Assessment of Soil Arching in a Pile-supported Railway Embankment under the Moving Train Load and Earthquake

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Doctor of Philosophy

under the supervision of Dr. Sanjay Nimbalkar and A/Prof. Behzad Fatahi

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, *Naveen Kumar Meena* declare that this thesis, is submitted in fulfilment of the requirements for the award of *Doctor of Philosophy*, in the *School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Date: 03/January/2022

Dedicated

To my family and friends

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List of publications

RELATED TO THE THESIS:

Journal articles

1. **Meena, N. K.** Nimbalkar, S. Fatahi, B. and Yang, G. (2020). "Effects of soil arching on behavior of pile-supported railway embankment: 2D FEM approach", *Computers and Geotechnics*, vol. 123, pp. 103601.
2. **Meena, N. K.** and Nimbalkar, S. "Two-Dimensional Analytical Solution of Soil Arching in a Pile-supported Geosynthetic-reinforced Railway Embankment", *Geosynthetics International*, (***Under review***)
3. **Meena, N. K.** Nimbalkar, S. and Fatahi, B. "Investigation of soil arching in a geosynthetic-reinforced pile-supported embankment under the earthquake". (***draft under preparation***)

Book chapter

1. Nimbalkar, S. and **Meena, N. K.** (2022). "Static and Seismic Assessment of Soil Arching in Piled Embankments" In: Kolathayar S., Pal I., Chian S.C., Mondal A. (eds) *Civil Engineering for Disaster Risk Reduction*. Springer Tracts in Civil Engineering. Springer, Singapore.

Peer-reviewed conference papers

1. **Meena, N. K.** Nimbalkar, S. and Fatahi, B. (2019). "Finite element modeling of soil arching in pile supported embankment: 2D approach", In *International Congress and Exhibition "Sustainable Civil Infrastructures"* (pp. 40-50). Springer, Cham.

2. **Meena, N. K.**, and Nimbalkar, S. (2019). "Seismic assessment of soil arching in piled embankment using finite element approach", In *4th Australasian Conference on Computational Mechanics*, Hobart, Australia, p. 24.
3. **Meena, N. K.**, Nimbalkar, S., and Fatahi, B. (2021). "Finite Element Analysis of Soil Arching in Piled Embankment", In *International Conference of the International Association for Computer Methods and Advances in Geomechanics* (pp. 817-824). Springer, Cham.
4. **Meena, N. K.**, Nimbalkar, S. (2021). "Soil Arching in Geosynthetic-Reinforced Pile-supported Railway Embankments under the Seismic Condition", *Australian Earthquake Engineering Society (AEES) conference*.
5. **Meena, N. K.**, Nimbalkar, S., and Fatahi, B. (2022). "Finite element simulation of the soil arching in a pile-supported railway embankment considering train loading", In *Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering*, Sydney 2022.

OTHERS:

1. **Meena, N. K.,** and Nimbalkar, S. (2019). "Effect of water drawdown and dynamic loads on piled raft: two-dimensional finite element approach", *Infrastructures*, 4(4), 75.
2. Rajeev, A., **Meena, N. K.**, and Pallav, K. (2019). "Comparative Study of Seismic Design and Performance of OMRF Building Using Indian, British, and European Codes", *Infrastructures*, 4(4), 71.

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The following symbols and abbreviations are used in this thesis:

Notations

A	Effective surface area of a pile
A_{Emtop}	Area of embankment top
A_{ef}	Effective surface area of a single pile
A_{h}	Horizontal acceleration
A_{p}	Cross-sectional area of a pile
A_{s}	Area of clear pile spacing
A_{sb}	Area of subballast
A_{v}	Vertical acceleration
A_{wall}	Area of the pile wall
$A_{\sigma track}$	Area of applied stress due to the track
$A_{\sigma train}$	Area of applied stress due to the train loading
$A_{\sigma RT}$	Area of applied stress on the soil arching crown
b'	Plate width
C_{c}	Soil arching coefficient
c'	Effective cohesion
D	Pile diameter
D_{act}	Active depth of subsoil
d	Width of the pile wall
E	Elastics modulus
E_{em}	Elastics modulus of embankment
E_{eq}	Equivalent elastic modulus of a pile

