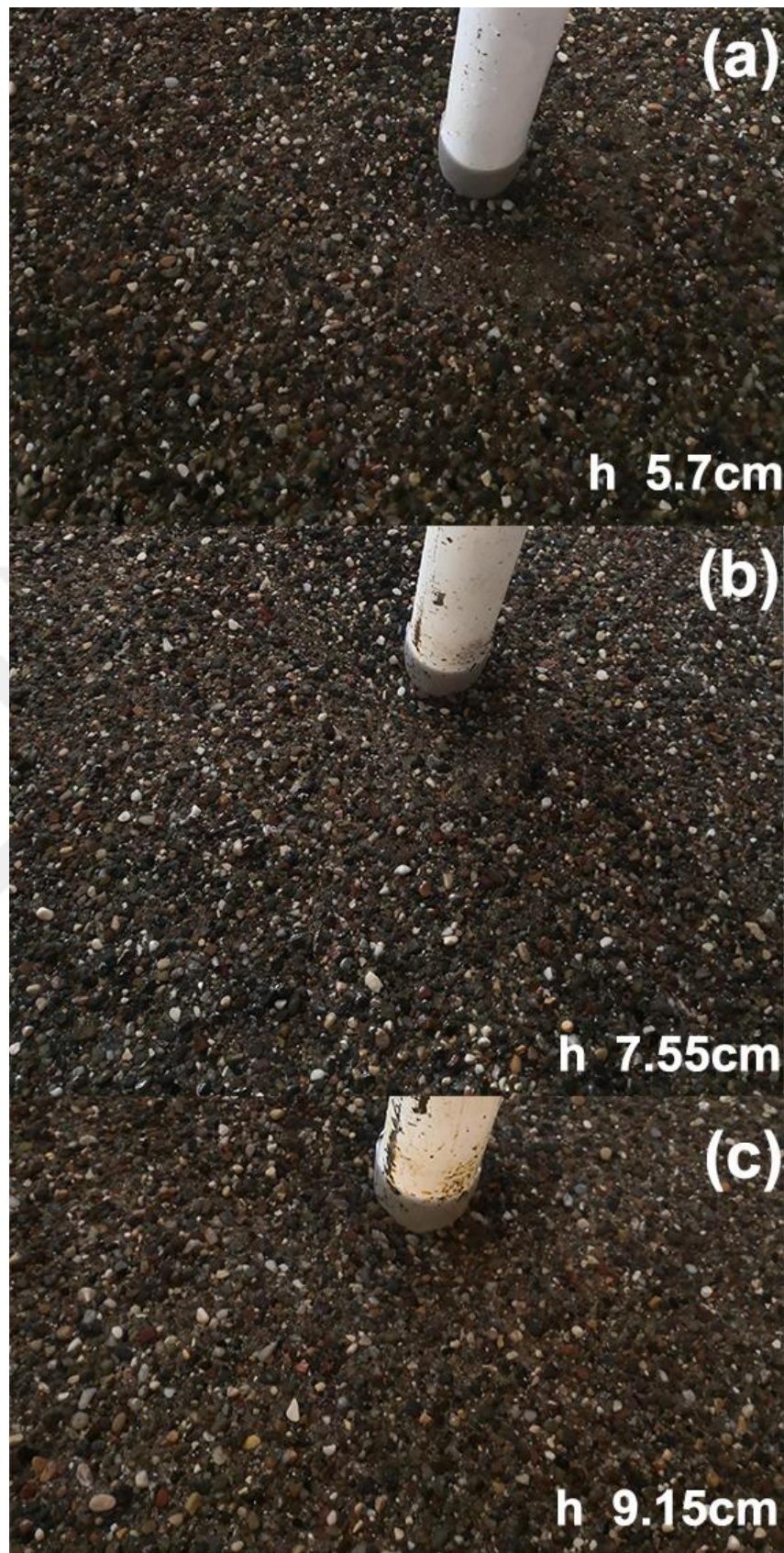


Figure 5.34 Local Scour for Scenarios: NC1D5H1, NC1D5H2, NC1D5H3.



Figure 5.35 Local Scour for Scenarios: NC2D7H1, NC2D7H2, NC2D7H3.

5.4 Nano Silica - Sand Bed

The third phase of this investigation aimed to assess the influence of mixing nano silica into the sand under the same circumstances as those used in the control test phase. Several investigations were carried out to examine the effects of various hydraulic circumstances on nano-silica-sand beds. The experiments included testing three different diameters of piers. The findings from this research phase are illustrated in Figures 5.36-5.41 and displayed in Table 5.4. These figures provide a visual comparison between the experimental group and the control group. The main objective of the research was to investigate the impact of different ratios of nano-silica to sand, ranging from 0% to 1% with increments of 0.25%.

According to the results, it was found that the fraction optimum fraction when using a 3cm pier diameter is 0.25%, as illustrated in Figure 5.36. This percentage resulted in the least amount of local scour depths for all flow depths. The scour depths were reduced by 48%, 57%, and 59.6% for flow depths of 5.7 cm, 7.55 cm, and 9.1 cm, respectively, as illustrated in Fig 5.37. The measured corresponding local scour depths were 2.33 cm, 1.46 cm, and 0.737 cm.

When the diameter of the pier increases to 5 cm, the ideal ratio of nano Silica also increases to 0.5%, as illustrated in Figure 5.38. The minimal depths of local scour were consistently observed at this 0.5% for all flow depths. The scour depths were reduced by 38.5%, 40%, and 42.6% for flow depths of 5.7 cm, 7.55 cm, and 9.1 cm, respectively, as illustrated in Fig 5.39. This resulted in scour depths of 5.13 cm, 3.21 cm, and 1.76 cm.

The results showed that a nano Silica ratio of 0.75 percent was optimum for piers with a diameter of 7.5 centimeters, as shown in Figure 5.40. This particular ratio resulted in the smallest depths of local scour for all flow depths. Maximum scour depth reductions of 19.9%, 22.7%, and 24.65% were recorded for flow depths of 5.7 cm, 7.55 cm, and 9.1 cm, respectively, as shown in Figure 5.41. These reductions corresponded to depths of 9 cm, 6.78 cm, and 4.98 cm.

The mixing of nanosilica into the sand had a substantial effect on reducing local scour and minimizing extent of erosion in the area. Figures 5.42-5.50 illustrate the effect by displaying the depth of local scour.

By increasing the nano-silica ratio, the scour depth near the pier gradually decreased, effectively mitigating erosion. The positive effect persisted until the optimal ratio was achieved, leading to the lowest local scour depth. The reduction rate decreased significantly beyond the optimum ratio, until the depth of scour was comparable to the reference tests performed without nano Silica.

The relationship between the densimetric Froude number (Fr_0) and the (ds) to the characteristic diameter (D) is depicted in Figures 5.51-5.53. The nature of their relationship can be described as a direct proportionality, as demonstrated by the observed correlation between the variable Fr_0 and its corresponding increase. The depth of scour for the optimum scenarios are shown in Figures 5.54-5.56.

Table 5.4 Results summary of the mixing nano-silica with sand.

Run	D (cm)	h (cm)	Nano Silica (%)	V (m/s)	ds (cm)	Reduction (%)
CD3H1	3	5.7	0	0.701	4.5	0%
NS1D3H1			0.25		2.33	48%
NS2D3H1			0.5		2.7	40%
NS3D3H1			0.75		2.84	37%
NS4D3H1			1		2.96	34%
CD3H2		7.55	0	0.529	3.4	0%
NS1D3H2			0.25		1.46	57%
NS2D3H2			0.5		1.94	42.9%
NS3D3H2			0.75		2.12	37.6%
NS4D3H2			1		2.19	35.5%
CD3H3		9.1	0	0.439	1.83	0%
NS1D3H3			0.25		0.738	59.6%
NS2D3H3			0.5		1.02	44.2%
NS3D3H3			0.75		1.13	38.2%
NS4D3H3			1		1.19	34.9%

CD5H1	5	5.7	0	0.701	8.35	0%
NS1D5H1			0.25		6	28.1%
NS2D5H1			0.5		5.13	38.5%
NS3D5H1			0.75		5.68	31.9%
NS4D5H1			1		7.2	13.7%
CD5H2		7.55	0	0.529	5.35	0%
NS1D5H2			0.25		3.73	30.2%
NS2D5H2			0.5		3.21	40%
NS3D5H2		7.55	0.75	0.529	3.65	31.7%
NS4D5H2			1		4.31	19.4%
CD5H3		9.1	0	0.439	3.07	0%
NS1D5H3			0.25		2.04	33.5%
NS2D5H3			0.5		1.76	42.6%
NS3D5H3			0.75		1.95	36.5%
NS4D5H3			1		2.37	22.8%
CD7H1	7.5	5.7	0	0.701	11.24	0%
NS1D7H1			0.25		10.1	10.14%
NS2D7H1			0.5		9.19	18.23%
NS3D7H1			0.75		9	19.9%
NS4D7H1			1		10.7	4.8%
CD7H2		7.55	0	0.529	8.78	0%
NS1D7H2			0.25		7.8	11.16%
NS2D7H2			0.5		6.96	20.7%
NS3D7H2			0.75		6.78	22.7%
NS4D7H2			1		8.1	7.74%
CD7H3		9.1	0	0.439	6.61	0%

NS1D7H3			0.25		5.61	15.12%
NS2D7H3			0.5		5.16	21.9%
NS3D7H3			0.75		4.98	24.65%
NS4D7H3			1		6.16	6.8%

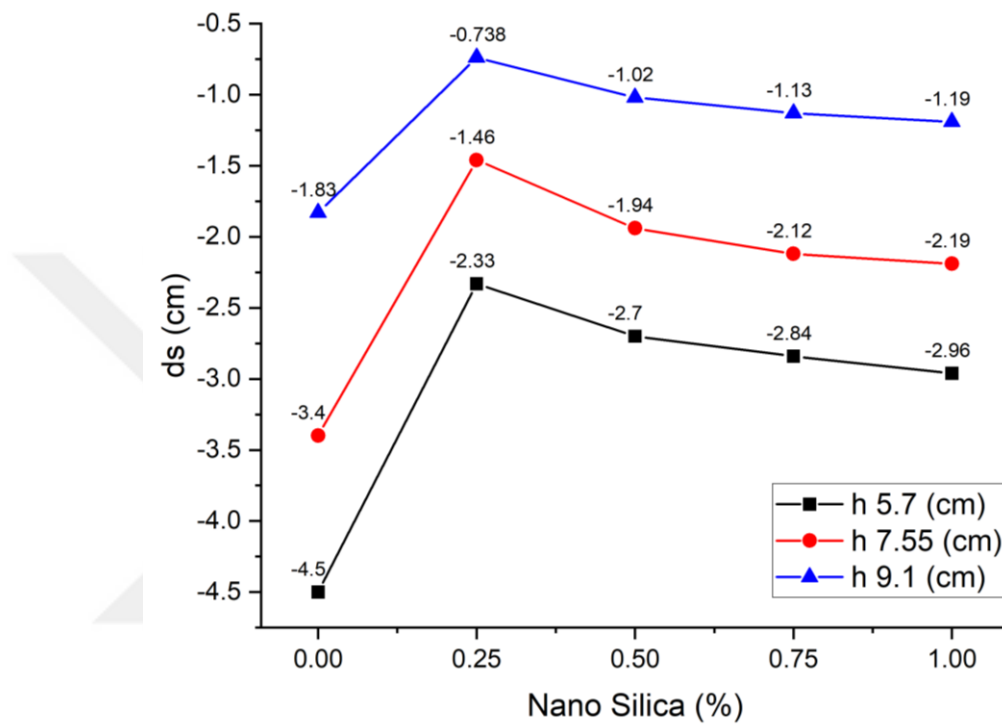


Figure 5.36 Correlation between scour depth and nano silica fraction based on flow depth, for 3 cm pier diameter cases.

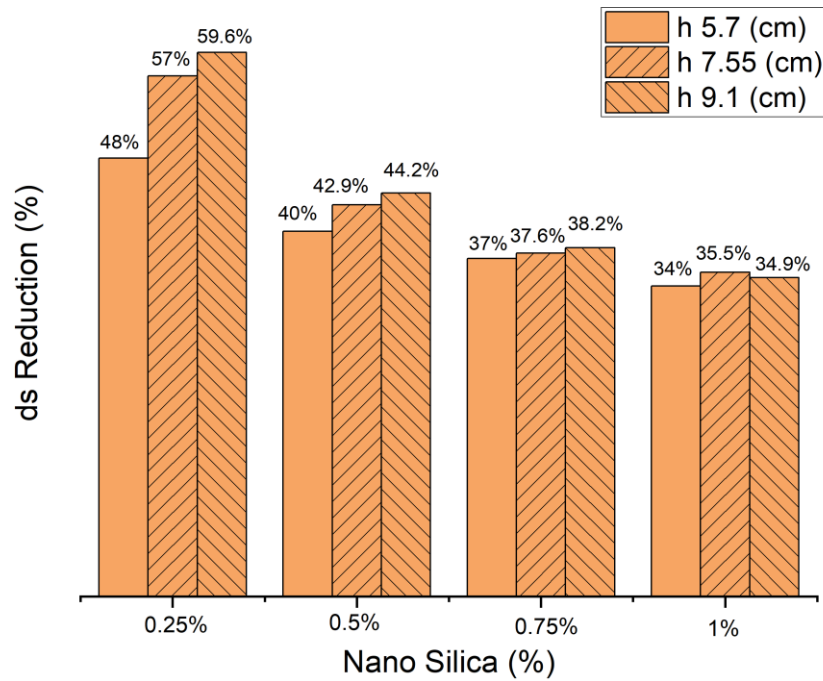


Figure 5.37 The ratio of ds reduction for 3 cm pier.

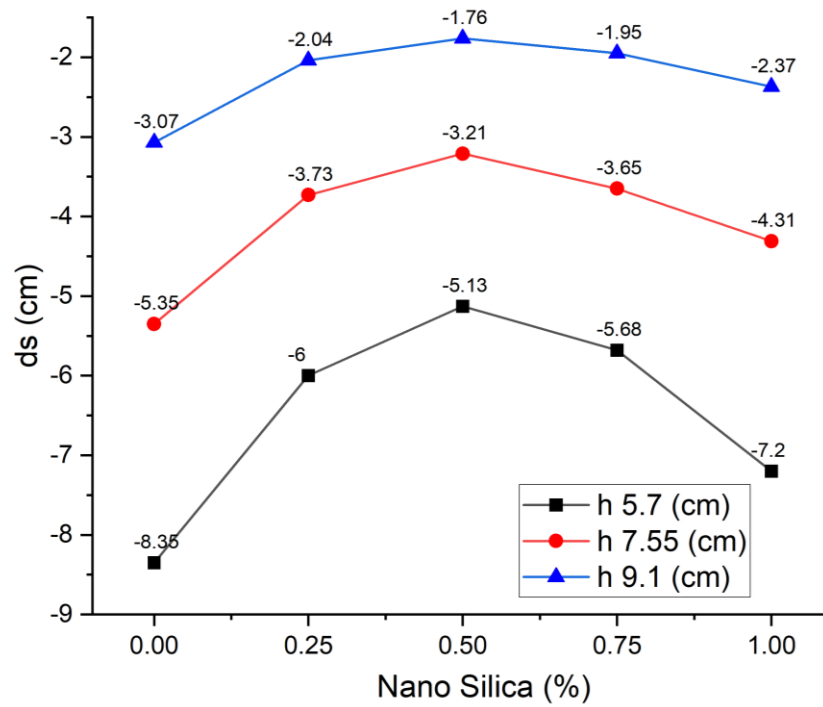


Figure 5.38 Correlation between scour depth and nano silica fraction based on flow depth, for 5 cm pier diameter cases.

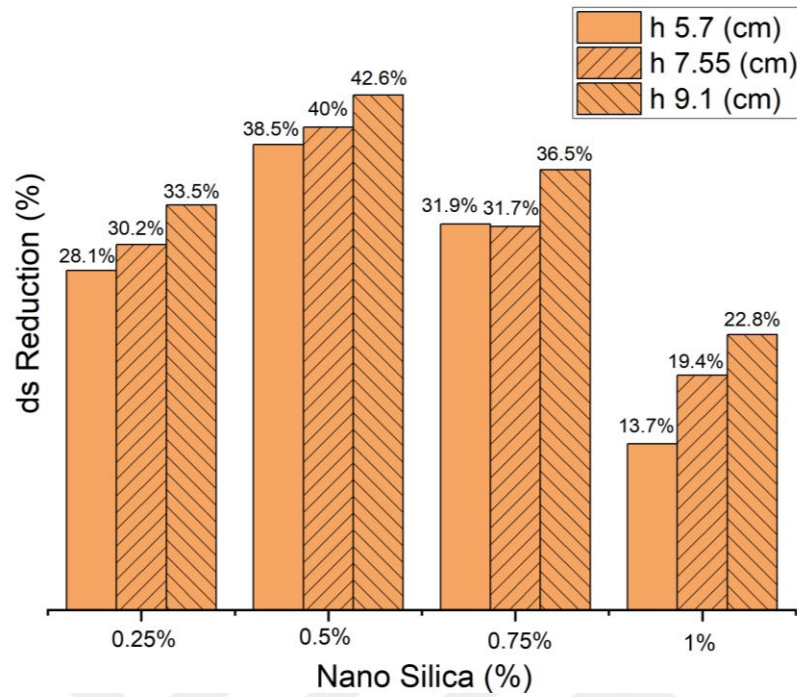


Figure 5.39 The ratio of ds reduction for 5 cm pier.

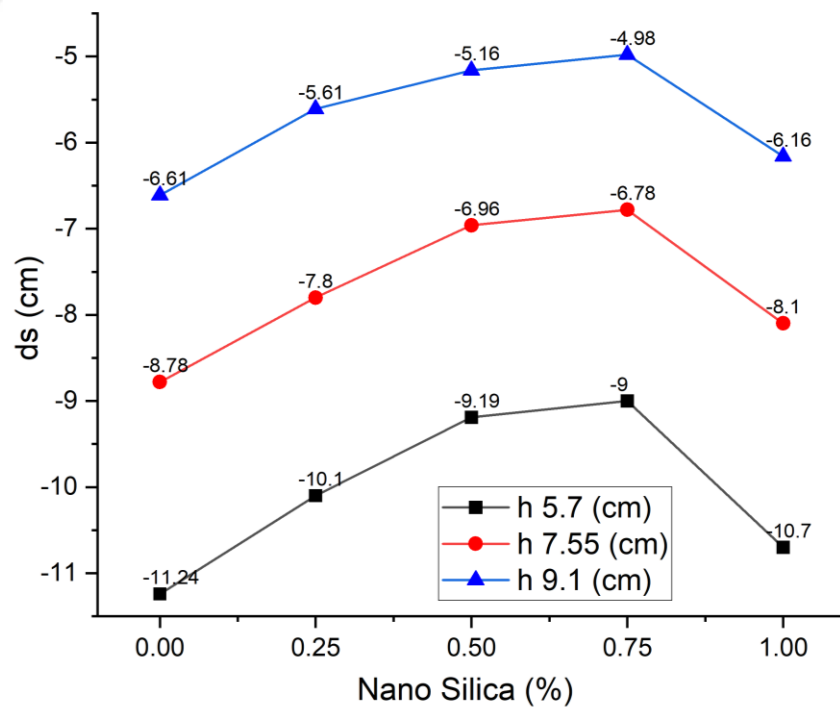


Figure 5.40 Correlation between scour depth and nano silica fraction based on flow depth, for 3 cm pier diameter cases.

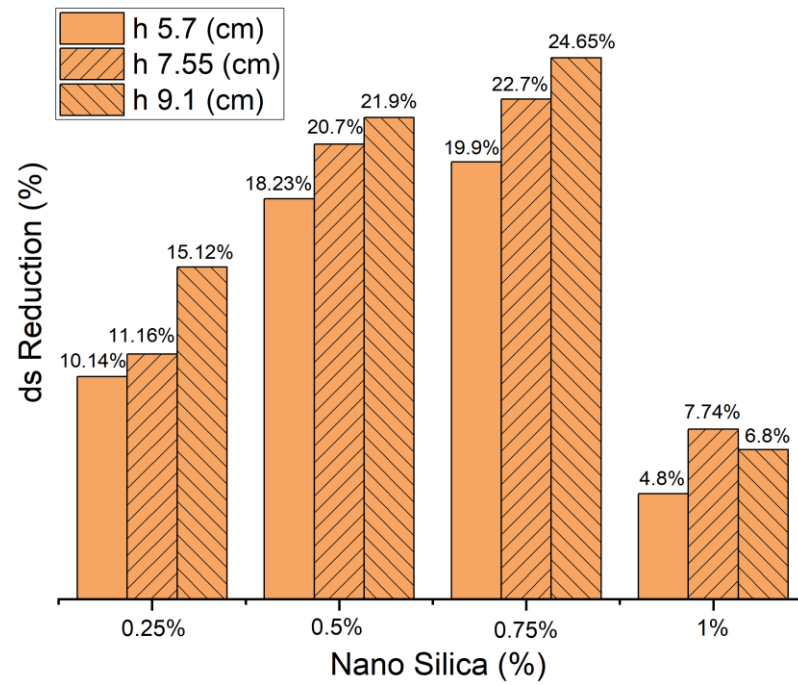


Figure 5.41 The ratio of ds reduction for 7.5 cm pier.

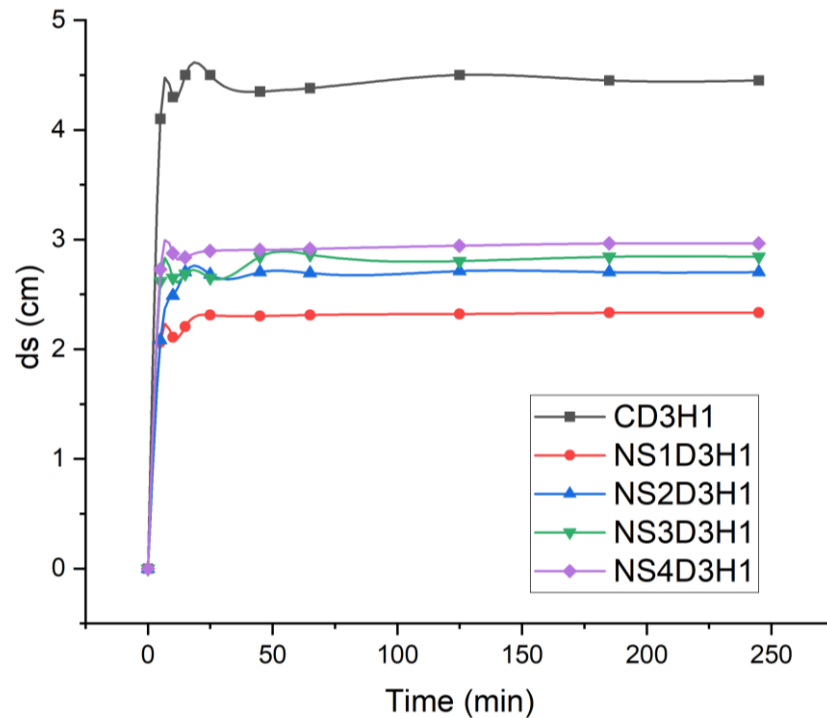


Figure 5.42 Changes in scour depth (ds) in the scenarios of a D 3 cm with h 5.7 cm (Nano silica- sand bed) over time.

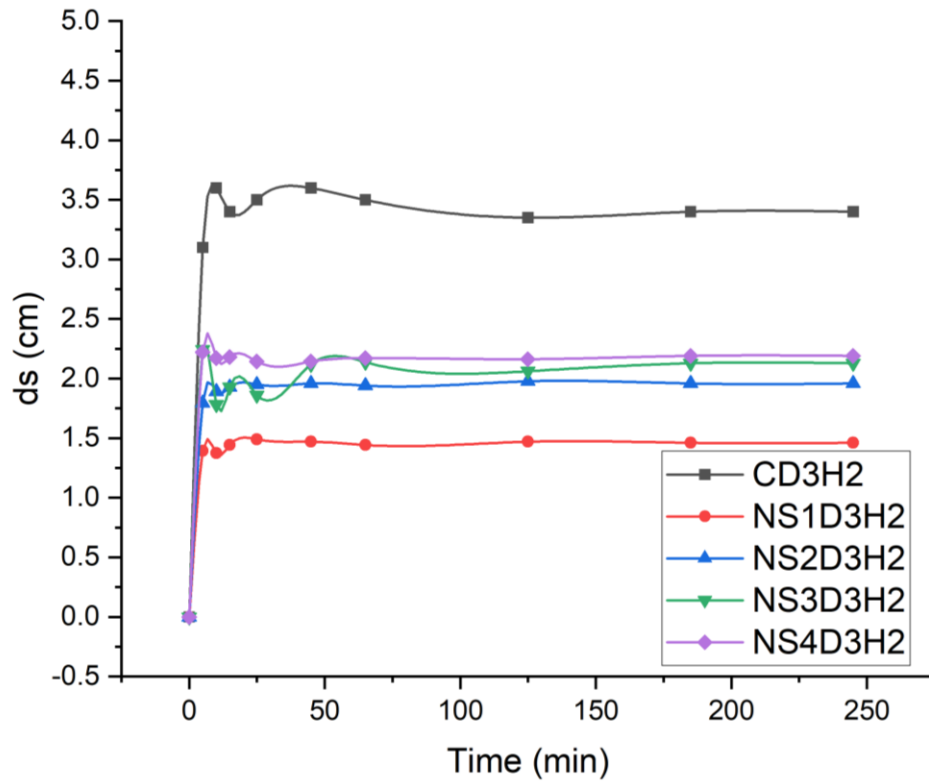


Figure 5.43 Changes in scour depth (ds) in the scenarios of a D 3 cm with h 7.55 cm (Nano silica- sand bed) over time.