E_{geo}	Elastics modulus of geosynthetic layer
E_p	Elastic modulus of a pile
E_{sub}	Elastic modulus of subsoil
E_{set}	Settlement efficacy
E_{str}	Stress efficacy
E_o	One-dimensional modulus of the subsoil
g	Gravity load
F	Uniform force acting on the embankment lateral boundary
F_d	Design wheel load
F_s	Static wheel load
f_{eq}	Dominant frequency
h	Embankment height
h_{arch}	Soil arching height
h_{opt}	Optimum embankment height
h'	Embankment depth up to soil arching crown
I_{pile}	Second moment of the area of a pile
I_{sub}	Second moment of the area of subsoil
I_{wall}	Second moment of the area of a pile wall
J	Stiffness of geosynthetic layer
K	Lateral stress coefficient
K_o	Lateral stress coefficient at rest
K_a	Lateral stress coefficient at active stage
K_p	Lateral stress coefficient at passive stage
k_h	Coefficient of horizontal acceleration

k_s	Modulus of the subgrade reaction
k_{soil}	Soil stiffness parameter
k_v	Coefficient of vertical acceleration
N_{em}	Normalised embankment height
N_{vs}	Normalised vertical stress
l	Length of sleeper
l_d	diagonal spacing between pile
M_L	Earthquake magnitude
m	Mass of the embankment
P	Total force acting on the pile head
P_c	Vertical stress on the pile head
Q	Total force carried by the pile
q	Surcharge on the embankment top
r	Radial distance of soil arching
s	Pile spacing
s_x	Pile spacing in x-axis
s_y	Pile spacing in y-axis
T	Tension in geosynthetic layer
T_{max}	Maximum tension in a geosynthetic layer
t_{EQ}	Earthquake excitation time
t_{geo}	Thickness of geosynthetic layer
V	Train speed
W_{track}	Total weight of track
y	Maximum deflection of geosynthetic layer

a, b, and c	Elastic modulus coefficients relating to *SAR*
α and β	Damping coefficients
α' and β'	Mean value of impact factor
γ	Unit weight
γ'	Standard deviation of the impact factor
ε_{geo}	Axial strain in geosynthetic layer
Φ	Dynamic impact factor
λ	Interface factor
$\Delta_{lateral}$	Lateral displacement
μ	Interface frictional coefficient
δ	Soil settlement without piles
δ_{int}	Interface friction angle between pile and the surrounding subsoil
δ_{em}	Settlement of embankment
δ_{es}	Total settlement of subsoil
δ_{P}	Soil settlement with piles
δ_{sp}	Settlement of a plate
$\delta/(s\text{-}d)$	Normalised settlement of embankment
υ	Poisson's ratio
ρ	Material density
σ_{geo}	Vertical stress on the geosynthetic layer
σ_{h}	Horizontal stress
σ_{i}	Vertical stress, just below the inner boundary of the soil arching
σ_{max}	Maximum vertical stress