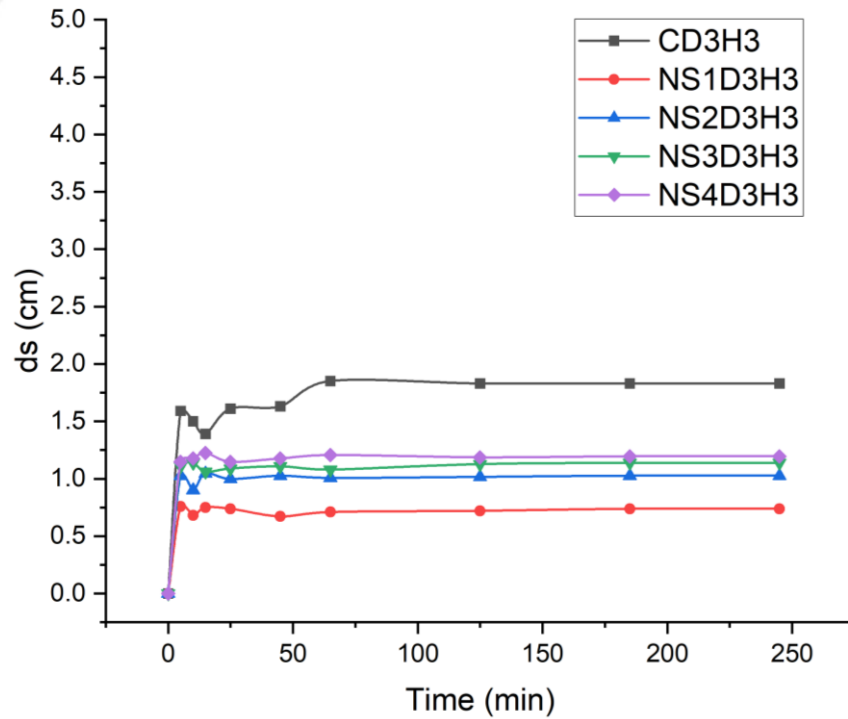


Figure 5.44 Changes in scour depth (ds) in the scenarios of a D 3 cm with h 9.1 cm (Nano silica- sand bed) over time.

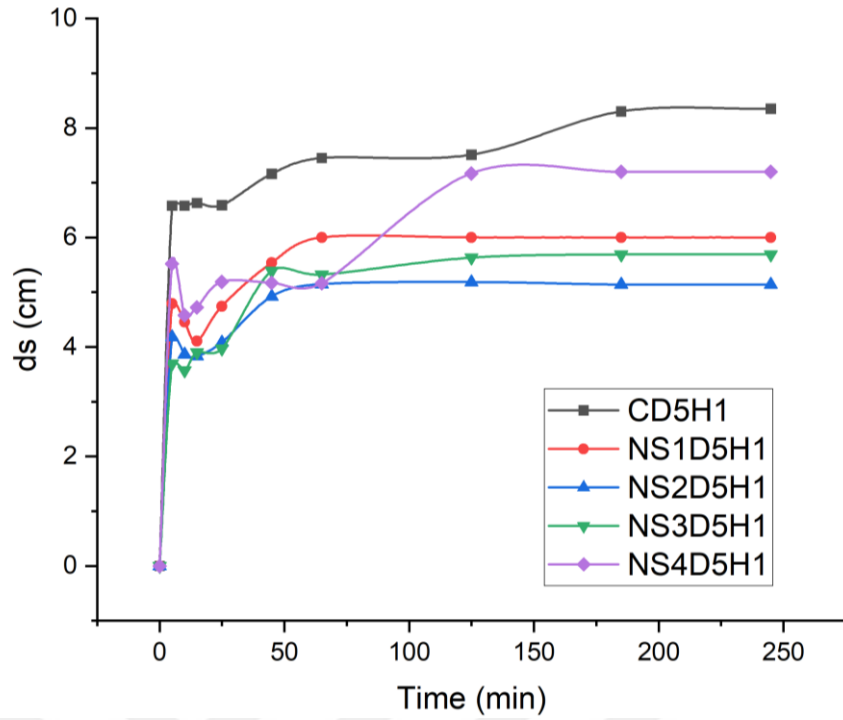


Figure 5.45 Changes in scour depth (ds) in the scenarios of a D 5 cm with h 5.7 cm (Nano silica- sand bed) over time.

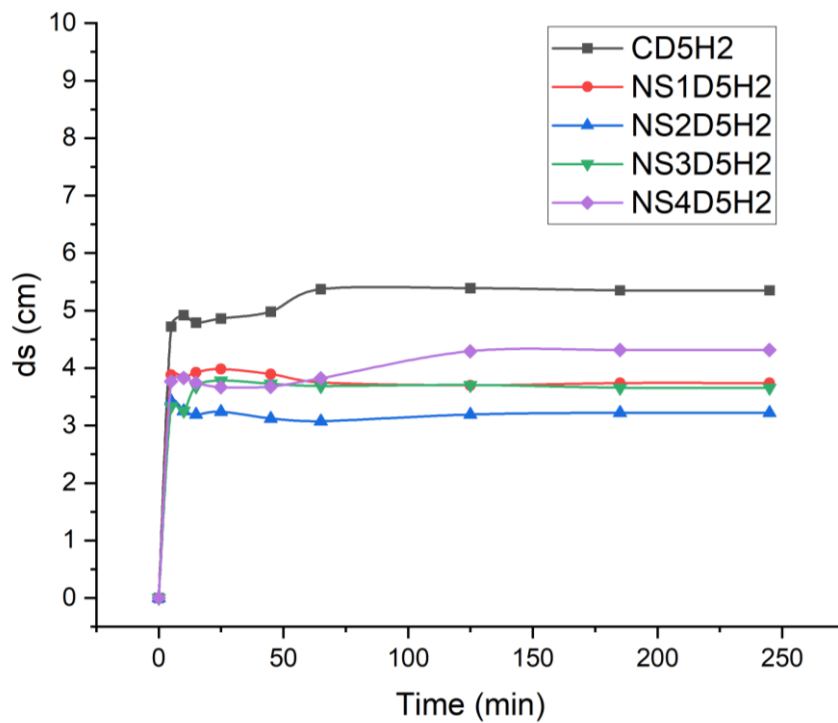


Figure 5.46 Changes in scour depth (ds) in the scenarios of a D 5 cm with h 7.55 cm (Nano silica- sand bed) over time.

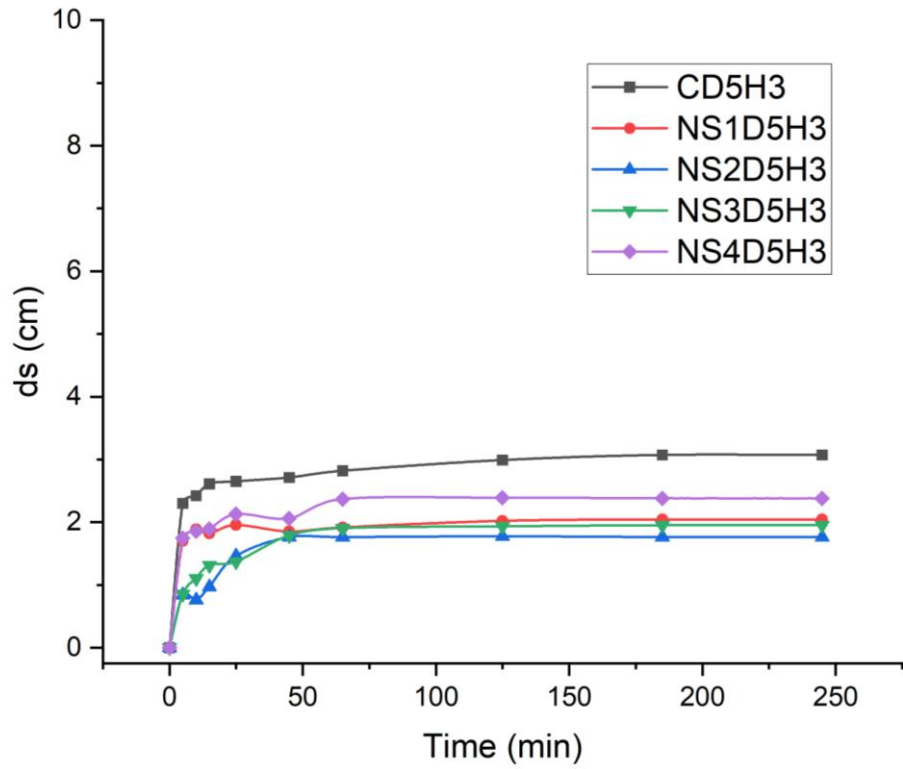


Figure 5.47 Changes in scour depth (ds) in the scenarios of a D 5 cm with h 9.1 cm (Nano silica- sand bed) over time.

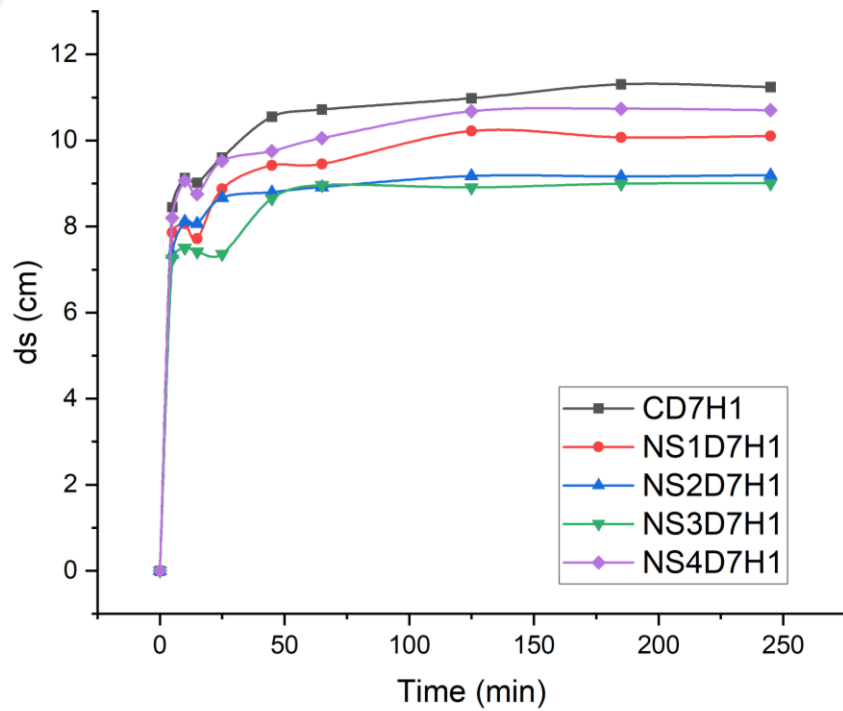


Figure 5.48 Changes in scour depth (ds) in the scenarios of a D 7.5 cm with h 5.7 cm (Nano silica- sand bed) over time.

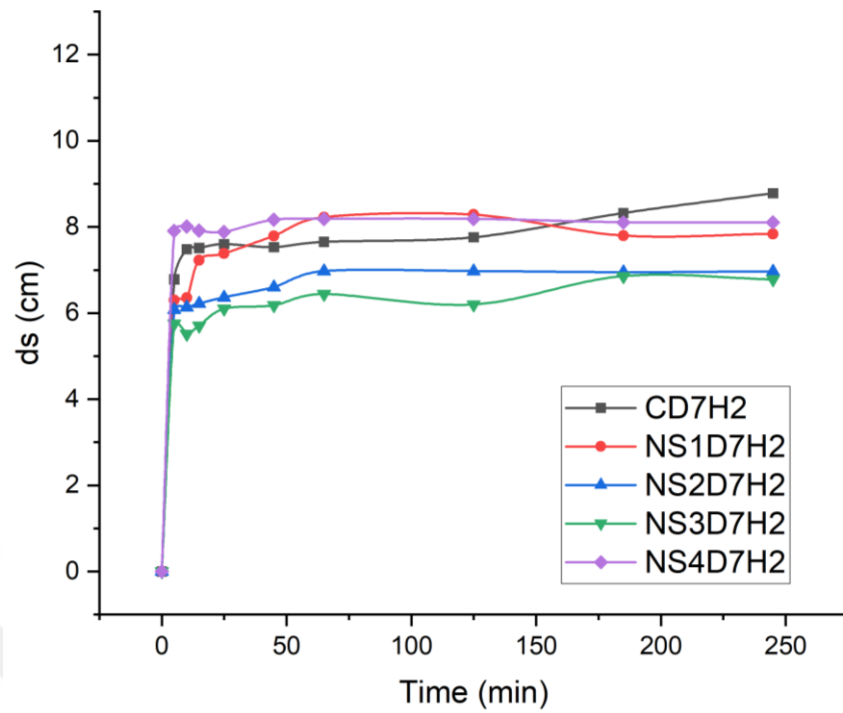


Figure 5.49 Changes in scour depth (ds) in the scenarios of a D 7.5 cm with h 7.55 cm (Nano silica- sand bed) over time.

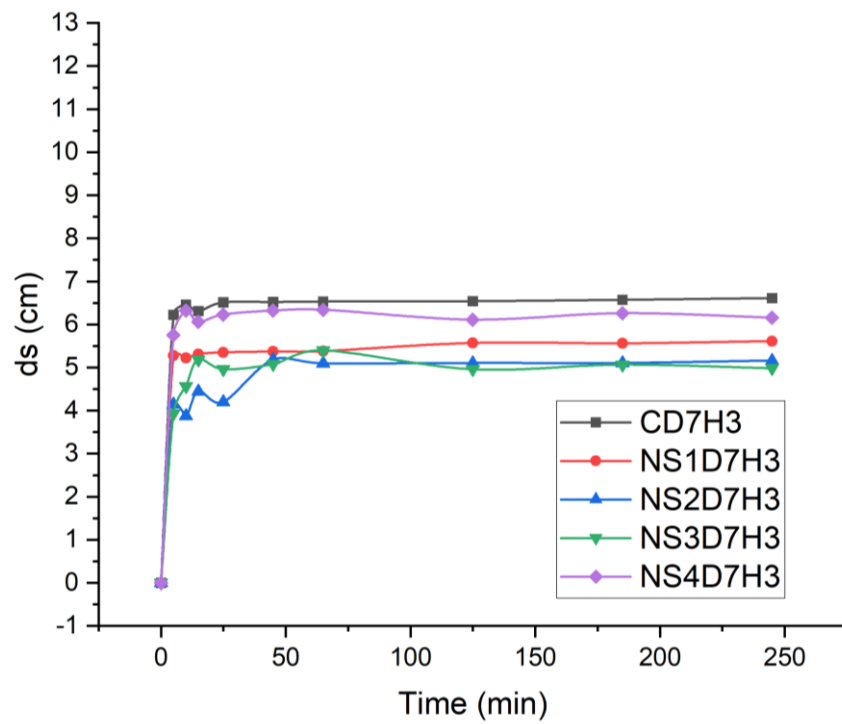


Figure 5.50 Changes in scour depth (ds) in the scenarios of a D 7.5 cm with h 9.1 cm (Nano silica- sand bed) over time.

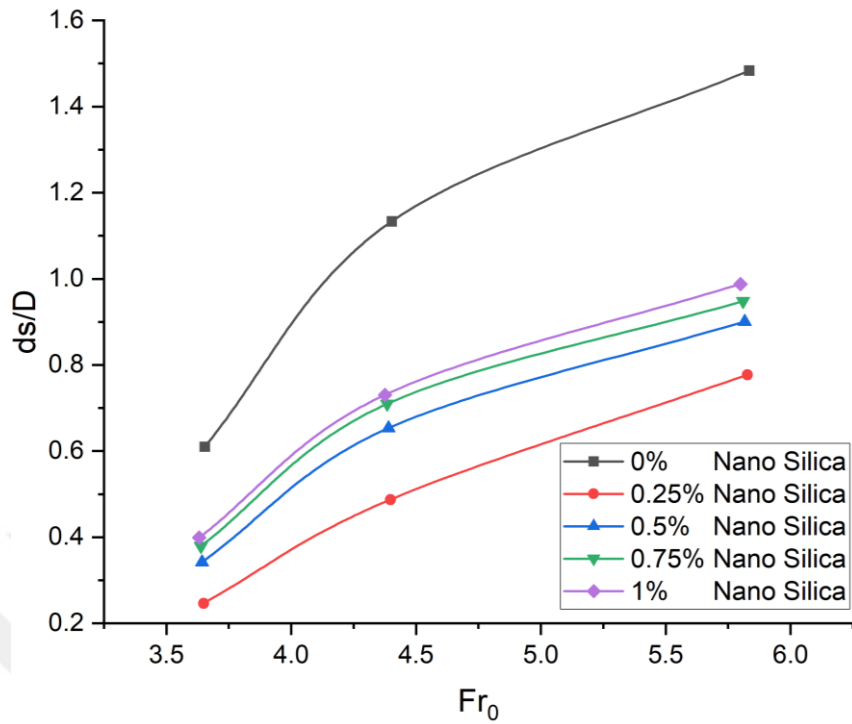


Figure 5.51 Correlation of ds/D Ratio and Fr_0 as a Function of Nano Silica Ratio for a 3 cm Diameter Pier.

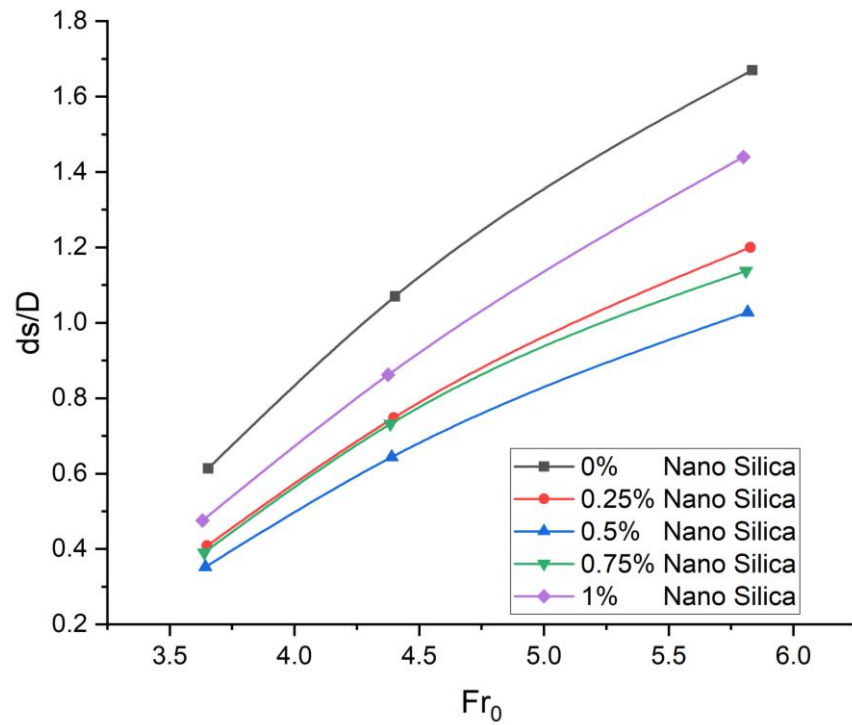


Figure 5.52 Correlation of ds/D Ratio and Fr_0 as a Function of Nano Silica Ratio for a 5 cm Diameter Pier.

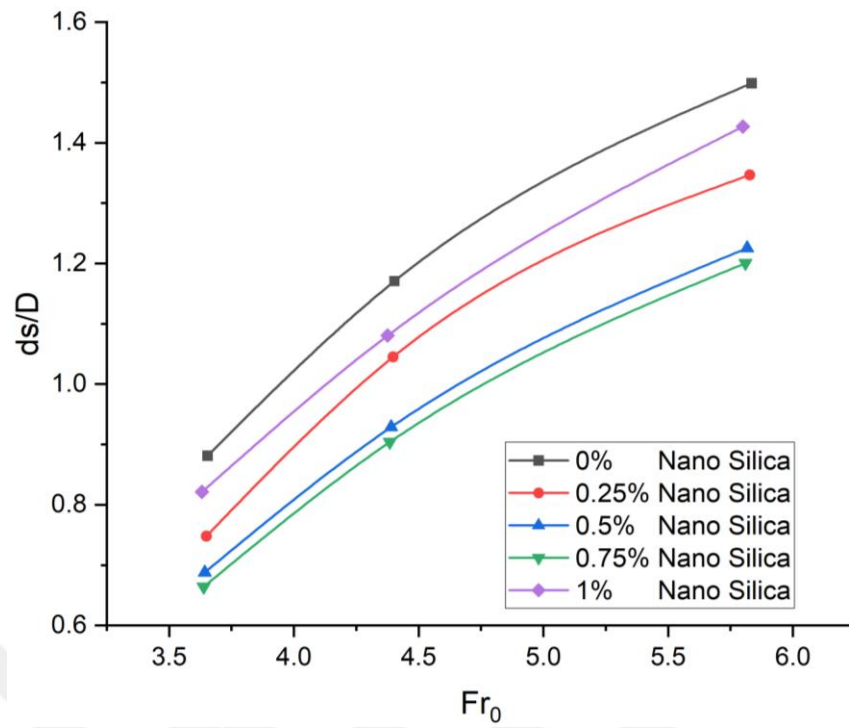


Figure 5.53 Correlation of ds/D Ratio and Fr_0 as a Function of Nano Silica Ratio for a 7.5 cm Diameter Pier.

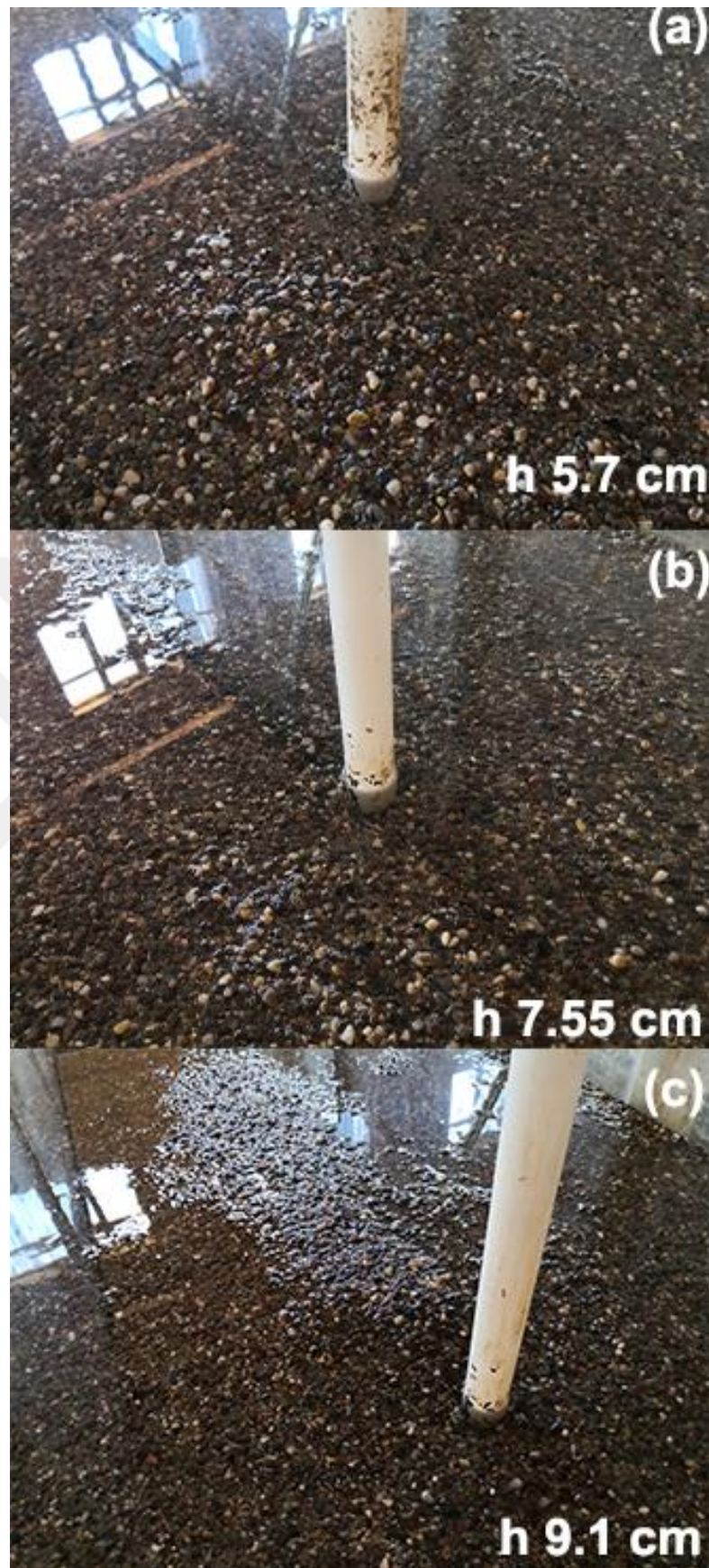


Figure 5.54 Local scour for scenarios: NC1D3H1, NC1D3H2, NC1D3H3.



Figure 5.55 Local scour for scenarios: NC2D5H1, NC2D5H2, NC2D5H3.



Figure 5.56 Local scour for scenarios: NC3D7H1, NC3D7H2, NC3D7H3.