σ_n Normal stress in the interface

σ_p Vertical stress on the pile

σ_r Radial stress in soil arching

σ_s Vertical stress on the subsoil

σ_t Train-induced vertical stress

σ_{track} Self-weight of the rail track

σ_{train} Self-weight of the moving train

σ_{RT} Total vertical stress on the soil arching crown

σ_{up} Upward vertical reaction stress on the bottom of the geosynthetic layer

σ_v Vertical stress

σ_{vEQ} Additional vertical stress due to a seismic excitation

σ_o Radial stress at soil arching crown

σ_θ Tangential stress in soil arching

τ Shear stress along with the geosynthetic layer interface

τ_{bottom} Shear stress along with the geosynthetic layer and subsoil

τ_{top} Shear stress along with the geosynthetic layer and embankment

ϕ' Effective friction angle of soil

ψ Dilation angle of soil

ξ_o Damping ratio

Abbreviations

2D Two-dimensional

3D Three-dimensional

ARE	American Railways Engineering Association
ARR	Area replacement ratio
CA	Concentric arch
CINPE4	Four-node plane strain linear infinite element
CPE4R	Four-node plane strain element with reduced integration
CPE8R	Eight-node, reduced-integration, two-dimensional, quadratic solid element
DAF	Dynamic amplification factor
DEM	Discrete element method
EA	Equivalent area
EEM	Equivalent elastic modulus
EFS	Equivalent flexural stiffness
FEM	Finite element method
FFT	Fast Fourier transform
FLAC	Fast lagrangian analysis of continua
GRC	Ground reaction curve
GRPS	Geosynthetic-reinforced pile-supported
MC	Mohr-Coulomb
MCC	Modified Cam Clay
ORE	Office of Research and Experiments
PFC	Particle flow code
PGA	Peak ground acceleration
SAR	Soil arching ratio
SCR	Stress concentration ratio

Abstract

The pile-supported embankments provide feasible solutions for railway infrastructure projects on the soft soil and allow rapid construction with less differential settlement. In the pile-supported embankments, the embankment load including surcharge is transferred to the pile heads through a load transfer mechanism known as soil arching. The pile-supported railway embankments often encounter dynamic loading due to the moving trains and earthquake. The dynamic loading may influence the soil arching phenomenon. Over the past decade, soil arching has been significantly studied under static conditions, and several analytical methods have been proposed to evaluate soil arching. However, the dynamic behaviour of soil arching under moving train-induced load and earthquake is yet to be investigated. Furthermore, the vertical stress on soil arching crown in the existing analytical methods is considered only due to self-weight of embankment and the stress distribution due to additional surcharge is neglected, resulting in inaccurate predictions.

In this thesis, finite element method (FEM)-based numerical analyses are performed to investigate the dynamic behaviour of soil arching. The physical visualisation of the soil arching phenomenon in the pile-supported embankments is very complex and usually requires a large setup. Therefore, numerical analysis is the unsurpassed approach to investigate soil arching. The two-dimensional (2D) unit cell model is analysed. A 2D idealisation method (i.e. equivalent area method) is used to convert a hypothetical three-dimensional (3D) problem into 2D to reduce the complexity and computational time.

This work begins with investigating the soil arching in a railway embankment under static condition. The equivalent dynamic load induced by a moving train is

chosen for train loading. The results confirm that the analysed numerical model can predict the soil arching phenomenon in a pile-supported railway embankment with reasonable accuracy. The key parameters of pile-supported embankments and their optimum value are identified. The inclusion of a geosynthetic layer is also investigated. The comparison of different analytical methods has also been reported to identify the variation in different methods. Subsequently, the accuracy of the existing analytical methods is improved by incorporating a realistic approximation of vertical stress on the soil arching crown. Results show that the failure of soil arching at the pile top is critical in the 3D condition, whereas the soil arching failure at the crown is more critical in the 2D condition.

Subsequently, the influence of earthquake-induced loading on soil arching phenomenon is investigated. The results show that soil arching is significantly affected under the seismic excitation. The parametric investigation reveals that friction angle of embankment fill should be higher for better performance of pile-supported embankment during an earthquake. The geosynthetic layer at the base of the embankment encourages stress transfer to the pile head through the membrane effect. Also, the amplitude of the earthquake significantly affects the mobilisation of soil arching.

Finally, the mobilisation of soil arching under moving train-induced dynamic loading is investigated. The results revealed that the dynamic loading significantly affects the soil arching phenomenon and should be considered during the design of a pile-supported railway embankment. The application of a geosynthetic layer enhances the load transfer from the subsoil to the pile head through the membrane effect.

Therefore, the findings of this thesis enhance the current knowledge of the dynamic behaviour of soil arching under the moving train load and earthquake. The presented analytical methods can be used for accurate evaluation of vertical stress on the soil arching crown.