CHAPTER 6

LOCAL SCOUR PREDICTION

6.1 Introduction

In this section, we present the prediction process for scour rate in a nano materials-sand bed. The collected data from this experimental study underwent statistical analysis, including regression analysis. A comparison was conducted between these two approaches to determine the best method for predicting the local scour depth. The dataset was subjected to regression analysis to investigate the correlations between factors and forecast the scour depth. By comparing the results collected and calculated data, Finding the optimal approach to forecasting the scour depth of the nano materials-sand bed was our primary objective. Importantly, this section only contains data for the nano materials-sand bed.

6.2 Regression Analysis

A regression analysis was applied for predicting the rate of scour depth of the nano materials-sand, utilizing the factors specified in Equation 6.1. The variables were determined using dimensional analysis, a method employed to discover the most significant elements in predicting scour depth. Tables 5.3-5.4 exhibit the compiled data, encompassing the variables and their corresponding scour depths.

$$\frac{d_s}{D} = f\left(\frac{h}{D}, \frac{d_{50}}{D}, Re_p, Mr, \sigma_g, Fr_o\right) \quad 6.1$$

Exclusion of runs involving only sand from the dataset was done to guarantee the accuracy of the analysis. This exclusion was necessary to focus specifically on the influence of nano clay in the scour mechanism. By eliminating the runs with only sand, we could isolate the impact of the nano clay and obtain more reliable predictions.

During the multiple regression analyses, it was observed that the variables σ_g and Re_p (Reynolds number) had insignificant exponents. There was not a noticeable impact of

these factors on the nano clay-sand bed's local scour depth. Therefore, they were disregarded in the final analysis.

As a result of excluding σ_g and Rep , Equation 6.1, which initially included these variables, was simplified and reduced to Equation 6.2. This revised equation provides a more focused and accurate representation of The correlations of the remaining factors and the depth of local scour in the nanomaterials-sand bed.

$$\frac{d_s}{D} = f\left(\frac{h}{D}, \frac{d_{50}}{D}, Mr, Fr_o\right) \quad 6.2$$

The equation shown below reflects the rate of scour in a material consisting of sand - nano clay, as determined using regression analysis:

$$\frac{d_s}{D} = \left(816.547 \left(\frac{h}{D}\right)^{-1.957} \left(\frac{d_{50}}{D}\right)^{1.347} Mr^{0.171} Fr_o^{-0.374}\right) \quad 6.3$$

Evaluation of the outcomes derived from equation 6.3 was the primary goal of the statistical evaluation. The study found that the actual value and the computed value from equation 6.3, were strongly related to one another—by calculating the correlation coefficient (r). The obtained r -value of 0.9769 shows that a significantly high level of consistency between the observed and predicted values.

An additional metric for assessing the degree of accuracy of the predictions was the coefficient of determination (R^2), which was found out to be 0.95314. This value suggests a strong correlation between the variables, indicating that the predictions made by the model based on equation 6.3 are highly accurate. Additionally, the root mean square error (RMSE) of 0.083 indicates that the predictions have low error, further supporting the model's accuracy.

The statistical results, showcased in Figure 6.1, demonstrate the strong correlation between predicted and actual values. This visual representation reinforces the suitability of the model for accurately predicting the depth of local scour. Thus, equation 6.3 can be used with certainty to predict the local scour in every scenario when sand and nano clay are mixed. on the highly correlated predictions provided by the model. Fig. 6.2 shows the relation between all variables.

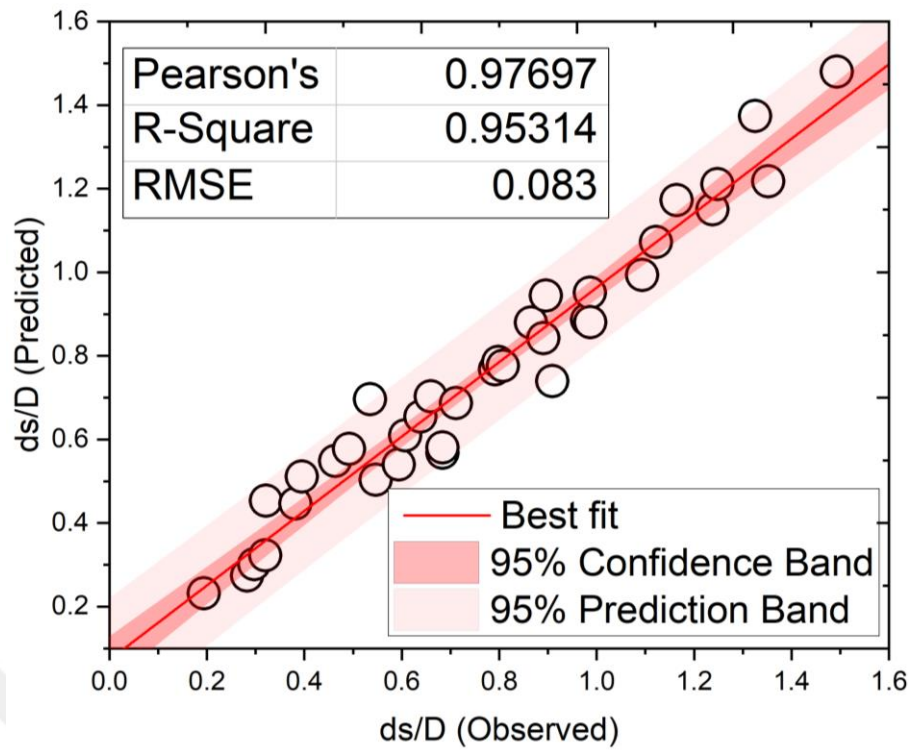


Figure 6.1 Predicted and observed ds/D (Nano clay-sand bed).

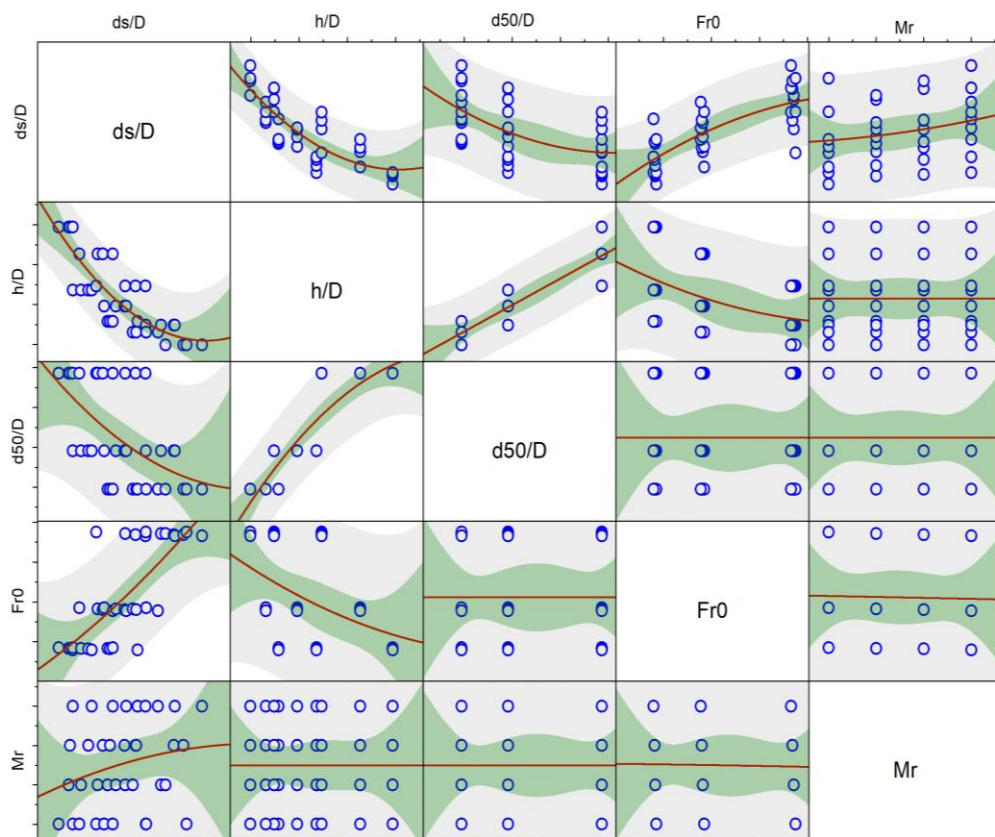


Figure 6.2 The correlation between the variables Nano clay-sand bed.

The equation shown below reflects the rate of scour in a material consisting of nano silica and sand, as determined using regression analysis:

$$\frac{d_s}{D} = 198.615 \left(\frac{h}{D}\right)^{-1.673} \left(\frac{d_{50}}{D}\right)^{1.203} Mr^{0.085} Fr_o^{-0.113} \quad 6.4$$

To assess the accuracy of this equation, statistical analysis was conducted. The Pearson correlation coefficient (r) was applied to measure the level of the correlation between the observed values and the calculated values obtained via equation 6.4. The Pearson correlation coefficient (r) was found to be 0.937, The predicted values show a significant degree of consistency with the actual values..

In addition, the was (R^2) computed as 0.87, indicating that there are reliable and accurate forecasts with minimal error. The root mean square error (RMSE) was determined to be 0.112, further supporting the accuracy of the predictions.

The statistical results in Figure 6.3 illustrate a close agreement between the model's predictions and the actual values. Thus, it can be inferred that the model is highly suitable for estimating the level of local scour in circumstances when sand - nano Silica bed. Equation 6.4 can be utilized in such cases to make accurate predictions. Fig. 6.4 shows the relation between all variables.

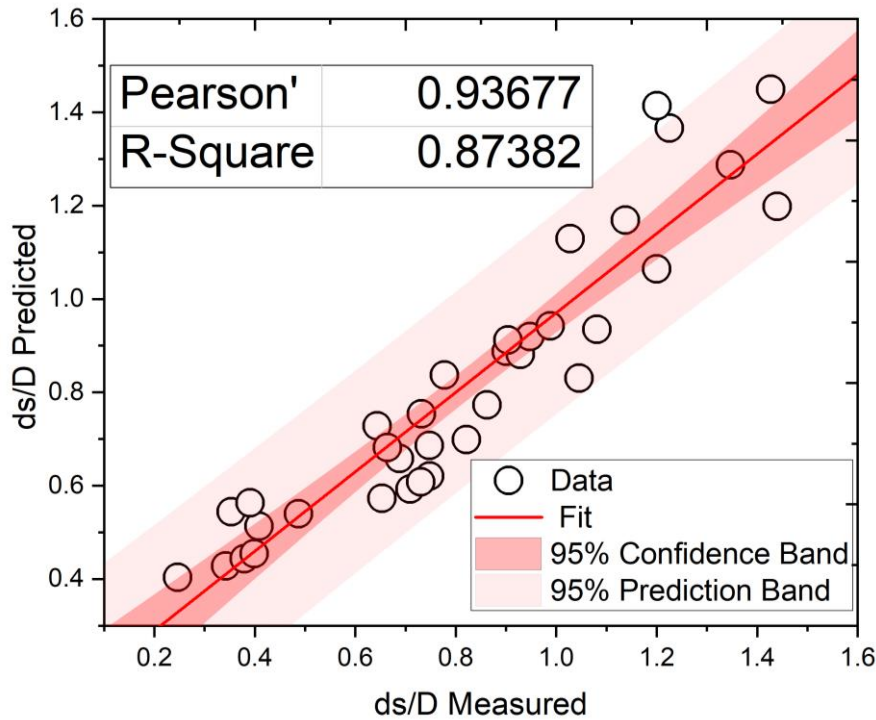


Figure 6.3 Predicted and observed ds/D (Nano Silica-sand bed).

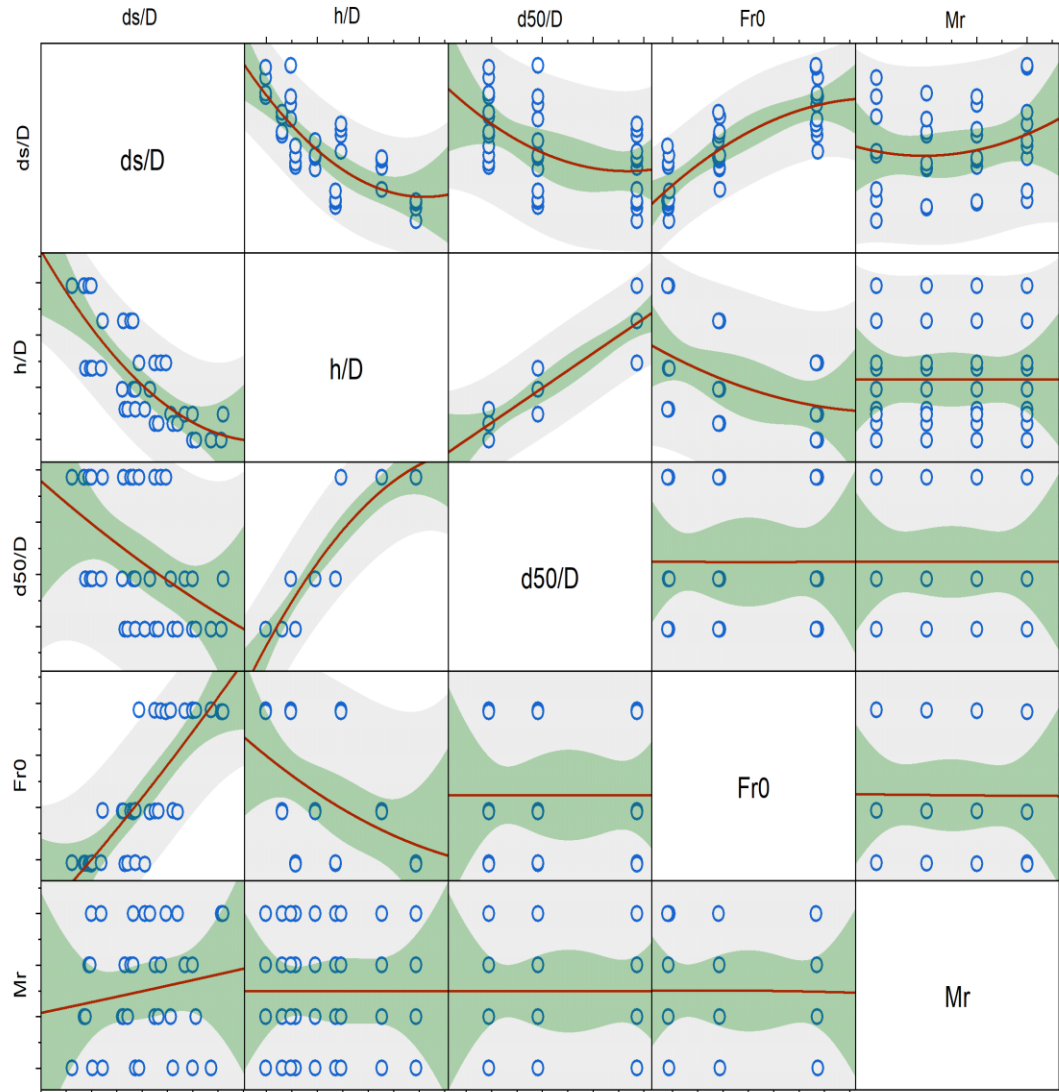


Figure 6.4 The correlation between the variables Nano silica-sand bed.

CHAPTER 7

CONCLUSION AND RECOMMENDATION

7.1 Conclusion

The primary aim of this extensive experimental investigation was to carefully examine and clarify the complex relationship between nanomaterials and the depth of local scour when combined with sand. The research protocol consisted of 81 carefully planned experiments, which were divided into three distinct and interconnected segments. Every segment was carefully designed to offer crucial insights into the intricate dynamics of scour depth under different hydraulic and nanomaterial conditions.

The study initially focused on conducting fundamental control tests. Throughout this phase, an overall total of nine tests were carried out. The research experiments were conducted by using different flow depths while keeping the discharge rate constant. Additionally, a non-uniform sand bed was used as the baseline scenario for all the experiments. The control group played a vital role in the investigation by providing a necessary reference point to measure and compare the effects of nanomaterials in the later stages.

The second phase of the experimental investigation was to examine the impact of nano clay, a significant nanomaterial, on the depth of local scour. A series of 36 trials were conducted, wherein the hydraulic conditions were maintained identical to those seen in the control tests. In this phase, we systematically varied the ratio of nano clay, including four different proportions: 0.25%, 0.5%, 0.75%, and 1%. By systematically varying the nano clay content, we were able to thoroughly evaluate the impact of different concentrations of nanomaterials on the depth of scour, compared to the control tests. The researchers aimed to find the optimal nano clay ratio for scour prevention and reduction.

The last phase of the experimental investigation was specifically designed to explore the impacts of nano silica, which is another important nanomaterial. Similar to the second phase, we conducted 36 tests with different ratios of nano silica (0.25%, 0.5%, 0.75%, and 1%). Throughout these tests, we ensured that the hydraulic conditions remained consistent, just like in the control tests. This segment aims to provide clear information on the specific impact of nano silica on local scour depth under different scenarios. It seeks to elucidate the essential details regarding how nano silica contributes to the phenomenon of local scour depth.

Moreover, this research extended beyond the simple examination of experimental data. The analysis was expanded to include the development of prediction equations, which were derived using advanced non-linear regression techniques. The purpose of formulating these equations was to mathematically represent the relationships between flow conditions, sand properties, and nanomaterial concentrations. This allows for a more predictive understanding of scour depth.

In addition, regression analysis was carefully developed in conjunction with the experimental approach. The objective of developing these models was to forecast the local scour in beds that are made up of a mixture of sand and nanomaterials.

The aforementioned steps and their respective outcomes yielded numerous significant findings, which can be regarded as the conclusive outcomes of this study:

Initially, our initial experimental phase (control tests) focused exclusively on using non-uniform sand as the bed material. During this phase, we have discovered a significant relationship between critical parameters. A direct correlation between the pier's diameter and the local scour rate was observed. It was observed that when the flow depth decreased, there was a corresponding rise in the depth of local scour. This highlights the complex and nonlinear nature of these relationships. These outcomes make significant contributions to our understanding of scouring phenomena, improving our overall understanding of the dynamic and complex processes in this field.

Secondly, the nano clay utilization has shown a substantial influence on the scour mechanism. Particularly affected by the fraction of nano clay utilized is the scour depth. The important discovery was that a decrease in the proportion of nano clay

resulted in a reduction in local scour depth, and a rise in the nano clay amount resulted in a corresponding rise in the depth of local scour. This shows that reducing pier scour could be possible by optimizing the fraction of nano clay to sand. The recommended proportion of nano clay for narrow piers with a ratio of h/D less than 1.4 is 0.25%, according to the findings of our study. This concentration has been shown to significantly reduce scour depth. It is important to mention that the ideal mixing proportion remained constant for narrow piers. However, for wider piers with a flow shallowness exceeding 1.4, an increased optimal mixing ratio of 0.5% was observed. These findings emphasize the possibility of developing customized solutions that are specifically designed to meet the requirements of different piers.

Moreover, The utilization of nanosilica led to a substantial decrease in depth of scour, especially noticeable when considering smaller diameters of the pier and higher water depths. The test results indicated that the highest reduction percentages were 59.6% for $D = 3$ cm, 42.6% for $D = 5$ cm, and 24.65% for $D = 7.5$ cm. This highlights the effectiveness of nanosilica as a viable solution for reducing depth local scour. It was observed the ideal nanosilica ratios rise as the diameter of the cylindrical pier increased, while using sand with similar properties. It is noteworthy that these optimal ratios closely matched the quantity of fine particles found in non-uniform sand, which further highlights their appropriateness.

Furthermore, the utilization of regression analysis with normalized variables has demonstrated remarkable predictive capabilities for determining local scour depth. The incorporation of Fr_0 as a critical factor, prioritizing sediment motion over critical velocity, is attributed to the success achieved. This method offers the potential to enhance the effectiveness of mitigation strategies by improving the accuracy in predicting scour depth.

Finally, this research holds great importance for practical application. The use of nanomaterials shows great potential in addressing the issue of bridge pier scour. The practical application of optimal nanomaterial ratios in non-uniform sand is facilitated by their close proximity to the fine sand particle content. By using this new method in bridge construction, it can be put into place without any problems. This gives us useful information and could lead to more study in preventing erosion and stabilizing riverbeds. In addition, the utilization of nano clay and nanosilica offers numerous

benefits. These include their safety, eco-friendliness, cost-effectiveness, and suitability for various stages of construction and remediation.

Overall, this work represents a substantial advancement in the pursuit of sustainable and economically efficient approaches to solve bridge pier scour. It is expected that future research in this field will result in more advancements and insights, ultimately leading to the development of stronger solutions for protecting bridge infrastructure.

7.2 Recommendations

1. More research is necessary to investigate the application of different pier shapes when mixed with sand beds infused with nanomaterials.
2. Improve the methods of numerical modeling to simulate scouring processes. When nanomaterials are included, computational fluid dynamics (CFD) and other modeling techniques should be used to improve the predicted accuracy of scour development under various conditions.
3. Conduct on-site studies to verify lab findings and assess the viability and efficiency of nanomaterials for reducing actual bridge pier scour. This might mean doing experimental programs at real bridge locations.
4. Examine the extent of local scour in a collection of piers on sand beds infused with nanomaterials.
5. Examine the effects of reorienting bridge piers to scour depth in situations with sand infused with nanomaterials.
6. Examine the local scour rate in sand and nanomaterial compacted beds.

REFERENCES

- Abdalla, M. G. (January 20, 2017). A Study on Scour for Irrigation Canals in Egypt, “Case Study: The First Reach of El-ibrahimeya Canal”. *American Journal of Engineering and Technology Management*, 1, No. 4,, 65-77.
<https://doi.org/10.11648/j.ajetm.20160104.13>
- Aguirre-Pe, J., Olivero, M. 1. a. L., & Moncada, A. T. (2003). Particle densimetric Froude number for estimating sediment transport. *Journal of Hydraulic Engineering*, 129(6), 428-437.
[https://doi.org/https://doi.org/10.1061/\(ASCE\)0733-9429\(2003\)129:6\(428\)](https://doi.org/https://doi.org/10.1061/(ASCE)0733-9429(2003)129:6(428))
- Ajansı, A. Çaycuma'da köprü çöktü. In. Anadolu Ajansı: Anadolu Ajansı.
- Akhlaghi, E., Babarsad, M. S., Derikvand, E., & Abedini, M. (2020). Assessment the effects of different parameters to rate scour around single piers and pile groups: a review. *Archives of Computational Methods in Engineering*, 27(1), 183-197.
- Al-Shukur, A.-H. K., & Obeid, Z. H. (2016). Experimental study of bridge pier shape to minimize local scour. *International Journal of Civil Engineering and Technology*, 7(1), 162-171.
- Alasta, M. S., Ali, A. S. A., Ebrahimi, S., Ashiq, M. M., Dheyab, A. S., AlMasri, A., Alqatanani, A., & Khorram, M. (2022). Modeling of local scour depth around bridge pier using FLOW 3D. *CRPASE: Transactions of Civil and Environmental Engineering*, 8(2), 1-9.
- Amos, C. L., Daborn, G., Christian, H., Atkinson, A., & Robertson, A. (1992). In situ erosion measurements on fine-grained sediments from the Bay of Fundy. *Marine geology*, 108(2), 175-196.
- Ansari, S., Kothiyari, U., & Ranga Raju, K. (2002). Influence of cohesion on scour around bridge piers. *Journal of hydraulic research*, 40(6), 717-729.
- Apsilidis, N., Diplas, P., Dancey, C. L., Vlachos, P. P., & Raben, S. G. (2010). *Local Scour at Bridge Piers: The Role of Reynolds Number on Horseshoe Vortex Dynamics* Scour and Erosion,

- Arved J. Raudkivi, R. E. (1983). Clear-Water Scour at Cylindrical Piers. *Journal of Hydraulic Engineering*, 109(3). [https://doi.org/10.1061/\(ASCE\)0733-9429\(1983\)109:3\(338\)](https://doi.org/10.1061/(ASCE)0733-9429(1983)109:3(338))
- Baker, C. J. (1980). The turbulent horseshoe vortex. *Journal of Wind Engineering and Industrial Aerodynamics*, 6(1), 9-23. [https://doi.org/https://doi.org/10.1016/0167-6105\(80\)90018-5](https://doi.org/https://doi.org/10.1016/0167-6105(80)90018-5)
- Baker, R. E. (1986). Local scour at bridge piers in non uniform sediment.
- Baykal, C., Sumer, B. M., Fuhrman, D. R., Jacobsen, N. G., & Fredsoe, J. (2015). Numerical investigation of flow and scour around a vertical circular cylinder. *Philos Trans A Math Phys Eng Sci*, 373(2033). <https://doi.org/10.1098/rsta.2014.0104>
- Bierawski, L. G., & Maeno, S. (2006). DEM-FEM model of highly saturated soil motion due to seepage force. *Journal of waterway, port, coastal, and ocean engineering*, 132(5), 401-409.
- Breusers, H., Nicollet, G., & Shen, H. (1977). Local scour around cylindrical piers. *Journal of hydraulic research*, 15(3), 211-252. <https://doi.org/https://doi.org/10.1080/00221687709499645>
- Breusers, H., & Raudkivi, A. J. (1991). *Scouring*. Balkema Rotterdam.
- C136-01, A. (2001). Test Method for Sieve Analysis of Fine and Coarse Aggregates.
- Chandrasekaran, S. (2020). *Design of marine risers with functionally graded materials*. Woodhead Publishing.
- Chaudhuri, S., & Debnath, K. (2013). Observations on initiation of pier scour and equilibrium scour hole profiles in cohesive sediments. *ISH Journal of Hydraulic Engineering*, 19(1), 27-37.
- Chaudhuri, S., Pandey, M., Debnath, K., & Oliveto, G. (2022). A comparative study on equilibrium scour volume around circular cylinders in clay–sand mixed cohesive beds, at near threshold velocity of sand—an experimental approach. *Water Supply*, 22(8), 6777-6791. <https://doi.org/https://doi.org/10.2166/ws.2022.250>
- Chepil, W. (1958). The use of evenly spaced hemispheres to evaluate aerodynamic forces on a soil surface. *Eos, Transactions American Geophysical Union*, 39(3), 397-404.

- Chiew, Y.-M., & Melville, B. W. (1987). Local scour around bridge piers. *Journal of hydraulic research*, 25(1), 15-26.
<https://doi.org/https://doi.org/10.1080/00221688709499285>
- Chiew, Y., & Melville, B. (1996). Temporal development of local scour depth at bridge piers. North American Water and Environment Congress, ASCE, Anaheim, California, USA,
- Chiew, Y. M. (1984). Local scour at bridge piers. *Publication of: Auckland University, New Zealand*.
- Choi, S.-U., Choi, B., & Lee, S. (2017). Prediction of local scour around bridge piers using the ANFIS method. *Neural Computing and Applications*, 28, 335-344.
- Choi, S.-U., & Choi, S. (2022). Prediction of local scour around bridge piers in the cohesive bed using support vector machines. *KSCE Journal of Civil Engineering*, 26(5), 2174-2182.
- Choi, S. U., & Cheong, S. (2006). Prediction of local scour around bridge piers using artificial neural networks 1. *JAWRA Journal of the American Water Resources Association*, 42(2), 487-494.
- Daneshfaraz, R., Abam, M., Heidarpour, M., Abbasi, S., Seifollahi, M., & Abraham, J. (2022). The impact of cables on local scouring of bridge piers using experimental study and ANN, ANFIS algorithms. *Water Supply*, 22(1), 1075-1093.
- Dargahi, B. (1989). The turbulent flow field around a circular cylinder. *Experiments in Fluids*, 8(1), 1-12. <https://doi.org/10.1007/BF00203058>
- Das, V. K., Chaudhuri, S., Barman, K., Roy, S., & Debnath, K. (2022). Pier scours in fine-grained non-cohesive sediment and downstream siltation, an experimental approach. *Physical Geography*, 43(3), 365-382.
- Debnath, K., & Chaudhuri, S. (2010a). Bridge pier scour in clay-sand mixed sediments at near-threshold velocity for sand. *Journal of Hydraulic Engineering*, 136(9), 597-609.
- Debnath, K., & Chaudhuri, S. (2010b). Laboratory experiments on local scour around cylinder for clay and clay–sand mixed beds. *Engineering Geology*, 111(1-4), 51-61. <https://doi.org/https://doi.org/10.1016/j.enggeo.2009.12.003>
- Debnath, K., & Chaudhuri, S. (2012). Local scour around non-circular piers in clay–sand mixed cohesive sediment beds. *Engineering Geology*, 151, 1-14.

- Debnath, K., Nikora, V., & Elliott, A. (2007). Stream bank erosion: in situ flume tests. *Journal of irrigation and drainage engineering*, 133(3), 256-264.
[https://doi.org/https://doi.org/10.1061/\(ASCE\)0733-9437\(2007\)133:3\(25\)](https://doi.org/https://doi.org/10.1061/(ASCE)0733-9437(2007)133:3(25))
- Dey, S. (1995). Three-dimensional vortex flow field around a circular cylinder in a quasi-equilibrium scour hole. *Sādhanā*, 20(6), 871-885.
<https://doi.org/10.1007/BF02745871>
- Dey, S., Bose, S. K., & Sastry, G. L. (1995). Clear water scour at circular piers: a model. *Journal of Hydraulic Engineering*, 121(12), 869-876.
[https://doi.org/https://doi.org/10.1061/\(ASCE\)0733-9429\(1995\)121:12\(869\)](https://doi.org/https://doi.org/10.1061/(ASCE)0733-9429(1995)121:12(869))
- Dey, S., & Papanicolaou, A. (2008). Sediment threshold under stream flow: A state-of-the-art review. *KSCE Journal of Civil Engineering*, 12(1), 45-60.
<https://doi.org/10.1007/s12205-008-8045-3>
- Dey, S., & Raikar, R. V. (2007). Characteristics of horseshoe vortex in developing scour holes at piers. *Journal of Hydraulic Engineering*, 133(4), 399-413.
- Dey, S., & Zanke, U. C. E. (2004). Sediment Threshold with Upward Seepage. *Journal of Engineering Mechanics*, 130(9), 1118-1123.
[https://doi.org/10.1061/\(asce\)0733-9399\(2004\)130:9\(1118\)](https://doi.org/10.1061/(asce)0733-9399(2004)130:9(1118))
- Dheyab, A. S., & Günal, M. EXPERIMENTAL INVESTIGATION OF LOCAL SCOUR DEPTH AROUND CYLINDRICAL BRIDGE PIERS IN NON-COHESIVE SEDIMENTS AT NEAR-THRESHOLD VELOCITY FOR SAND.
- Dheyab, A. S., & Günal, M. (2023). Experimental Investigation on the Effectiveness of Nanosilica for Reducing Local Scour Around Cylindrical Bridge Piers. *Arabian Journal for Science and Engineering*, 1-13.
<https://doi.org/https://doi.org/10.1007/s13369-023-08446-9>
- Dheyab, A. S., & GÜNAL, M. (2024a). *Experimental And Numerical Study for Local Scour Around Cylindrical Bridge Pier in Non-Cohesive Sediment Bed* 4th International Congress of Engineering and Natural Sciences (ICENSS 2024), Ankara / TURKEY.
- Dheyab, A. S., & Günal, M. (2024b). An experimental investigation for the determination of the optimum ratio of nano clay for reducing local scour around a cylindrical bridge pier. *Water Supply*, ws2024164.

- Dheyab, A. S., & GÜNAL, M. (2024c). Prediction of Local Scour Depth Around Bridge Piers in Clay-Sand Bed using The ANN Method. *Iraqi Journal of Civil Engineering* 18(1), 50-60. <https://doi.org/10.37650/ijce.2024.180104>
- Ettema, R. (1976). *Influence of bed material gradation on local scour*. University of Auckland.
- Ettema, R. (1980). Scour at bridge piers.
- Ettema, R., Melville, B. W., & Barkdoll, B. (1998). Scale effect in pier-scour experiments. *Journal of Hydraulic Engineering*, 124(6), 639-642.
- Farooq, R., & Ghumman, A. R. (2019). Impact assessment of pier shape and modifications on scouring around bridge pier. *Water*, 11(9), 1761.
- Fernando De Falco, R. M. (2002). The monitoring of bridges for scour by sonar and sediment. *NDT&E International*, 35(2), 117-123.
- FHWA-RD-03-052, F. H. A. R. a. T. (2005). *Chapter 2 - Field Observations and Evaluations of Streambed Scour At Bridges*. <https://www.fhwa.dot.gov/publications/research/infrastructure/hydraulics/03052/02.cfm>
- Firat, M., & Gungor, M. (2009). Generalized regression neural networks and feed forward neural networks for prediction of scour depth around bridge piers. *Advances in Engineering Software*, 40(8), 731-737.
- Forde, M. C., McCann, D. M., Clark, M. R., Broughton, K. J., Fenning, P. J., & Brown, A. (1999). Radar measurement of bridge scour. *NDT & E International*, 32(8), 481-492. [https://doi.org/https://doi.org/10.1016/S0963-8695\(99\)00026-2](https://doi.org/https://doi.org/10.1016/S0963-8695(99)00026-2)
- Gaydarov, N., Zakharov, Y., Ivanov, K., Semenov, K., Lebedev, V., Nudner, I., Belyaev, N., Mishina, A., & Schemelinin, L. (2014). Numerical and experimental studies of soil scour caused by currents near foundations of gravity-type platforms. Proceedings of the 2014 International Conference on Civil Engineering, Energy and Environment (CEEE 2014),
- Ghasemi, E., Zahiri, A., & Rahimi, H. (2018). Using nanostructures to control local scour of bridge piers for steady and unsteady flows. *Jordan Journal of Civil Engineering*, 12(2).
- Hager, W. H., & Oliveto, G. (2002). Shields' entrainment criterion in bridge hydraulics. *Journal of Hydraulic Engineering*, 128(5), 538-542.

- Hamill, L. (1999). *Bridge hydraulics*.
- Hodi, B. (2009). Effect of blockage and densimetric Froude number on circular bridge pier local scour.
- Ibrahim, M., Helmy, A., Alafrawi, M., & El-Hazek, A. (2022). Using nanomaterial to minimize the local scour downstream of sluice gate. *Alexandria Engineering Journal*, 61(4), 3201-3214.
- Irvine, T. (2009). KARMAN VORTEX SHEDDING AND THE STROUHAL NUMBER.
- Ismael, A., Gunal, M., & Hussein, H. (2015). Effect of Bridge Pier Position on Scour Reduction According to Flow Direction. *Arabian Journal for Science and Engineering*, 40(6), 1579-1590. <https://doi.org/10.1007/s13369-015-1625-x>
- Jalal, H. K., & Hassan, W. H. (2020). Three-dimensional numerical simulation of local scour around circular bridge pier using Flow-3D software. IOP Conference Series: Materials Science and Engineering,
- Kaya, S., Seker, D. Z., Yasa, N. E., Kabdasli, S., & Tanik, A. (2007). Utility of remote sensing technology for determining characteristics of sandy beaches. *CLEAN–Soil, Air, Water*, 35(6), 654-659.
- Kho, K. T., Valentine, E., & Glendinning, S. (2004). An experimental study of local scour around circular bridge piers in cohesive soils. Proceedings 2nd International Conference on Scour and Erosion (ICSE-2). November 14.–17., 2004, Singapore,
- Kothyari, U. C., & Jain, R. K. (2008). Influence of cohesion on the incipient motion condition of sediment mixtures. *Water resources research*, 44(4).
- Lagasse, P. F., Zevenbergen, L. W., Spitz, W., & Arneson, L. A. (2012). Stream Stability at Highway Structures, Fourth Edition [Tech Report]. <https://rosap.nrl.bts.gov/view/dot/42687>
- Laursen, E. M., & Toch, A. (1956). *Scour around bridge piers and abutments* (Vol. 4). Iowa Highway Research Board Ames, IA.
- Lavelle, J., Mofjeld, H., & Baker, E. (1984). An in situ erosion rate for a fine-grained marine sediment. *Journal of Geophysical Research: Oceans*, 89(C4), 6543-6552.
- Lee, S. O., & Sturm, T. W. (2009). Effect of sediment size scaling on physical modeling of bridge pier scour. *Journal of Hydraulic Engineering*, 135(10), 793-802.

- Leone, E., Kobayashi, N., Francone, A., Bartolo, S. D., Strafella, D., D'Alessandro, F., & Tomasicchio, G. R. (2021). Use of nanosilica for increasing dune erosion resistance during a sea storm. *Journal of Marine Science and Engineering*, 9(6), 620.
- Liang, B., Du, S., Pan, X., & Zhang, L. (2020). Local Scour for Vertical Piles in Steady Currents: Review of Mechanisms, Influencing Factors and Empirical Equations. *Journal of Marine Science and Engineering*, 8(1), 4. <https://www.mdpi.com/2077-1312/8/1/4>
- Lienhard, J. H. (1966). *Synopsis of lift, drag, and vortex frequency data for rigid circular cylinders* (Vol. 300). Technical Extension Service, Washington State University Pullman, WA.
- Mavis, F., & Laushey, L. (1949). Formula for velocity at beginning of bed-load movement is reappraised. *Civil Engineering*, 19, 38-39.
- Melville, B. (2008a). The physics of local scour at bridge piers. Fourth international conference on scour and erosion,
- MELVILLE, B. (2008b). *THE PHYSICS OF LOCAL SCOUR AT BRIDGE PIERS* Fourth International Conference on Scour and Erosion,
- Melville, B. W. (1997). Pier and abutment scour: integrated approach. *Journal of Hydraulic Engineering*, 123(2), 125-136.
- Melville, B. W., & Chiew, Y.-M. (1999). Time scale for local scour at bridge piers. *Journal of Hydraulic Engineering*, 125(1), 59-65.
- Melville, B. W., & Coleman, S. E. (2000). *Bridge scour*. Water Resources Publication.
- Molinas, A., & Hosni, M. M. (1999). *Effects of gradation and cohesion on bridge scour: Volume 4: Experimental study of scour around circular piers in cohesive soils*.
- Molinas, A., Jones, S., & Hosny, M. (1999). Effects of cohesive material properties on local scour around piers. *Transportation research record*, 1690(1), 164-174.
- Moncada-M, A. T., Aguirre-Pe, J., Bolívar, J. C., & Flores, E. J. (2009). Scour protection of circular bridge piers with collars and slots. *Journal of Hydraulic Research*, 47(1), 119-126. <https://doi.org/10.3826/jhr.2009.3244>
- Morsi, S., & Alexander, A. (1972). An investigation of particle trajectories in two-phase flow systems. *Journal of Fluid Mechanics*, 55(2), 193-208.

- Mueller, D. S. (1996). *Local scour at bridge piers in nonuniform sediment under dynamic conditions*. Colorado State University.
- Muzzammil, M. (2010). ANFIS approach to the scour depth prediction at a bridge abutment. *Journal of Hydroinformatics*, 12(4), 474-485.
- Najafzadeh, M., Etemad-Shahidi, A., & Lim, S. Y. (2016). Scour prediction in long contractions using ANFIS and SVM. *Ocean Engineering*, 111, 128-135.
- Nassar, M. A., Ibrahim, A. A., & Negm, A. M. (2009). Modeling of Local Scour Down Stream of Hydraulic Structures Using Support Vector Machines (SVMS). Proc. Of 6th Int. Conf. on Environmental Hydrology, Cairo, Egypt,
- Norhasri, M. M., Hamidah, M., & Fadzil, A. M. (2017). Applications of using nano material in concrete: A review. *Construction and Building Materials*, 133, 91-97.
- Novak, P., & Nalluri, C. (1974). *CORRELATION OF SEDIMENT INCIPIENT MOTION AND DEPOSITION*.
- Parchure, T. M., & Mehta, A. J. (1985). Erosion of soft cohesive sediment deposits. *Journal of Hydraulic Engineering*, 111(10), 1308-1326.
- Pizarro, A., Manfreda, S., & Tubaldi, E. (2020a). The science behind scour at bridge foundations: A review. *Water*, 12(2), 374.
- Pizarro, A., Manfreda, S., & Tubaldi, E. (2020b). The Science behind Scour at Bridge Foundations: A Review. *Water*, 12(2). <https://doi.org/10.3390/w12020374>
- Prendergast, L. J., & Gavin, K. (2014). A review of bridge scour monitoring techniques. *Journal of Rock Mechanics and Geotechnical Engineering*, 6(2), 138-149. <https://doi.org/10.1016/j.jrmge.2014.01.007>
- R. Ettema, E. A. M., B. W. Melville, A. A. Yassin. (1998). LOCAL SCOUR AT SKEWED PIERS. *Journal of Hydraulic Engineering*, 124(7). [https://doi.org/https://doi.org/10.1061/\(ASCE\)0733-9429\(1998\)124:7\(756\)](https://doi.org/https://doi.org/10.1061/(ASCE)0733-9429(1998)124:7(756))
- Raeisi, N., & Ghomeshi, M. (2020). Effect of bridge pier diameter on maximum depth of scour impacts on the environment. *SN Applied Sciences*, 2(11), 1-12.
- Rambabu, M., Rao, S. N., & Sundar, V. (2003). Current-induced scour around a vertical pile in cohesive soil. *Ocean Engineering*, 30(7), 893-920.
- Ranjbar Zahedani, M., Keshavarzi, A., Khabbaz, H., & Ball, J. (2019). *Flow Structures Around a Circular Bridge Pier with a Submerged Prism*

- at *Upstream* Proceedings of the 4th World Congress on Civil, Structural, and Environmental Engineering,
- Raudkivi, A. J. (1986). Functional trends of scour at bridge piers. *Journal of Hydraulic Engineering*, 112(1), 1-13.
- Raudkivi, A. J., & Ettema, R. (1983). Clear-water scour at cylindrical piers. *Journal of Hydraulic Engineering*, 109(3), 338-350.
[https://doi.org/10.1061/\(ASCE\)0733-9429\(1983\)109:3\(338\)](https://doi.org/10.1061/(ASCE)0733-9429(1983)109:3(338))
- Ravens, T. M., & Gschwend, P. M. (1999). Flume measurements of sediment erodibility in Boston Harbor. *Journal of Hydraulic Engineering*, 125(10), 998-1005.
- Richardson, E., & Davis, S. (2001). Evaluating scour at bridges: Hydraulic engineering circular No. 18. Rep. FHWA NHI, 01-001.
- Richardson, E. V., & Davis, S. R. (2001). *Evaluating scour at bridges*.
- Richardson, E. V. a. D., S.R. (2001). *Evaluating Scour at Bridges*, .
https://www.fhwa.dot.gov/engineering/hydraulics/library_arc.cfm?pub_number=17&id=37
- Richardson, J. E., & Panchang, V. G. (1998). Three-dimensional simulation of scour-inducing flow at bridge piers. *Journal of Hydraulic Engineering*, 124(5), 530-540.
- Robert Ettema, G. K., Marian Muste. (2006). Similitude of Large-Scale Turbulence in Experiments. *Journal of Hydraulic Engineering*, 132(1).
[https://doi.org/10.1061/\(ASCE\)0733-9429\(2006\)132:1\(33\)](https://doi.org/10.1061/(ASCE)0733-9429(2006)132:1(33))
- Rubinow, S. I., & Keller, J. B. (1961). The transverse force on a spinning sphere moving in a viscous fluid. *Journal of Fluid Mechanics*, 11(3), 447-459.
- Ruff, J. F., & Abt, S. R. (1980). Evaluating Scour at Culvert Outlets. *Transportation research record*, 785, 37.
- Saffman, P. (1965). The lift on a small sphere in a slow shear flow. *Journal of Fluid Mechanics*, 22(2), 385-400.
- Salaheldin, T. M., Imran, J., & Chaudhry, M. H. (2004). Numerical modeling of three-dimensional flow field around circular piers. *Journal of Hydraulic Engineering*, 130(2), 91-100.
- Schaap, H. S., & Caner, A. (2021). Bridge collapses in Turkey: causes and remedies. *Structure and Infrastructure Engineering*, 1-16.
<https://doi.org/10.1080/15732479.2020.1867198>

- Schlichting, H., & Kestin, J. (1961). *Boundary layer theory* (Vol. 121). Springer.
- Sheppard, D. M., Odeh, M., & Glasser, T. (2004). Large scale clear-water local pier scour experiments. *Journal of Hydraulic Engineering*, 130(10), 957-963.
- Shields, A. (1936). *APPLICATION OF SIMILARITY PRINCIPLES AND TURBULENCE RESEARCH TO BED-LOAD MOVEMENT* [Technischen Hochschule Berlin].
- Shirole AM, H. R. (1991). *PLANNING FOR A COMPREHENSIVE BRIDGE SAFETY ASSURANCE PROGRAM* Bridge Engineering Conference, 3rd, Denver, Colorado, USA.
- Sonia Devi, Y., & Barbhuiya, A. (2017). Bridge pier scour in cohesive soil: a review. *Sādhanā*, 42(10), 1803-1819.
- Steinmetz, D. R. (2007). *Texture evolution in processing of polystyrene-clay nanocomposites* [Drexel University].
- Tabarsa, A., Latifi, N., Meehan, C. L., & Manahiloh, K. N. (2018). Laboratory investigation and field evaluation of loess improvement using nanoclay—A sustainable material for construction. *Construction and Building Materials*, 158, 454-463.
- Ting, F. C., Briaud, J.-L., Chen, H., Gudavalli, R., Perugu, S., & Wei, G. (2001). Flume tests for scour in clay at circular piers. *Journal of Hydraulic Engineering*, 127(11), 969-978.
- Tolhurst, T., Black, K., Paterson, D., Mitchener, H., Termaat, G., & Shayler, S. (2000). A comparison and measurement standardisation of four in situ devices for determining the erosion shear stress of intertidal sediments. *Continental Shelf Research*, 20(10-11), 1397-1418.
- Uddin, F. (2008). Clays, nanoclays, and montmorillonite minerals. *Metallurgical and Materials Transactions A*, 39(12), 2804-2814.
- Van Rijn, L. C. (1993). *Principles of sediment transport in rivers, estuaries and coastal seas* (Vol. 1006). Aqua publications Amsterdam.
- Vijayasree, B., Eldho, T., Mazumder, B., & Ahmad, N. (2019). Influence of bridge pier shape on flow field and scour geometry. *International Journal of River Basin Management*, 17(1), 109-129.
- Wang, C., Yu, X., & Liang, F. (2017a). A review of bridge scour: mechanism, estimation, monitoring and countermeasures. *Natural Hazards*, 87, 1881-1906.

- Wang, C., Yu, X., & Liang, F. (2017b). A review of bridge scour: mechanism, estimation, monitoring and countermeasures. *Natural Hazards*, 87(3), 1881-1906. <https://doi.org/10.1007/s11069-017-2842-2>
- Webmaster, N. E. D. O. C. (2020). *Yangtze River Mouth*. Ocean Color Webmaster.
- Whitehouse, R. (1998). *Scour at marine structures*.
- Williams, P., Balachandar, R., & Bolisetti, T. (2016). Effect of densimetric Froude number on local bridge pier scour.
- Yang, C. T. (1973). Incipient motion and sediment transport. *Journal of the hydraulics division*, 99(10), 1679-1704.
- Yang, J., Low, Y. M., Lee, C.-H., & Chiew, Y.-M. (2018). Numerical simulation of scour around a submarine pipeline using computational fluid dynamics and discrete element method. *Applied Mathematical Modelling*, 55, 400-416.
- Yu, X., Zhang, W., & Houtink, A. (2020). Impact of river discharge seasonality change on tidal duration asymmetry in the Yangtze River Estuary. *Scientific reports*, 10(1), 1-17.
- Zanke, U. (1977). NEUER ANSATZ ZUR BERECHNUNG DES TRANSPORTBEGINNS VON SEDIMENTEN UNTER STROEMUNGSEINFLUSS.
- Zhao, M., Cheng, L., & Zang, Z. (2010). Experimental and numerical investigation of local scour around a submerged vertical circular cylinder in steady currents. *Coastal Engineering*, 57(8), 709-721. <https://doi.org/https://doi.org/10.1016/j.coastaleng.2010.03.002>

CURRICULUM VITAE

Abubaker Sami Dheyab DHEYAB

EDUCATION

09/2019 - 08/2024 **Doctor of Philosophy Degree in Civil Engineering**

Gaziantep University, Gaziantep, Turkey.

01/2016 - 11/2017 **Master's Degree in Civil Engineering**

Gaziantep University, Gaziantep, Turkey

09/2009- 06/2013 **Bachelor's Degree in Civil Engineering**

University of Anbar, Anbar, Iraq.

PUBLICATION

1. DHEYAB, A.S, Gunal, M. 2024, Arabian Journal for Science and Engineering, Experimental Investigation on the Effectiveness of Nano Silica for Reducing Local Scour around Cylindrical Bridge Piers. <https://doi.org/10.1007/s13369-023-08446-9>.
2. DHEYAB, A.S, Gunal, M. 2024, Water Supply, An experimental Investigation for the determination of the optimum ratio of Nano clay for reducing local scour around a cylindrical bridge pier <https://doi.org/10.2166/ws.2024.164>.
3. DHEYAB, A.S, Gunal, M. 2024, Iraqi Journal of Civil Engineering, Utilizing Artificial Neural Networks for Predicting Local Scour Depth in Clay-Sand Beds. 10.37650/ijce.2024.180104.
4. DHEYAB, A.S, Gunal, M. 2024, SELCUK 10th INTERNATIONAL CONFERENCE ON APPLIED SCIENCES, EXPERIMENTAL INVESTIGATION OF LOCAL SCOUR DEPTH AROUND CYLINDRICAL BRIDGE PIERS IN NON-COHESIVE SEDIMENTS AT NEAR- THRESHOLD VELOCITY FOR SAND.

5. DHEYAB, A.S, Gunal, M. 2024, 4.International Congress of Engineering and Natural Sciences Studies 24 -25 May 2024,Ankara,Experimental And Numerical Study for Local Scour Around Cylindrical Bridge Pier in non-cohesive sediment bed.
6. DHEYAB, A.S.Alasta, M.S., Ali, A.S.A., Ebrahimi, S., Ashiq, M.M., , AlMasri, A., Alqatanani, A., and Khorram, M. 2022. Modelling of Local Scour Depth Around Bridge Pier Using FLOW 3D. CRPASE: TRANSACTIONS OF CIVIL AND ENVIRONMENTAL ENGINEERING, 8(2): 1-9. doi:<https://doi.org/https://doi.org/10.52547/crpase.8.2.2781>.
7. DHEYAB, A.S., DHEYAALDIN, M.H., and ÖZAKÇA, M. 2017. Numerical Investigation of Structural Behaviour of Fiber Reinforced Polymers Filled Sandwich Panels. IJiet JOURNAL, DOI: <http://dx.doi.org/10.21172/ijiet.83.002>.
8. DHEYAALDIN, M.H., ÖZAKÇA, M., and DHEYAB, A.S. 2017. Effect of stiffeners on structural behaviour of steel liquids tank. The International Journal of Energy and Engineering Sciences, 2(3).